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THE EFFECT OF FUEL INJECTOR GEOMETRY ON THE FLOW STRUCTURE OF
A SWIRL STABILIZED GAS TURBINE BURNER

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Abstract

This thesis presents an experimental study on the effect of geometry on the flow structure of experimental swirl-stabilized gas turbine burners. The purpose of this project was to test a number of geometric changes to a burner and determine how these changes affected the flow field in order to evaluate how they might affect a combustion process.

Tests were initially conducted in a water channel on several full-scale experimental burner models, which included the use of elliptic outlet geometries and a vortex breakdown stabilizer. Velocity and phase-averaged PLIF measurements are presented for the different burner configurations. More extensive measurements were then conducted in a cold flow air channel on a series of one-quarter scale experimental swirlers. The scale models were designed with different geometries in order to test the effect of different blade angles and spacings. The models were also tested with a vortex breakdown stabilizer and a mixing section located between the swirler outlet and the sudden expansion. A scale model burner with an elliptic outlet was also tested. Stereo PIV measurements are presented for the different configurations.

Water channel measurements identified axial oscillation of the vortex breakdown bubble as the primary driving mechanism behind combustion instabilities. Tests showed that the elliptic geometry damped oscillation of the breakdown bubble and the vortex breakdown stabilizer physically anchored the breakdown bubble inside the burner cone. Tests in the air channel showed that wider blade spacing resulted in a reduced swirl number and a weaker vortex breakdown. A wider blade angle was observed to increase the swirl and the strength

of the vortex breakdown. Certain configurations of the breakdown stabilizer were seen to increase the strength of the vortex breakdown while other configurations forced it to form in an unstable configuration. The use of a mixing section at the swirler outlet caused the vortex breakdown bubble to propagate upstream inside of the mixing tube. The elliptic swirler exhibited a very complex flow structure, indicative of axis-switching.

For Susan

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1 Introduction

In the 1930's, as compressor aerodynamics matured to the necessary level, development of gas turbine engines producing positive net power became possible, and by the early 1940's their potential for electrical power production and aircraft propulsion was fully recognized. Since their industrial success, the gas turbine industry has become very competitive with manufacturers continually striving for higher efficiencies and more reliable machines.

Over the last three decades, as pollutant emission regulations have become increasingly strict, there has been a widespread movement towards the use of lean premixed combustion systems and convectively cooled combustion chambers. Lean premixed combustion systems allow reduced pollutant emissions and higher combustion efficiency, but are more susceptible to combustion instabilities. Combustion instabilities can result in reduced combustion efficiency and increased pollutant emissions, as well as damage to the entire gas turbine installation.

The purpose of this project is to conduct research into passive methods of controlling combustion instabilities and reducing pollutant emissions. In the first part of the project, gas turbine burners with various geometric modifications, including the use of non-circular outlets and vortex generators, were tested in a cold flow water channel. The purpose of the tests was to identify the mechanisms behind certain combustion instabilities and to evaluate how modifications to the burners affected the instabilities. In the second part of this project, velocity field measurements were conducted on a series of experimental scale-model gas turbine burners in a cold flow test rig in order to evaluate the effect of various geometric

modifications including blade spacing, blade angle, mixing section length and the effect of a solid body, called a lance, near the recirculation zone. Additionally, numerical simulations were conducted on the experimental swirlers in order to predict the flow structure.

1.1 Gas turbine combustion systems

A gas turbine operates on an open Brayton cycle. Air entering the engine undergoes a nearly isentropic compression process and is then mixed with fuel. The flammable mixture is combusted and the working fluid undergoes a nearly constant pressure temperature rise, followed by a nearly isentropic expansion as the hot, high-pressure fluid passes through the turbine section generating net positive work. Since an open cycle is used, the low-pressure, high-temperature exhaust gas is not cycled back to the compressor, but may be used to boil water for a steam turbine in a cogenerative power plant or to preheat the air between the compressor and combustor in a regenerative power plant.[1]

Standard gas turbine combustion chambers use a diffusion type flame where excess fuel is rapidly mixed with air and combusted, then diluted with additional air before exiting the combustion chamber. In recent years manufacturers have begun to move away from standard combustion chambers in favour of combustion systems that are able to provide increased combustion efficiency with reduced exhaust emissions. Modern schemes of improving combustion efficiency while reducing pollutant emissions are discussed in section 1.3.

1.2 Flame stabilization

The purpose of the burner in a gas turbine engine is to mix the fuel and air and to stabilize the combustion process inside the combustion chamber. In order to stabilize the flame, the burner decelerates the incoming high-speed air to a velocity below the turbulent flame speed. The flame front stabilizes along the locus of points where the air velocity is equal to the flame speed. Such a deceleration can be accomplished in several different ways, most of which involve creating a stagnation point.

By far, the most common method of flame stabilization in modern gas turbine combustors is swirl stabilization. A swirl stabilized burner imparts an azimuthal velocity component to the flammable mixture upstream of the combustion zone. The degree of swirl in the flow is quantified by the dimensionless parameter, S_N , known as the swirl number. There are different ways of defining the swirl number, however the most common is:

$$S_N = \frac{\int_0^R \rho U W r^2 dr}{R \int_0^R \rho U^2 r dr} \quad (1)$$

Where U and W are the axial and tangential velocity components respectively, and R is the swirler radius. This number is a ratio of the axial flux of angular momentum to the axial thrust. Recirculation is generally not observed for swirl numbers below 0.4, so most swirl-stabilized burners are designed for swirl numbers greater than 0.6.[2] The swirling flow spreads as it moves downstream and centrifugal force creates a low pressure zone in the centre of the flow. At a certain point downstream, the low pressure region in the centre of the flow causes the vortex to collapse inwards on itself in a process known as vortex breakdown. This creates a recirculation zone in the centre of the flow. The structure and stability of the

vortex breakdown is crucial to the combustion and is discussed further in section 1.5.

Some swirl stabilized combustion systems also feature a sudden expansion at the outlet of the swirler which creates a second recirculation zone around the circumference of the swirling flow. Swirl stabilized burners create one or two recirculating regions of strong shear and high turbulence and therefore provide much better mixing than can be obtained from other stabilization methods. Swirl stabilized combustion is also advantageous because it is stable over a wide range of operating conditions.

Another important parameter in the design of a swirler stabilized burner is its discharge coefficient, defined as:

$$C_D = \frac{\dot{m}}{\rho A \sqrt{\frac{2dP}{\rho}}} \quad (2)$$

Where A is the actual swirler outlet area. This is a quantity that relates the actual mass flow rate through a burner to the theoretical mass flow rate based on its pressure drop. The discharge coefficient is smaller for burners that induce a greater pressure drop. In general, swirl stabilized burners have a low discharge coefficient because the vortex breakdown bubble effectively blocks off the central portion of its outlet.[3] The quantity $A \cdot C_D$ is known as the effective outlet area of the swirler.

1.3 Low emission combustion systems

Around the middle of the twentieth century, regulations were introduced to reduce the amount of pollutant emissions from combustion systems. The first efforts in the 1950's were aimed at reducing the amount of visible smoke and particulate matter in exhaust. The

Clean Air Act of 1963 and its amendments in 1970, 1977 and 1990 have imposed increasingly strict emission standards and have targeted additional sources of pollution.[4]

With gas turbine engines, the primary concern is with production of carbon monoxide (CO), unburnt hydrocarbons (UHC), and nitric oxides (NO_x). Since nearly all gas turbines burn either natural gas or heating oil, which are relatively clean fuels, production of sulfur-based pollutants and particulate matter or smoke is usually of lesser concern.

CO and UHC are usually produced by incomplete combustion. Complete combustion is the idealized situation where all carbon present in the fuel is oxidized to carbon dioxide, all hydrogen is oxidized to water and all nitrogen passes through the combustion zone as diatomic nitrogen gas. In lean combustion, gaseous oxygen may also exist in the exhaust gas. Complete combustion of gaseous methane with excess air is shown in the following reaction:

Incomplete combustion is to be avoided since this represents wastage of both fuel and money. While CO and UHC are usually indicative of rich combustion, they may also be present in lean combustion. Localized quenching or poor mixing may cause small pockets of flammable mixture to pass through the flame front without reacting, even though the flame is not extinguished. Reduction of CO and UHC emissions can be achieved most easily by increasing the residence time, increasing the flame temperature, or burning with a equivalence ratio near 0.8. Unfortunately these methods exacerbate the production of NO_x.

Thermal NO_x and prompt NO_x are the sources that are of greatest concern in gas turbine engines. Thermal NO_x is produced by the oxidation of atmospheric nitrogen in high

temperature regions of the combustion zone. Oxygen radicals which are present in the flame from dissociation of O_2 atoms react with atmospheric nitrogen gas through the following reaction [5]:

Since the first step has a very high activation energy, it is the rate determining step and demonstrates why NO emissions are low at cooler temperatures but increase drastically at higher temperatures. Formation of thermal NO_x is a relatively slow process, taking up to 10 ms at 2500 K to reach equilibrium, and is very dependent on residence time in the flame.[3]

Prompt NO_x is formed in the combustion zone much more quickly than thermal NO. It was discovered that the formation of prompt NO_x is caused by a series of reactions initiating with the formation of HCN. Prompt NO_x comprises a significant amount of the total NO_x at low pressures and also for equivalence ratios above $\phi=1.5$. [5, 4]

Most approaches to reducing NO_x formation in standard combustion chambers are directed toward reducing the overall flame temperature, eliminating hot spots in the combustion zone and reducing the residence time. Unfortunately, as was mentioned above, these methods promote formation of CO and UHC. [3]

One of the simplest ways of reducing NO_x emissions is by reducing the overall flame temperature. Although this can be accomplished by the addition of excess air, problems with ignition and flame stability may result. An early method of reducing the flame temperature was to inject water or steam upstream of the combustion chamber liner or directly into the

combustion zone. There are a number of drawbacks associated water injection including increased capital costs, slightly increased fuel consumption, high costs for water treatment, potential corrosion of machine components, higher maintenance costs, increase in CO and UHC emissions, and an increase in combustion pressure pulsations.[3] For these reasons, many gas turbine manufacturers have developed combustion systems that are capable of meeting emissions standards without injection of water or steam. Such systems are known as dry low NO_x combustors.

One type of dry low NO_x combustor that has become increasingly popular over the last 25 years is the lean premix combustor. Such combustors feature a distributed fuel source which allows rapid and complete mixing of the fuel and air before the flammable mixture reaches the combustion zone. Such a system reduces the overall flame temperature relative to a standard combustor and eliminates hot spots in the flame that are caused by poor mixing.

ALSTOM Power Ltd. uses conical premix burners known as the EV (Environmental Vortex) and AEV (Advanced Environmental Vortex) burners. These burners have demonstrated good performance in a wide range of dry low- NO_x applications. The EV series burners are formed by two offset cone halves which form two constant width slots. Gaseous fuel may be injected into the combustion air entering the burner through a series of fuel holes inside the slots. The burner may also be operated with liquid fuel through an injection lance positioned at the cone apex. The flame is stabilized in the free space near the burner outlet. The AEV series of burners consist of a short swirler with four conical blades. Immediately downstream

of the swirler is a cylindrical mixing tube which allows additional time for complete mixing of fuel and air. Like the EV burners, the AEV burners also inject premix gaseous fuel into the slots between the conical blades and premix liquid fuel is injected through an injector at the apex of the conical swirler.[3]

1.4 Combustion instabilities

Premixed flames such as those in a dry low NO_x combustor allow improved combustion efficiency and lower pollutant emissions, but are more susceptible to combustion instabilities. Combustion instabilities can result in not only reduced combustion efficiency, but also damage to equipment. Furthermore, the deteriorated combustion process can actually lead to increased exhaust emissions.

Combustion instabilities can be classified as either intrinsic instabilities such as the Landau-Darrieus instability, or system instabilities such as the Kelvin-Helmholtz instability.[6] As the name suggests, intrinsic instabilities are intrinsic to the combustion process and do not depend on the specific combustion system. System instabilities, on the other hand, depend on the system in which the combustion process takes place and may be caused by a variety of different processes. In general, system instabilities occur because of coupling between heat release fluctuations and other system parameters such as fluid dynamic and acoustic instabilities.

In 1878, Lord Rayleigh reported on the first known work on the effects of energy release on pressure waves. He observed that combustion stability depends on the phase relationship

between pressure waves in the combustion zone and fluctuating heat release. If the heat release is in phase with the pressure fluctuations, the instability will be amplified and the system will become unstable. If the heat release and the pressure fluctuation are out of phase, the instability will be damped. Some of the most common mechanisms by which unsteady combustion may occur include a pulsating fuel supply or oscillating flame front, both caused by strong pressure oscillations, convective entropy and vorticity waves, and vortex driven instabilities.[6]

Because of the strong shear flows associated with most flame stabilization methods, the Kelvin-Helmholtz instability, a vortex driven instability, is dominant in many combustion systems. The Kelvin-Helmholtz instability is an instability in the shear layer between two flows which may have different velocities. A small disturbance can cause destabilization of the shear layer which may amplify the disturbance through the shear layer. Amplification of such a disturbance is caused by transport of vorticity, as demonstrated in figure 1. In this figure, vorticity is transported away from point A and accumulates at point C , as shown by the curved arrows. Rotation of the flow about point C causes exponential growth of the instability which results in vortex roll-up in the shear layer.[7] Such large-scale vortices are interchangeably known as large eddies, organized structures, coherent structures or simply vortices.

A large amount of research has been conducted into reacting and non-reacting shear flows over the last few decades to better understand how such flows affect the combustion process. The growth and mixing processes of shear layers are controlled by the formation and

Figure 1: Mechanism of Kelvin-Helmholtz instability through vorticity transport in a shear layer [7]

evolution of coherent structures, which are vital for large scale mixing, and their subsequent breakdown into small scale turbulence, which is vital for molecular scale mixing and initiation of the combustion process.[8] Figure 2 demonstrates how vortices shed and evolve from a circular non-swirling jet. The frequency of the initial vortex shedding is known as the most amplified frequency, and is predicted by linear stability methods to correspond to a Strouhal number of approximately 0.017, based on initial momentum thickness and mean flow velocity. Outward movement of vortices to areas of lower flow velocity allows vortices closer to the core to catch up to and merge with the slower moving vortices. Vortex merging causes the shear layer to widen and the frequency of the vortices to decrease. Eventually the widening shear layer meets in the centre of the jet at the tip of an enclosed volume known as the potential core. Vortex merging can occur several times between the nozzle opening and the end of the potential core. The frequency of the vortices at the end of the potential core is

called the preferred mode, and is usually a second or third subharmonic of the most amplified frequency with a Strouhal number of 0.25–0.5 based on the jet diameter.[8] In addition to circumferential coherent structures there are associated longitudinal instabilities that are excited. Further downstream they interact with the coherent structures causing breakdown into fine-scale turbulence. The size of the vortices that form and shed in the shear layer are closely related to the frequency of the acoustic waves generated by combustion noise. If the acoustic frequency is equal to the most amplified frequency, the vortices will be smallest, and they will be larger when the acoustic frequency is equal to the preferred mode. A process called collective interaction occurs when the acoustic frequency is lower than the preferred mode, and a several small initially shed vortices roll up into a single large vortex.[8]

It is well known that acoustic waves affect the frequency of vortex shedding, and that there is a definite possibility for the phase relation between the acoustics and vortex shedding to satisfy the Rayleigh criterion and become unstable. Rogers and Marble explored this relationship in the 1950's. They observed that periodic combustion due to vortices shed from a bluff body was driving a high frequency acoustic mode. Transverse acoustic oscillations caused periodic shedding of vortices of flammable mixture from the bluff body, which then traveled downstream to the flame front where combustion occurred. If the delay time between shedding and combustion was appropriately phased, the pressure waves caused by combustion fed energy back to the acoustic oscillations in a resonant manner.[6]

Yu et al. outlined three necessary conditions in order to sustain combustion instability. First, the acoustic fluctuations must be large in order to control vortex formation. Second,

Figure 2: Evolution of vortices shed from a circular nozzle [8]

the heat release from the vortices must be properly phased relative to the acoustic fluctuation, as outlined by the Rayleigh criterion. Lastly, the heat release needs to occur during a short period of time within a limited region of the combustion chamber.[6] These three conditions indicate that the stability of a given combustion system is very much related to the parameters of that specific system. Extensive research has been conducted into vortex formation and evolution in planar and axisymmetric flows, but there is comparatively little material available dealing with swirling flows, for which the fluid dynamics are much more complicated.

1.5 Vortex breakdown process

Most gas turbine engines use an aerodynamically generated recirculation zone to stabilize the combustion process. This recirculation zone forms along the centreline of the burner and is known as a vortex breakdown bubble. The structure and stability of the vortex breakdown bubble is crucial to the stability of combustion systems.

Experimental observation of the vortex breakdown process was first made in the late 1950's. This phenomenon was closely studied in the following years. Benjamin performed an experimental analysis on the vortex breakdown process in order to develop an explanation for its occurrence.[9] He disagreed with the theories that vortex breakdown was the result of flow instabilities or the result of flow information being propagated upstream through infinitesimal standing waves. His conclusion, rather, was that vortex breakdown represented a finite transition between two dynamically conjugate axisymmetric flow regimes and was analogous to the hydraulic jump observed in open channel flow.

Harvey conducted some of the first flow visualizations of vortex breakdown inside a divergent Perspex tube with adjustable inlet vanes.[10] He noted that intrusive velocity measurements were meaningless since introduction of a probe disturbed the breakdown. Instead, he performed flow visualizations in by injecting titanium tetrachloride smoke into the air flow at the inlet to the tube. Harvey concluded that the breakdown process was an intermediate stage between supercritical and subcritical flow regimes. He further concluded that vortex breakdown is not a flow instability based on the fact that the breakdown bubble closed and allowed the normal vortex flow to be restored rather than degenerating into

turbulence.

Sarpkaya conducted flow visualizations in order to investigate the structure of vortex breakdown at low Reynolds numbers (500-11000).[11] His test apparatus consisted of a divergent Perspex test section downstream of an inlet with a series of inlet vanes whose angle could be finely adjusted. He identified three separate types of vortex breakdown, namely spiral, axisymmetric and double helix. The double helix breakdown is of little practical interest since it occurs over a very narrow range of Reynolds and only at high swirl numbers. It is also very sensitive to inlet conditions and outside disturbances. At low Reynolds numbers, the vortex core was observed to suddenly kink to one side and then deform into a spiral that performed several revolutions in the same direction as the swirling flow before breaking up into large scale turbulence. Such a spiral breakdown is most commonly observed in flow over delta wings at high angles of attack. At higher Reynolds numbers, it was observed that the location of the vortex breakdown moved upstream and developed into a stationary axisymmetric backflow region in the centre of the flow, known as a vortex breakdown bubble. Axisymmetric breakdowns of this type are usually observed in swirl stabilized combustion chambers. A breakdown hysteresis region was also identified where both the spiral and axisymmetric breakdown were able to exist. Additional tests showed that increasing the swirl or decelerating the flow downstream of an axisymmetric vortex breakdown caused the breakdown bubble to move upstream and decrease in diameter.

Sarpkaya conducted additional measurements on the structure of vortex breakdown at higher Reynolds numbers (1000-225,000) using the same test apparatus as in reference [11].

In this set of tests the results outlined in reference [11] were first duplicated. Experiments were then conducted on the effect of turbulence on vortex breakdown. He discovered that at a Reynolds number of about 50,000 the axisymmetric breakdown broke up into turbulence at its downstream end. As the Reynolds number was increased, the breakdown bubble became smaller to the point where it was no longer visible. The flow structure then existed as a cone-shaped turbulent wake immediately downstream of the stagnation point. It was not possible to determine whether a bubble actually existed due to the high frequency oscillation of the stagnation point. Sarpkaya identified this as a fourth type of vortex breakdown called the conical type.[12]

1.6 Methods of passive combustion control

Methods for controlling combustion instabilities can be classified as either active or passive. Active methods involve actively and continuously perturbing combustion parameters, such as air or fuel flow, in a manner such that the growth and persistence of oscillations are interrupted. Active control has several advantages in that sometimes it may be applied in the field without excessive down-time and it can be adapted to perform over a wide range of operating conditions. Disadvantages to active control are that the necessary equipment may be very expensive and must be very rugged to withstand the severe environment of a gas turbine. Additionally, an appropriate control system is required since, according to the Rayleigh criterion, active methods also have the potential to destabilize combustion. Passive combustion control systems involve modifying the geometry of the combustion chamber,

burner or plenum chamber in order to alter either the flow structure or resonant behaviour of the combustion chamber to make the system less prone to instabilities. Passive control methods are advantageous in that once installed they require no further attention, and the wide variety of methods available allow suppression of many different instabilities. Passive control methods, however, are designed to have greatest degree of effectiveness around one operating point and therefore must be designed for a specific operating point. Depending on the application they may be expensive in terms of down-time to retrofit to an existing machine, and they must also be rugged enough to withstand conditions within the combustion system.

1.6.1 Non-circular burner geometries

Over the past 25 years, numerous studies have been conducted on jets emanating from non-circular nozzles. Non-circular jets may be preferable to axisymmetric jets in combustion applications as a result of their increased entrainment and mixing. This is a result of axis-switching, which is a phenomenon by which the cross section of a spreading jet evolves through shapes similar to those of the jet outlet with the axes rotated at angles characteristic of the jet nozzle.[13, 14] Axis-switching is the result of Biot-Savart self induction and is associated with non-uniform azimuthal shear-layer curvature and interaction between streamwise and azimuthal vorticity. Coherent structures from axisymmetric jets convect downstream without changing shape, while non-axisymmetric coherent structures are deformed in a complex three dimensional manner which assists in the axis-switching process; the segments of

the vortex with the smallest radius of curvature move downstream at a faster rate than the remaining sections.

Recent studies of nozzles with corners have demonstrated that the sharp corners increase the amount of fine scale turbulence compared to the flat sections (Schadow et al, Toyoda & Hussain), and enhance mass entrainment (Vandsburger & Ding).[13]

The shear layer of a jet with corners spreads at a different rate along the flat sides compared to the corners and thus the jet may undergo axis-switching. Grinstein et al. looked at various parameters that affect the development of square subsonic jets. Axis-switching was found to be related to vortex deformation dynamics which are enhanced at low turbulence levels and in jets with a thin initial shear layer. It was found that the Reynolds and Mach numbers do not have a strong effect on jet deformation. High azimuthal coherence and a thin shear layer relative to the jet dimensions were found to be crucial to initiate vortex deformation and self-induction. In jets, such as pipe jets, where these conditions are not met, axis-switching is not observed.[13] Vortex deformation occurs in square jets when the corner sections bend downstream as a result of their small radius of curvature. Shear stresses stretch the vortex and create small-scale axial vortices. This process causes the initial axis-switching and increases turbulence at the corners.[13]

In combusting jets, flames are generally characterized by large coherent structures along the flat sides and small flamelets at the corners. Gutmark et al. observed this effect in acoustically forced triangular flames. The differences between the sides and corners were more obvious for smaller, acute corner angles. Axis-switching was observed for square and equilateral

triangular flames, but not for isosceles triangular flames with a 30° vertex angle.[14]

If fuel is injected into fine-scale turbulence at the corners of a non-circular nozzle instead of into the coherent structures along the flat sides, excitation of combustion instabilities may be avoided by preventing realization of the Rayleigh criterion. At the same time, large scale structures along the flat sides entrain fresh mixture into the hot combustion products to sustain combustion. Early initiation of combustion will occur at the corners of the nozzle. Since air entrainment is low in these areas, the flame temperature will be locally higher, leading to efficient and stable combustion.[13]

Schadow et al. used a triangular nozzle geometry to reduce the pressure oscillations in a coaxial dump combustor similar to that of a ramjet combustor.[15] When a circular nozzle was used or when fuel was injected into the flat sides of the triangular nozzle, pressure oscillations of up to 37% of the mean pressure were measured. When fuel was injected into the corners of the nozzle the pressure oscillations were reduced to below 10% of the mean pressure. The amplitude of the pressure oscillations were seen to be dependent on the direction of fuel injection and the penetration of fuel into the air jet. In addition, a higher combustion efficiency and a lower flammability limit were attained with the triangular nozzle.

Elongated jets, such as those from elliptic or rectangular nozzles, exhibit greater entrainment compared to circular nozzles. Improved large-scale mixing of elliptic jets is due to axis-switching, while increased small scale mixing is a result of amplification of high azimuthal instability modes. Numerous experiments have shown that the occurrence of axis-switching is strongly dependent on initial conditions. Quinn compared his results from

a non-reacting 5:1 elliptic orifice jet to those of Husain & Hussain and Ho & Gutmark, who used contoured 2:1 elliptic nozzles. All jets had similar Reynolds numbers and initial turbulence levels, however the location of the first axis-switching varied from 3 to 7 equivalent diameters downstream of the exit nozzle. These differences were attributed to using an orifice nozzle instead of a contoured nozzle which gives a different momentum thickness. Also, the jet tested by Husain & Hussain had a nearly uniform momentum thickness in contrast to that of Ho & Gutmark which had a 26% circumferential variation in momentum thickness. These two jets also exhibited different entrainment rates.[13]

Austin and Ho explored the temperature effects of elliptic jets and found that increased temperature at the jet exit caused increased entrainment and caused the first axis-switching location to move closer to the jet nozzle.[14] Austin also showed that heated or low speed jets entrain up to 30% more mass than cold or high speed jets.[13] Tsuchiya et al. demonstrated that the axial turbulence component along the axis of the jet increases more quickly for large aspect ratio orifice elliptic jets.[13]

Rectangular jets are shown to exhibit the effects of aspect ratio associated with elliptic jets while maintaining the flow features of sharp corners. Nozzle geometry, aspect ratio and the Reynolds number and initial turbulence level of the jet all contribute to the development of the jet.[13] Hertzberg & Ho found that the vortex dynamics of a 2:1 rectangular jet were similar to those of elliptic jets, and the location of the first axis-switching was directly proportional to aspect ratio.[13] Tsuchiya et al. conducted measurements with four rectangular orifice jets with aspect ratios from 1–5. The downstream location of the first axis-switching

varied from less than one to nearly ten times the narrow dimension of the jet. Quinn reported similar results in experiments of rectangular orifice jets. He compared jets with aspect ratios between 1 and 20 and observed initial axis-switching occurring between 1 and 12 equivalent diameters.[13] In both cases, the growth rate of the jet was large along the minor exit plane while the jet width at the major axis was reduced due to the vena contracta effect. Following the first axis-switching, the growth rate of the major axis became larger than that of the minor axis and a second axis-switching occurred. The location of the second axis-switching was much less sensitive to initial conditions. Shih et al. investigated instability modes of a 4:1 rectangular jet and found that in the low subsonic range axisymmetric instabilities were dominant while asymmetric instabilities dominated for higher jet velocities. In the range of $0.6 < M < 0.85$, both instabilities coexisted with continuous switching between the two. [13]

Schadow et al. investigated a hot fuel-rich jet exhausted into a co-flowing air stream which was afterburned in a secondary combustion chamber. They observed temperatures 20% higher when the hot jet issued from an elliptic nozzle compared to a circular nozzle. Elliptic nozzles with aspect ratios of 2.0, 3.0 and 3.5 were tested. It was found that the greatest heat release was realized with the 3.0 aspect ratio nozzle. Schadow et al. also compared circular and elliptic nozzles in a ramjet dump combustor. They found that an elliptic jet more than doubled the temperature rise due to enhanced mixing.[13]

Gollahalli et al. compared diffusion flames from circular nozzles to elliptic nozzles. The elliptic flames were found to be less stable with a higher flame temperature and lower soot

concentration, and similar NO_x concentrations in the far field. Kolluri et al. observed a 20% reduction in NO_x with an elliptic Ventury inlet used in an inshot burner in a gas furnace. This was due to increased air entrainment.[13]

Koshigoe et al. determined three necessary requirements in order to initiate deformation of a non-circular vortex ring. The non-axisymmetric shape of the nozzle causes separation of different instability modes and localized amplification at different locations around the nozzle circumference. The first requirement is that the modes must be sufficiently localized with little overlapping. Secondly, the modes must have similar amplification rates. If the initial shear layer is relatively uniform around the circumference the growth rates of the velocity fluctuations will be similar, and this requirement will be fulfilled. Finally, there must be a sufficient phase difference between the two instabilities such that the downstream location where vortex roll-up is completed is different around the circumference of the jet. The initial momentum thickness distribution and geometry of the nozzle are the most important factors in meeting these criteria.[13, 14]

Husain & Hussain and Grinstein et al. conducted research into the effects of initial conditions of jets on axis-switching. Nonuniform initial momentum thickness has been identified as a major factor in inhibiting axis-switching. While orifice nozzles provide a fairly uniform initial momentum thickness, the momentum thickness of pipe jets is, in general, thicker and larger in regions with low radii of curvature. For a 3:1 elliptic pipe jet, Schadow et al. observed no axis-switching, associated with similar shear layer growth rates at both the major and minor axes. Ho & Gutmark, however, observed a high spreading rate at the minor axis

and almost no growth rate at the major axis of a contoured nozzle elliptic jet. Accordingly, axis-switching was observed near the nozzle outlet. Similar results have been observed when triangular (Koshigoe et al.) and square (Grinstein et al.) orifice jets were compared to pipe jets.[13] In addition to non-uniform momentum thickness, pipe jets have the further effect that secondary flows, which are directed away from the centreline of the jet, are induced in the corners, which tends to enhance shear layer growth.

One of the earliest theories on the mechanism controlling axis-switching was proposed by Abramovich. He stated that pressure differentials on vortex rings cause shortening of the long sides of an elongated jet and lengthening of the short sides. Through this mechanism the jet cross section gradually deforms until both lengths are equal, at which point the pressure differential ceases to exist. At this point inertia causes the jet to continue deforming until the axis-switching process is completed. A pressure differential opposite to the previous one then exists and a second axis-switching begins. This theory is consistent with the results of Tam and Thiess who demonstrated that the instability modes with faster spatial growth rates are associated with maximum pressure fluctuations occurring at the centres of the flat side of rectangular shear layers.[13, 14]

Deformation of vortex rings of non-circular jets can occur as a result of Biot-Savart self-induction which is related to non-uniform shear layer curvature around the circumference of the jet.[13] If a simple model of a vortex ring is used, such that it is assumed to be inviscid and incompressible and modeled as a thin tube, the self-induced velocity, $\mathbf{u}$, which causes vortex ring deformations has been described by Batchelor as:

$$\mathbf{u} \sim C\mathbf{b}\log(1/\sigma) \quad (5)$$

Where C and σ represent the local curvature and cross section of the tube respectively, and $\mathbf{b}$ is the binormal to the plane containing the tube. This relation shows that locations on a non-circular jet with highest curvature, such as corner sections and major axis sections of elliptic jets, move downstream faster and then towards the jet axis. As sections with lower curvature eventually develop higher curvature, they too move ahead by the same mechanism. The vortex ring then becomes essentially flat with its axes rotated by an angle characteristic of its shape.[14] Equation 5 also predicts that a circular vortex ring will propagate without deformation.[13] Numerical simulations were conducted to examine the effects of self-induction on pseudo-elliptic (Kiya et al.) and rectangular (Grinstein) vortex rings. Other effects, such as interaction with other coherent structures, azimuthal non-uniformity of shear layer and streamwise vorticity were purposely excluded from these simulations. For aspect ratios below four, the isolated vortex rings deformed regularly, each time approximately recovering flatness and shape with axes switched.[13, 14, 16]

Vortices in jets, however, are non-isolated and interactions with other coherent structures cause very different behaviour. Early experiments did not recognize the effects of other vortices, in particular braid vortices, and it was believed that successive axis-switching was related solely to self-induction. Experimentation and numerical simulations have shown that the first axis-switching is caused by self induction related to non-uniform azimuthal curvature, but that later axis-switchings of the jet are not linked to axis-rotations of the vortex ring. Interactions with braid vortices and other vortex rings can inhibit axis-switchings of

non-isolated rings. Such rings do not recover flatness after initial self deformation.[13] In the case of a square jet, for example, braid vortices induce flattening of the portions of the ring that are left behind, which can initiate a second axis-rotation of the jet.[14]

1.6.2 Vortex generators

The use of tabs or vortex generators around a circular nozzle is another effective method of passively suppressing combustion instabilities. Vortex generators create small streamwise vortices which improve small scale mixing in addition to breaking the axisymmetry of coherent structures.[13] Axial vortex generators increase entrainment compared to circular nozzles and are especially effective when used in conjunction with non-circular nozzles.

Bradbury & Khadem were among the first to use tabs at the exit of a jet. They found that using two tabs was most effective configuration and that the potential core length was reduced as well as the centreline velocity. Generation of axial vorticity has also been accomplished through the use of vortex generators or tabs at the nozzle exit (Ahuja & Brown, Zaman), “entrainment manipulators” located upstream of the jet exit (Monkewitz & Pfizenmaier) and with corrugated nozzles (Lasheras et al.).

Grinstein et al. performed a study combining experimental and computational results of circular jets emerging into a quiescent atmosphere. The focus of the study was on near field entrainment and combustion dynamics of fuel injected in a thin ring around the edge of the jet. OH PLIF was used to visualize the reaction zones. Both azimuthal and axisymmetric modes of the jet were excited. Three dimensional images of the reaction zone

were constructed from multiple two dimensional images attained at constant phase angle to study the structure of the reaction zone. Computational methods were used to obtain an understanding of the dynamics and structure of the fluid dynamic mechanisms underlying the flame structure. Flow visualizations and computational jets resembled each other very closely, showing a tight coupling between braid vortices and coherent structures. Due to the streamwise vorticity introduced at the jet exit, the shear layer and coherent structures of the jet were deformed into a pentagonal shape. As with non-circular nozzles, the sudden change in azimuthal curvature at the corners caused self-deformation of the coherent structures and a 36° axis rotation. Evolution of the jet was characterized by self-induced deformation as a result of azimuthal excitation at the nozzle exit, as well as dynamics of braid vortices forming in the braid regions between vortex rings and interactions between coherent structures and braid vortices. The mixing pattern of the jet was affected by these processes which caused regions of high fuel concentration resulting in inactive sections of the flame and regions with a proper fuel-air ratio resulting in intense combustion. Vorticity dynamics and the resulting mixing process determine fuel concentration in the flame and therefore the heat release pattern. Understanding of these processes allows selection of optimal fuel injection features to improve combustion in a jet.[14, 16]

1.6.3 Lobed nozzles

The use of lobed mixers (Fig. 3) has been shown to be effective in reducing both thermoacoustic instabilities and NO_x emissions by improving mixing. A mixer plate with lobes

having an appropriate geometry (i.e. lobe height, pitch and profile) generates arrays of intense large-scale vorticity which rapidly break down into small-scale turbulence. This results in increased bulk and molecular-scale mixing.

Figure 3: Typical lobed mixer plate showing configuration of streamwise vorticity [16]

McVey & Kennedy used a lobed mixing plate to enhance mixing and combustion efficiency in subsonic streams. They stressed the importance of enhancing molecular mixing of the two streams while maintaining large-scale mixing through generation of streamwise vorticity. Tillman et al. tested several configurations of lobed nozzles to improve mixing of a Mach 1.5 jet at 1000°F emerging into a free stream flowing at Mach 0.5. The nozzle was designed to introduce axial vorticity without affecting the discharge of the jet. The lobed nozzle significantly improved mixing while reducing the potential core length by one half relative to a rectangular nozzle with a 3.7 aspect ratio operating at the same conditions.[14, 13]

Ukeiley et al. measured the streamwise velocity downstream of a lobed mixer using an array of 15 hotwires. Using a one-dimensional scalar version of Proper Orthogonal Decom-

position they were able to objectively identify coherent structures. The flow was broken up into several eigenmodes of varying power levels. Further analysis showed a natural shedding frequency of about 700 Hz. The dominant eigenmode contained up to 42% of the total streamwise kinetic energy and the five strongest eigenmodes accounted for 82%. Furthermore, it was discovered that at some spatial locations the flow field could be adequately represented by only the first five eigenmodes.[17, 18, 19]

Mitchell et al. compared two different lobed fuel injector geometries to a non-lobed geometry. The non-lobed mixer provided almost no mixing between the fuel and air streams before combustion resulting in a diffusion flame. They found that one of the lobed mixers created a locally lean premixed flame which resulted in lower NO_x emissions while the other created a nearly stoichiometric mixture which increased NO_x emissions. Both lobed injectors caused increased CO emissions for lean combustion. Their study emphasized the importance of local mixture ratio on combustion emissions.[20]

1.6.4 Control of vortex breakdown

Formation of coherent structures in a swirl stabilized burner occurs not only on the outer shear layer as in a dump combustor, but also on the inner shear layer. Either of these shear layers has the potential to drive a combustion instability. Additionally, motion of the vortex breakdown may also cause combustion instabilities.

Kilik conducted a thorough study of the effects of various modifications to swirlers. His study showed that an increase in vane angle, an increase in the number of vanes, a decrease

in the vane aspect ratio and changing from flat to curved vanes increased the size of the recirculation zone and the reverse mass flow rate. Comparison of his data for curved vanes with the results of Mathur & MacCalum for straight vanes show that vane type and vane angle have a strong influence on the rate of flow recirculation. The rate of flow recirculation increases with increasing vane angle and is also increased by using curved vanes instead of flat vanes.[2]

Paschereit et al. developed a novel way of suppressing combustion instabilities in an AL-STOM EV burner by stabilizing the vortex breakdown location.[21] A combustion instability was observed in tests simulating engine start-up, and was also observed to exist in premix operation. The instability was observed to be related to the fluctuating pilot flame, and CFD simulations showed that fluctuations in the flame location were related to the behaviour of the vortex breakdown. Pressure waves inside the combustion chamber forced the breakdown bubble inside the burner cone where it was eliminated. Immediately after the disappearance of the breakdown bubble, the flame exited the burner and stabilized at the sudden expansion. The vortex breakdown then re-established and the instability cycle repeated. In order to control the instability, the pilot fuel injector was extended beyond the apex of the burner cone and into the swirler cone such that the end of the fuel injector was approximately at the upstream end of the breakdown bubble. In atmospheric tests, the extended fuel injector was shown to reduce the instability level by more than 30% and the NO_x emissions by up to 15%. In elevated pressure tests the instability level during start-up was reduced by 90%. Engine tests also confirmed the effectiveness of the extended fuel injector in reducing combustion

instability levels.

1.7 Thesis objective

The objective of this thesis is to present the results of a study conducted to determine how changes to the geometry of a swirl stabilized gas turbine burner affect the flow field in the combustion chamber. A description of the test equipment is presented first, followed by a description of the experimental and numerical methods used. Extensive experimental results are presented, followed by results of numerical modeling of the experimental swirlers.

2 Test apparatus

2.1 ALSTOM Power Ltd. water channel

The test apparatus used in the experiments conducted at ALSTOM Power Ltd. was a vertical water channel with a rectangular cross-section (fig. 4). Water was pumped from a five cubic metre reservoir through a series of flow conditioners and through the test section where a full size burner model could be mounted at any axial location. The volumetric flow rate of water passing through the test section was displayed on a digital flow meter upstream of the test section and was controlled by manually adjusting the speed of the pump. Two swiveling mounts for hot-film probes were located downstream of the burner model. The outlet of the test section was an overflow system where the water spilled into a sleeve surrounding the downstream end of the test section. The test section had a glass top in order to conduct visualizations looking directly into the burner cone. The water was piped from the overflow sleeve into either the reservoir tank or down a drain. If the water was not reused, the tank could be drained in as little as twenty minutes even if it was continuously filled. A second smaller tank used to hold fluorescein dye was located near the test rig. A small pump passed dye through a rotameter and into the test section where the dye could be injected through the burner or into the main water flow.

For the current set of tests, an experimental burner model that simulated the main design features of ALSTOM's burners was used. This model featured a plastic triangular window in its side to allow full visual access to the inside of the burner cone. For certain tests this

burner was also fitted several passive control devices.

The water channel was equipped with a forcing mechanism to apply pressure pulsations to the flow. This allowed thermoacoustic instabilities to be simulated inside the water channel. The forcing mechanism consisted of a brass piston inside a stainless steel tube that was fitted to the side of the water channel between the flow conditioners and the test section. A volume behind the piston rising the height of the water channel was flooded with water to equalize the hydrostatic pressure across the piston. The piston was actuated by a computer controlled linear motor manufactured by Baldor. In these tests, the piston was actuated sinusoidally with an amplitude that displaced 10% of the bulk flow.

In certain tests phase-locked images were acquired by triggering a camera at the same frequency as the flow instability (see section 3.1). In these tests a DANTEC hot-film probe was mounted in one of the probe mounts downstream of the burner model to obtain a reference signal.

2.2 University of Cincinnati test facility

2.2.1 Cold flow test channel

The test apparatus used in these experiments was a cold-flow channel in the Aerospace Engineering laboratory at the University of Cincinnati. The test-rig (figs. 5 and 6) consisted of a circular plenum chamber upstream of the swirl stabilized burner model and a circular combustion chamber downstream of the burner. The plenum chamber had an inside diameter of 3.786" and consisted of three PVC pipe sections connected to each other by 9" flanges.

The first section was 14.7" in length and housed a perforated cone followed by a one inch length of $\frac{1}{8}$ "-18 gauge stainless steel honeycomb and three progressively finer screens (0.014", 0.0095" and 0.0019") to reduce the turbulence intensity of the incoming air. The second section was 4.0" in length and could be removed in order to change the acoustic resonance frequency of the plenum chamber. This section also served as the injection point for flow seeding required for PIV measurements. The third section was 11.0" in length and interfaced with parts used to mount the swirler models.

Figure 7 shows a swirler model secured inside the test-rig to a mounting plate that had a sliding fit with the last section of the plenum chamber. The mounting plate had a circular cavity 2.0" in diameter in its centre into which the swirler models mounted with a sliding fit. Four cap screws secured the swirler models to the mounting plate. The mounting plate had four slotted bolt holes around its circumference which allowed the plate to be secured to the downstream flange of the plenum chamber in any azimuthal orientation. A series of small holes were spaced every 9° on the surface of the mounting plate that was in contact with the plenum chamber. An indexing pin mounted in the downstream surface of the plenum chamber fit into any of the holes and allowed the mounting plate to be positioned very accurately.

The combustion chamber consisted of a Perspex tube that allowed full optical access to the region downstream of the burner. The tube was 18.0" long with a 4.0" inside diameter. A nozzle plate at the exit of the combustion chamber reduced the diameter to 2.0" through an angle of 30° . The tube was clamped securely in place between the exit nozzle and the

swirler mounting plate by threaded rods.

A groove was machined in the downstream surface of the mounting plate immediately around the swirler cavity. If a zero mixing tube length was desired, the groove was filled with an aluminum ring that sat flush with the downstream face of the mounting plate (see figure 7) and the transparent tube was mounted directly to the front of the mounting plate. When a non-zero mixing tube length was desired, a series of spacer plates was used to position a secondary plate the required distance downstream of the swirler. The mixing tube consisted of several modular pieces that connected smoothly and were held in place between the mounting plate and the second plate. The length of the mixing tube could be adjusted to lengths of 0, 0.5", 1.0", 1.5" and 2.0".

The test rig was supplied with air from a pressurized tank. The air pressure was reduced to a constant pressure of 75 psi by a pressure regulator shortly upstream of the test rig. The air passed through a Master-Touch thermal flow meter manufactured by Eldridge Products Inc. The flow meter used two resistance temperature detector (RTD) elements. One sensor measured the temperature of the flow passing through the flow meter and the other was raised to a constant temperature above that of the gas stream through resistance heating. The first sensor allowed for temperature compensation of the flow meter, and the second sensor was calibrated to measure the flow rate based on the amount of current required to maintain its constant temperature. The unit was calibrated to 75 psi with a maximum flow rate of 0.174 kg/s (300 SCFM). The mass flow rate was controlled by a gate valve immediately downstream of the flow meter.

2.2.2 Experimental swirler models

The five swirler models were conical six-bladed swirlers constructed through stereolithography (SLA) and were mounted on the ends of short lengths of $\frac{1}{2}$ " outside diameter stainless steel tubing. Each swirler reflected the main design features of the machine burners manufactured by ALSTOM Power Ltd. The swirlers had a hollow manifold at their upstream ends which could be supplied with a secondary gas to simulate gaseous fuel injection. Each of the six blades consisted of a slice of a conical shell with a hollow tube mounted at its leading edge. The six blades were held in place at their downstream ends by a circular plate known as the front panel. Several small threaded inserts were mounted in the downstream face of the front panel in order to attach a transition piece to the swirlers. The transition piece was a diffuser with a fifth-order polynomial contour that smoothly transitioned from the concave surface of the swirler blades to a circular contour the same diameter as the swirler. The purpose of the transition piece was to eliminate the step that would otherwise exist between the outlet of the burner and the mixing tube when there was a non-zero mixing tube length downstream of the burner exit. The burner was tested without the transition piece only when the front panel was flush with the sudden expansion into the combustion chamber. The front panel was adhered to an aluminum mounting ring that extended upstream from the burner exit and surrounded the downstream portion of the blades. Four threaded holes were spaced circumferentially around the mounting ring and were used to mount the swirler models inside the test-rig.

The experimental swirlers were designed as ten separate pieces in AutoCAD 2000 (fig.

9). The ten pieces included the manifold, the front panel, the transition piece, six blades and the mounting ring. Each piece except for the mounting rig was exported as an stl (stereolithography) format electronic file and was manufactured by Morris Technologies of Cincinnati, Ohio. The mounting ring was constructed from aluminum. The pieces were manufactured separately and were later assembled.

The main criteria used in designing the burners were the cone angle and the ratio of burner outlet area to total slot area. The first swirler, the XEVa (fig. 10), was considered the baseline model. The XEVb (fig. 11) had a similar design to the XEVa but its cone angle was increased by a factor of 1.64 and its slot area was increased by a factor of 2.25. The XEVc (fig. 12) was designed with the same cone angle as the XEVa and the same slot area as the XEVb, and the XEVd (fig. 13) was designed with the same cone angle as the XEVb and the same slot area as the XEVa. All XEV swirlers were designed to have the same outlet area with their transition pieces removed. The fifth burner, the XEVe-6 (fig. 14), was designed with the same cone angle and slot area as the XEVa and the same outlet area as the other four swirlers. The XEVe-6 swirler had an elliptical outlet with an eccentricity $e = 0.6$ ($AR = 1.67$).

The extendable lance (fig. 8) was a solid body extended into the swirler from the apex of the swirler cone. The lance consisted of a piece of $\frac{3}{8}$ " outside diameter stainless steel tubing that fit inside the mounting tube and protruded into the swirler cone. The lance was mounted to the swirler tube using a $\frac{1}{2}$ " x $\frac{3}{8}$ " Swagelok tubing adapter drilled out to $\frac{3}{8}$ ". The lance could be adjusted to any length.

Figure 4: ALSTOM Power Ltd. water channel

Figure 5: Three dimensional model of the cold flow channel

Figure 6: Photograph of the test rig

Figure 7: Experimental swirler mounted in the test rig, zero mixing tube length

Figure 8: Experimental swirler mounted in the test rig with mixing tube and lance

Figure 9: Exploded view of an experimental swirler model

Figure 10: Photograph of the XEVa

Figure 11: Photograph of the XEVb

Figure 12: Photograph of the XEVc

Figure 13: Photograph of the XEVd

Figure 14: Photograph of the XEVe-6

3 Experimental methods

3.1 Phase-Locked Laser Induced Fluorescence measurements

Laser Induced Fluorescence, or LIF, is a technique commonly used for flow visualizations and to investigate mixing within flows. It is based on the principle that certain molecules become excited and fluoresce when struck by light of certain wavelengths. By injecting fluorescein disodium upstream of the burner and illuminating the flow with an argon laser sheet it is possible to view regions of high and low dye concentration. When the dye is injected so that it is properly entrained into the flow, coherent structures may be visualized (fig. 15).

Figure 15: Schematic diagram of the PLIF system setup

For the current tests it was discovered that the quality of the visualization was highly dependent on the location of the dye injection. Initially the dye was injected into the burner through the premix fuel holes. This provided very good mixing of the dye with the bulk flow which resulted in a homogeneous mixture at the burner outlet, but a very poor visualization. Injection of dye directly into the outer shear layer at the outlet of the burner

gave similarly poor results. Dye injection through the pilot nozzle provided reasonably good visualizations since the dye was injected directly into the vortex breakdown bubble, however it was discovered that the dye jet affected the vortex breakdown process. It was discovered that the best method of dye injection for visualization of flow instabilities was to attach two plastic tubes to the outside of the burner cone at the very bottom of the slots. In this way the dye was entrained into the flow without diffusing and the flow field was not disturbed.

A very useful way of conducting flow visualizations is to lock the triggering of the camera to the phase of the flow instability using a reference signal. When the forcing mechanism was not used, the fluctuation of the flow was measured with a hot-film probe. When the forcing mechanism was activated, a trigger signal was generated by shining a laser beam across the top of the forcing mechanism and into a photodiode. As the linear motor reciprocated, the path of the laser beam was periodically broken, resulting in a square wave output signal from the photodiode at the frequency of the linear motor. The flow instability was measured with the hot-film probe with the forcing mechanism activated and was found to have the same frequency as the motor.

The reference signal was displayed on a dynamic signal analyzer in order to determine the dominant frequency, which was then isolated from noise through the use of a band-pass filter. Since the frequency of the dominant instability when the forcing mechanism was not activated was much more susceptible to slight variations in flow conditions (e.g. mass flowrate) than the dominant instability with the forcing mechanism activated, the frequency band had to be widened when the forcing mechanism was not used. The filtered signal was

displayed on both an oscilloscope and a dynamic signal analyzer to ensure that the correct frequency was being passed through the filter and that the signal was a pure tone. The filtered signal was used as a trigger for a signal generator that put out a square wave signal which was used to trigger the camera. The signal generator allowed the phase of the camera trigger signal to be shifted relative to the filtered input signal.

Two different cameras were used to acquire phase-locked images. The first was a Di-Cam 2 CCD camera which generated 8-bit monochrome 768 x 572 images. The Di-Cam was controlled by Matrox Inspector image acquisition and processing software run on a generic PC. A special macro was written in Matrox Inspector using Sax Visual Basic to digitally average sequences of two, four, eight, 16, 32, 64 or 128 single frames as the camera acquired them. The macro also allowed the user to acquire a sequence of single images. Additional Sax Visual Basic macros were written to process and organize the acquired images. The other camera was a LaVision NanoStar CCD camera which generated 12-bit 1024 x 1280 monochrome images. The NanoStar camera was part of a PIV system but also functioned well for flow visualization. The NanoStar camera was controlled by LaVision's DaVis 5 image acquisition software running on a Hewlett Packard PC. The DaVis 5 software package had the capability of generating mean images from a sequence of up to 31 single frames. After the images were acquired by the NanoStar camera, they were further processed and organized using the Sax Visual Basic macros.

For these tests, the flow was illuminated using an argon laser. The laser beam was passed from the laser to the test section by a fibre optic cable where the beam was split into a sheet

using cylindrical and spherical lenses. Although the output power of the laser was 300 mW, losses in the fibre optic cable reduced the power to approximately 120 mW at the test section. The laser sheet was focused to obtain the highest possible light energy concentration. It was positioned downstream of the burner either vertically along the centreline of the burner with the camera normal to its plane, or horizontally as close to the burner exit as possible with the camera steeply aimed through the front window of the test rig. For visualizations inside the burner cone, the laser sheet was aimed to illuminate the largest possible slice of the flow and the camera was oriented as close as possible to normal to the plane of the laser sheet.

3.2 Laser Doppler Anemometry measurements

In the experiments performed at ALSTOM Power Ltd. a DANTEC Dynamics two component Laser Doppler Anemometry (LDA) system was used. LDA is a highly accurate point-by-point technique for measuring fluid velocity and is non-intrusive. It is important to realize that LDA systems do not directly measure the velocity of the fluids, but rather measure the velocity of tiny tracer particles moving with the flow.

The operating principle of an LDA system is based on the Doppler shift of light reflected from a moving particle. Figure 16 shows a small particle moving with velocity vector $\overline{U}$ which is struck by an incident beam of laser light with a directional unit vector $\overline{e}_i$ and frequency f_i . Light is scattered in all directions and the system collects light scattered in the direction of unit vector $\overline{e}_s$, towards the receiving optics. Due to its motion, an observer moving with the particle would sense a slightly different frequency than the incident frequency, f_i . From

the perspective of the receiver, the moving particle transmits light with a slightly different frequency than that of the incident beam.

Figure 16: Scattering of light from a moving particle [22]

From Doppler theory, the frequency of the light entering the receiver is given by:

$$f_s = f_i \frac{1 - \overline{e_i} \cdot \frac{\overline{U}}{c}}{1 - \overline{e_s} \cdot \frac{\overline{U}}{c}} \quad (6)$$

In fluid measurements the fluid velocity vector, $\overline{U}$, is much smaller than the speed of light, c , and equation 6 may be linearized to:

$$f_s \cong f_i + \frac{f_i}{c} \overline{U} \cdot (\overline{e_s} - \overline{e_i}) = f_i + \Delta f \quad (7)$$

Since all parameters in equation 7 are known, the velocity vector $\overline{U}$ can be calculated provided that the Doppler frequency shift, Δf , can be measured with sufficient accuracy. Even in high supersonic flows, however, the particle velocity is much too low to generate a measurable Doppler shift. In order to measure velocities in a real flow, an extension of this technique is used where the frequency of scattered light from two sources is measured. In such a system, two coherent laser beams of equal power are intersected in the test section and the receiving optics collect light scattered by seeding particles passing through the tiny volume where the two beams intersect (known as the measuring volume). Figure 17 is an

extension of figure 16, where a moving particle is struck by two laser beams from different directions.

Figure 17: Scattering of light from two incident laser beams [22]

The frequency of the light scattered towards the receiving optics from both sources is given, as in equation 7, as:

$$\begin{aligned} f_{s,1} &= f_1 \left[1 + \frac{\overline{U}}{c} \cdot (\overline{e_s} - \overline{e_1}) \right] \\ f_{s,2} &= f_2 \left[1 + \frac{\overline{U}}{c} \cdot (\overline{e_s} - \overline{e_2}) \right] \end{aligned} \quad (8)$$

When two waves of slightly different frequency are superimposed the well-known phenomenon of a beat frequency results due to constructive and destructive interference. The beat frequency, f_D , corresponding to the different frequencies of the scattered light is calculated in equation 9 below. In this case $f_1 = f_2 = f_i$.

$$\begin{aligned} f_D &= f_{s,2} - f_{s,1} \\ &= \frac{1}{\lambda} \cdot 2 \sin(\theta/2) \cdot u_x = \frac{2 \sin(\theta/2)}{\lambda} u_x \end{aligned} \quad (9)$$

Solving equation 9 for u_x gives:

$$u_x = \frac{\lambda}{2 \sin(\theta/2)} f_D \quad (10)$$

This formula provides an accurate estimate of the magnitude of u_x , but leads to a problem of directional ambiguity since no information about the particle's direction can be discerned. If a frequency shift, f_0 , is applied to one of the beams, the problem of directional ambiguity can be resolved. In this case, equation 8 takes the form:

$$\begin{aligned} f_{s,2} &= (f_i + f_0) \left[1 + \frac{\overline{U}}{c} \cdot (\overline{e_s} - \overline{e_2}) \right] \\ f_{s,1} &= f_i \left[1 + \frac{\overline{U}}{c} \cdot (\overline{e_s} - \overline{e_1}) \right] \end{aligned} \quad (11)$$

Substituting these expressions into equation 9 gives the following result:

$$\begin{aligned} f_D &= f_{s,2} - f_{s,1} \\ &= f_0 + \frac{2 \sin(\theta/2)}{\lambda} u_x + f_0 \left| \frac{\overline{U}}{c} \right| |\overline{e_s} - \overline{e_2}| \cos \phi \end{aligned} \quad (12)$$

The final term in the last line of equation 12 is negligible since even in cases of extremely high velocity the ratio of $\overline{U}/c$ will be smaller than 10^{-5} , $e_s - e_2$ must be less than 2 and $\cos \phi$ can be no greater than unity. Therefore:

$$f_D \cong f_0 + \frac{2 \sin(\theta/2)}{\lambda} u_x \quad (13)$$

Which allows negative velocities to be resolved down to a certain value.

Figure 18 shows a schematic of the hardware of the LDA system. This system uses a backscatter configuration where the transmitting and receiving optics are mounted in a single probe, known as a transceiver.

The laser used in this system is a 100 mW Coherent helium-neon laser. The transmitting optics split the single incident laser beam into two beams of approximately equal intensity and shift the frequency of one beam relative to the other before focusing the beams in the test section.

Figure 18: Hardware schematic for the LDA system [23]

The frequency shift is performed by a acousto-optical modulator known as a Bragg cell. The Bragg cell is a slab of glass with an electro-mechanical transducer driven by an oscillator mounted on one side. The transducer generates a series of acoustic waves within the glass which creates a moving pattern of high and low density waves. The other side of the glass slab is shaped to minimize acoustic reflection and is fastened to a material that absorbs acoustic energy. The incident light beam strikes the moving wave fronts which act as a series of moving diffraction gratings and provide a fixed frequency shift, f_0 , to the reflected beam. Bragg cells are able to provide a very accurately controlled frequency shift in the range of 10 to 80 MHz.

The laser is passed to the transceiver using a fibre optic cable. A collimating lens focuses each laser beam to minimize its divergence as it passes through the transceiver. The col-

limited beams are focused by the front lens so that the beam waists intersect to form the measuring volume. The diameter of the beam waist, d_0 , is given as:

$$d_0 = \frac{4f\lambda}{\pi E d_i} \quad (14)$$

Where f is the focal length of the lens, λ is the wavelength of the incident light, d_i is the diameter of the beam before the front lens and E is beam expansion factor. Since the wavelength of the light and the diameter of the incident beam at a given focal length allow no adjustment, the only way to decrease the size of the measuring volume is to install a beam expander, which is a series of lenses installed instead of the front lens. The beam expander widens the beams exiting the transmitting head and increases the distance between each pair of beams. The angle between the two beams is increased which decreases the size of the measuring volume and improves the spatial resolution. A beam expander with an expansion factor of 1.4 was used for all measurements.[22]

In order to measure two velocity components, two pairs of orthogonal laser beams are required. Each velocity component is measured with a laser of a different colour and the scattered light is detected by a set of receiving optics which are filtered to receive only that colour of light. The sets of laser beams for both velocity components both come from a multi-colour argon-ion laser. The laser beam is split into two beams in the Bragg cell and then is steered through a prism that splits the multi-colour beams into four single colour beams. The beams are guided by a series of mirrors into separate fibre optic cables that send the beams to the transceiver.

The receiving optics collect the light scattered by particles passing through the measur-

ing volume and transform the light burst into an electrical signal which is passed to the processing hardware. Scattered light is collected by a set of receiving lenses and is focused through a pinhole aperture onto a photomultiplier. The lens and pinhole prevent most of the light from extraneous sources (e.g. flames, background lighting etc.) from striking the photomultiplier.[24]

The photodetector signal consists of a series of short Doppler frequency sine waves generated as particles pass through the measuring volume. The processing equipment consists of sophisticated signal processors that measure the frequency of the Doppler bursts and convert them into an analog signal. Because the system can record a data point only when a particle passes through the measuring volume, the temporal spacing of the data points is random and special data processing methods are required to properly evaluate the desired information such as mean and rms velocity and power spectra.

Although light is scattered by the seeding particles in all directions, its intensity is not equal in all directions. Figure 19 shows the variation in the intensity of scattered light with direction for different sizes of seeding particles. In this figure the direction of the incident light is shown by arrows on the left side of each plot, and light intensity scale is logarithmic. These plots show that the greatest amount of light is scattered directly away from the transmitter so that the signal is strongest when the system is operating in a forward scatter mode. Titanium dioxide particles with a mean diameter of $0.5\ \mu\text{m}$ were used. With laser light in the range of 476.5–514.0 nm, the ratio of d_p/λ is approximately 1.0, so that light is usually scattered in a manner similar to that shown in the middle plot of figure 19.

Figure 19: Intensity of scattered light in different directions from various particle sizes (Incident light represented by the arrow on the left, scale is logarithmic) [22]

Flow seeding is one of the most important aspects of conducting quality LDA measurements. Since LDA systems actually measure the velocity of seeding particles moving within the flow, it is very important that seeding particles follow the flow. Considering a single particle with neutral buoyancy suspended motionless within a stationary flow, if the flow begins to move, the particle will also begin to move along with it. Due to a number of factors including the particle's momentum, viscosity of the fluid and the rate of acceleration of the flow, the particle will slightly lag behind the fluid motion. The ability of a particle to follow the flow is characterized by the Stokes number, St_p , which is defined as:

$$St_p = \frac{\tau_k}{\tau_p} \quad (15)$$

Where τ_k is the Kolmogorov time scale and τ_p is a time constant for the particle representing its response to a step change in fluid velocity:

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu} \quad (16)$$

In order for a particle to be able to adequately follow the flow, the Stokes number must be greater than unity.[25]

The photodetector generates a current pulse that contains the frequency information related to the velocity as well as some noise (fig. 20).

Figure 20: Typical Doppler burst [23]

The first step in processing the raw signal is to filter the signal with a high-pass filter in order to remove the DC part of the signal known as the Doppler pedestal. A typical filtered burst signal is shown in figure 21.

Figure 21: Filtered Doppler burst [23]

Removal of the Doppler pedestal creates a signal that is easier for the processor to deal with. The processor measures the Doppler frequency of the filtered burst using dedicated burst spectrum analyzers which are able to compute the Fourier transform of the burst in the time that it takes the burst to occur. The Doppler frequency value is used in equation 13 to

evaluate the flow velocity. The processor uses the individual data points to construct a time trace of the fluctuating velocity with unevenly spaced data points. Specialized algorithms are required to evaluate average and rms velocity values and power spectra from the time traces.[24]

3.3 PIV measurements

Particle image velocimetry or PIV is the most advanced system for measuring fluid velocity commercially available today. PIV is an optical technique which can perform three-dimensional velocity measurements over an entire plane within a flow at once. This technique has the enormous advantages over LDA and other point-by-point measuring systems in that instantaneous velocity vector fields can be obtained, quantitative flow visualizations may be obtained, and data acquisition is much quicker.

The principle behind stereo PIV is very simple. The flow is seeded with tiny particles and is illuminated by a laser sheet. Two images are recorded by a pair of CCD cameras with a short time delay, Δt , between the two exposures. By calculating the average displacements, Δx and Δy , of a given set of neighbouring particles over the time delay, the average velocity components of the set of particles, u_x and u_y can be found. The third velocity component is resolved by comparing the apparent motion of a set of particles from the perspective of one camera to their apparent motion from the perspective of the other camera.

The system used at the University of Cincinnati was manufactured by TSI. The hardware was controlled by a PC and consisted of a synchronizer, two pulsed YAG lasers, optics to

focus the laser, two CCD cameras, and data processing software.

A pair of 120 mJ YAG lasers were used to illuminate the flow. The laser beams were transmitted to the test section through an articulated arm, and were split into sheets of variable thickness depending on the lenses used. Two 2048 x 2048 pixel CCD cameras were used for image acquisition. The triggering of the cameras and lasers was controlled by the synchronizer.

The synchronizer was responsible for accepting commands from the PC, sending accurately timed signals to the cameras and lasers and receiving pulse information from the cameras. A diagram illustrating the timing sequence for acquiring an image set is shown in figure 22. Upon receiving a command from the PC to begin acquiring data, the synchronizer sends a TTL trigger signal to the two cameras. The cameras respond with similar pulses to the synchronizer to verify that they are ready to acquire data. The cameras simultaneously activate their CCD arrays for an exposure time of 255 μ s. The synchronizer waits 250 μ s after the exposures have begun and then fires the first laser whose pulse duration is 6 ns. After the exposure is complete, the cameras pass the information received by their CCD arrays into their memory and begin transferring the information to RAM or directly to the hard drive. The cameras reactivate their CCD arrays while information is still being transferred to the PC and the laser fires a second time. There is a 200 ns delay between the cameras completing the first exposure and starting the second exposure. The cameras wait until the first image is transferred from their memory to the PC and then begin transferring the second image to the PC. The amount of time required for the cameras to transfer

both exposures to the computer determines the minimum amount of time between captures. Saving data directly to the hard drive requires approximately 1 s per capture while saving to RAM requires approximately 0.5 s per capture. The exposure times and pulse delay time may be modified in the software but are usually not adjusted. The delay time between laser pulses must be adjusted by the user in order to ensure that the seeding particles move an appropriate distance between the two frames. Too small or too great of a delay results in erroneous data.

Figure 22: Timing diagram for the PIV system

A schematic of the hardware of the stereo PIV system is shown in figure 23. In this setup, both cameras are focused on the centre of the test section. Scheimpflug adapters are mounted on the cameras to tilt the CCD chips relative to the lens to maintain focus over the entire field of view. The entire field of view will be in focus when the planes of the field of view, the lens and the CCD array intersect on a common line in space. There should be an angle of at least 30° between the two cameras in order to accurately resolve the velocity

component perpendicular to the laser sheet. The laser sheet is normally focused to have a thickness of approximately 1 mm.

Figure 23: Setup for a stereo PIV system [26]

The true displacement of a single particle within the laser sheet is represented by the blue vector in figure 23. Each camera observes the particle moving through a different displacement: the left camera observes a displacement shown by the red vector and the right camera observes a displacement shown by the purple vector. By comparing the apparent displacements between the two sets of images, the software is able to compute all three velocity components of the particle.

As with LDA measurements, PIV measures the velocity of seeding particles. The guidelines for flow seeding for PIV measurements are little different from those for LDA measurements. It is important in PIV measurements to carefully control the amount of seeding in the flow. If there are too few particles in the flow the data processing software does not have sufficient information to accurately compute a velocity value. On the other hand, if too much seeding is used the image becomes saturated (an occurrence known as speckle) and

the software is unable to distinguish individual particles.

Calibrating the stereo PIV system requires placing a calibration target in the test section along the plane of the laser sheet. The laser is deactivated and each camera acquires an image of the target. The target is a flat panel with a series of grooves machined in its surface. An array of evenly spaced dots are marked on its surface in a way that every other dot is located in one of the grooves. At the centre of the target is a cross known as a fiducial mark that the software is able to recognize. Upon processing the calibration images, the software first locates the fiducial mark in each image and then locates each calibration dot. The software then identifies each dot as being on either the front surface of the target or in one of the grooves. The user enters the spacing of the dots in the software and the depth of the grooves. This allows the software to calibrate displacement of the seeding particles between the sets of images to actual distance in the test section and also to account for the distortion caused by glass surfaces between the laser sheet and the cameras. An example of a set of stereo PIV calibration images is shown in figure 24. These images show the distortion that results from the cameras being oriented at angles to the laser sheet.

The software begins processing the particle images by dividing each single image into a grid of small 32 x 32 pixel squares, known as interrogation regions, that are processed individually (fig. 25). The software performs a cross correlation on each interrogation region. The correlation relates the pixel intensity, I , by:

$$R(s) = \int_{spot} I(X)I(X + s) dX \quad (17)$$

Where s is the separation vector between two particles. The result of the spatial correla-

Figure 24: Stereo PIV calibration images [26]

tion is similar to that shown in figure 26. The tall peak represents the average displacement of the particles in the interrogation zone and the shorter peaks represent random correlations. A peak centred in the correlation plot represents zero velocity so in this scheme there is no directional ambiguity.

Figure 25: Division of an image into interrogation regions [26]

The first step in three dimensional data processing is for the computer to perform a cross correlation on each set of images (left and right) separately, as though they were two-dimensional vector maps. The software uses an interrogation grid that is rectangular in the

Figure 26: Particle image velocimetry correlation [26]

plane of each camera's CCD chip for this step. This results in two different-looking two-dimensional vector maps, each representing the instantaneous flowfield as recorded from the perspective of each camera. An example of a pair of two-dimensional images acquired by a stereo PIV system is shown in figure 27.

Figure 27: Two-dimensional vector maps acquired simultaneously by a stereo PIV system [23]

Using data stored in the calibration images, the software maps points from a rectangular interrogation grid in the plane of the light sheet onto the left and right vector maps. The two-dimensional vector maps are individually resampled over the new interrogation points using an interpolation scheme to estimate the two-dimensional vectors based on their nearest neighbours. This gives the two-dimensional displacement as seen by each camera at each

point on a common interrogation grid, and the true three-dimensional displacement can be estimated by solving four equations with three unknowns through a least-squares scheme. The three-dimensional velocity map reconstructed from the two-dimensional vector maps in figure 27 is shown in figure 28. In this image the horizontal and vertical velocity components are represented by vectors and the velocity component perpendicular to the page is represented by coloured contours.

Figure 28: Three-dimensional PIV velocity map reconstructed from the 2-D maps in figure 27 [23]

While there are many great advantages to PIV, there are also several disadvantages. The field of view in the plane of the laser sheet for each of the 2048 x 2048 pixel CCD cameras was approximately 120 mm x 120 mm. Each pixel represented an area in the flow field measuring 0.059 mm x 0.059 mm, and each interrogation region covered an area of the flow measuring 1.875 mm x 1.875 mm. This is effectively the resolution of the PIV system, and is slightly greater than that of a typical LDA system and is much greater than that of a hotwire probe. A velocity vector calculated in an interrogation region is an average of the velocities of the seeding particles in that region, and this may result in error in regions of the flow with high

velocity gradients.

Additionally, data processing is slow for PIV systems. Each capture, which resulted in a single instantaneous three-dimensional velocity vector plot, required acquisition of four tiff format images using 8 Mb of hard drive space each. Each capture took approximately 100 seconds to process. While tens or hundreds of thousands of samples are easily possible with LDA and hotwire measurements, limited hard drive space and excessive processing time limit the current system to 100 samples at each data point. This results in a poorer average of the mean velocity data, and less smooth velocity contours and profiles. This makes calculation of certain values, such as swirl number, approximate. Additionally, because of the low number of samples acquired, rms velocity values can give an indication of the turbulence level, but have a wide margin of error.

4 Numerical methods

4.1 Computational swirler models

The swirler models used in the CFD simulations were identical to the experimental swirlers. The swirler models were modified in AutoCAD 2000 and then exported as ACIS solid model files. The internal channels created for injection of a secondary gas were eliminated in order to reduce computational effort since the actual flow through the interior of the swirlers is of little concern.

The solid swirler model was subtracted from a cylinder the same size as the plenum chamber. In CFD simulations the interest is not in the geometry of the swirler itself, but rather in the geometry of the flow path. By subtracting the swirler from the cylinder, the flow domain became a path defined by the swirler shape. The resulting geometry was the downstream section of the plenum chamber with a swirler-shaped obstacle. A solid combustion chamber representing the inside of the transparent tube was also constructed in AutoCAD.

A 60° slice was taken from the resulting flow domain for all configurations except for the XEVe-6. This was done to reduce computational effort since the swirlers have six planes of azimuthal symmetry. The entire domain of the XEVe-6 was simulated since the elliptic geometry did not yield appropriate symmetry planes.

The flow domain of each swirler was exported as six different files: the plenum chamber, the interior of the swirler, the exit of the front panel, the transition piece and two sections

of the combustion chamber. This was done to facilitate meshing.

4.2 Meshing and initializing the solution domain

The ACIS files representing the flow domains of the swirlers were imported into GAMBIT for meshing. The interior of the swirler and the plenum section were first imported and connected to each other along their adjoining faces. The exit section of the front panel was then imported and added to the interior of the burner cone. Both sections of the combustion chamber were then imported and all adjoining faces were then connected.

Where 60° model sections were used, corresponding side faces were linked so that they would be meshed identically; this is a requirement of periodic boundary conditions (see section 4.3.2). The interior of the swirler cone was meshed using the Cooper scheme which allows hexahedral elements to be used. Hexahedral elements are preferable to tetrahedral elements in crucial regions of the flow since numerical diffusion is minimized. The combustion chamber was also meshed with hexahedral elements using the Cooper scheme, and a boundary layer mesh was constructed starting at the upstream end of the combustion chamber. This allowed very fine elements to be created near the outlet of the burner where the flow was most interesting, and more coarse elements to be used further downstream where the flow was less crucial. The complex geometry of the plenum chamber necessitated use of a tetrahedral meshing scheme.

All adjoining faces in the interior of the mesh were specified as interior boundary conditions, and the air inlet was specified as a mass flow inlet. Side faces in 60° models sections

were specified as periodic boundary conditions. The combustion chamber outlet was specified as a pressure outlet, and all other faces in the model were assumed by GAMBIT to be solid walls. Refer to section 4.3.2 for more details on the types of boundary conditions used.

The mesh was exported by GAMBIT as a mesh (.msh) file, and was imported into FLUENT. The mesh was scaled to compensate for the fact that it was created using inch measurements while FLUENT uses SI units by default. The solver type, turbulence model, species model, operating conditions, boundary conditions and convergence criteria were all set (see section 4.3) and all velocity values were initialized to zero. Iterative computations were then performed in FLUENT 5.5 or FLUENT 6.0.

4.3 Solution parameters

4.3.1 Segregated solver

FLUENT allows the use of two different types of solvers: segregated or coupled. The segregated solver solves the continuity, momentum, energy and species equations sequentially while the coupled solver solves them simultaneously.

The segregated solver was originally designed to solve incompressible and mildly compressible equations while the coupled solver was designed for high-speed compressible flows. Both solvers have evolved with newer versions of FLUENT so that they are applicable to a wide range of flow conditions, although one is usually faster in certain situations. The segregated solver was used for the current set of simulations since they meet the traditional requirements for the segregated solver.

4.3.2 Boundary conditions

The boundary conditions for the models were specified as described in section 4.2. FLUENT allows a variety of different boundary conditions to be specified for different types of inlets, outlets, internal zones, face boundaries, and repeating boundaries. One type of boundary condition is usually preferable to the others based on the information that is given. For example, in the current simulations, a mass flow inlet boundary condition is preferable to a velocity inlet or a pressure inlet since the mass flow rate is known.

The inlet for the combustion air was specified as a mass flow inlet. A mass flow inlet requires the total mass flow rate or mass flux through the inlet area as well as the flow direction, total temperature, turbulence parameters and mixture fractions for species calculations. The mass flow rate of air was calculated based on a Reynolds number of $Re = 100,000$. This was the same as was selected for the cold-flow tests (see section 6). The flow direction was specified as being normal to the boundary and the total temperature was set to 300 K. Turbulence parameters were defined as recommended in the FLUENT manual. The turbulence intensity was selected as 2% for the combustion air, based on the expected performance of the flow conditioners in the test-rig. The turbulent length scale was calculated as:

$$l = 0.07L \tag{18}$$

Where l is the turbulent length scale and L is the diameter of the inlet face. The mass flow inlet boundary condition allows the user to specify a pressure value at the inlet. This is used only as an initial estimate in order to help the model converge more quickly.

The outlet at the end of the combustion chamber is the only outlet in this model, and

was specified as a pressure outlet. A pressure outlet requires the static pressure, backflow total temperature, backflow turbulence parameters and backflow species concentrations. The backflow parameters are necessary only if a flow reversal occurs on its boundary. Since the outlet is far removed from the outlet of the swirler, no backflow was expected at the outlet and the backflow parameters were not modified. This assumption was verified when the simulations were run. The static pressure at the outlet was specified as atmospheric pressure.

By default, FLUENT assumes that all unspecified faces are wall boundaries. Wall boundaries are used to bound fluid and solid regions and the no-slip condition was specified along all walls.

Since the model was constructed in several pieces (see section 4.2) the faces adjoining two separate sections of the model were specified as interior boundaries. FLUENT allows fluids to freely pass through interior boundaries.

When a 60° slice of the burner model was simulated instead of the entire model, the sides of the resulting wedge-shaped flow domain were specified in GAMBIT as periodic boundaries, and then further specified in FLUENT as rotational periodic boundaries. Periodic boundary conditions must be specified in pairs and must be meshed identically. FLUENT treats the flow on a periodic boundary as though the opposing periodic boundary is a direct neighbour to the cells adjacent to the first periodic boundary.

4.3.3 Material properties

Material properties were taken from Holman.[27] Table 1 lists the fluid properties that were used for air at 300 K.

Table 1: Properties of air at 300 K [27]

	air
ρ (kg/m ³)	1.1774
C_p (kJ/kg K)	1.0057
k (W/m K)	0.02624
μ (kg/m s)	$1.8462 \cdot 10^{-5}$

4.4 Solution scheme

4.4.1 Solution procedure

The segregated solver obtains a solution through an iterative process. Each iteration consists of five steps. In the first step, the fluid properties are updated from either the solution from the previous iteration or from the initialized solution. Second, the u , v and w momentum equations are solved in turn using the current values for pressure and face mass fluxes in order to evaluate new values for the velocity field. Next, since the velocity values may not satisfy the continuity equation, a “Poisson-type” equation for the pressure correction is derived from the continuity equation and linearized momentum equations. The pressure correction is solved to obtain the necessary corrections to the pressure and velocity fields and the face mass fluxes so that continuity is satisfied. Fourth, the equations for turbulence are solved based on the most recent values of other variables. The final step is to check for

convergence of the equation set. The iterative process continues if convergence is not within the limits specified by the user.

4.4.2 Discretization and linearization of the governing equations

FLUENT converts the governing equations to algebraic equations that can be solved numerically using a control-volume based technique. This technique consists of integrating the governing equations about each cell yielding discrete equations that conserve each quantity on a control volume basis. Considering the steady state conservation equation for transport of scalar quantity ϕ for an arbitrary control volume V , the governing equation is:

$$\oint \rho \phi \mathbf{v} \cdot d\mathbf{A} = \oint \Gamma_\phi \nabla \phi \cdot d\mathbf{A} + \int_V S_\phi dV \quad (19)$$

Where ρ is the density, $\mathbf{v}$ is the velocity vector, A is the surface area vector, Γ_ϕ is the diffusion coefficient for ϕ , and S_ϕ is a source term for ϕ on a volume basis. Discretization of equation 19 on a given cell results in:

$$\sum \mathbf{v}_f \phi_f A_f = \sum \Gamma_\phi (\nabla \phi)_n A_f + S_\phi V \quad (20)$$

Where ϕ_f is the value of ϕ convected through face f , $\mathbf{v}_f$ is the mass flux through the face, A_f is the area of the face, $(\nabla \phi)_f$ is the magnitude of $\nabla \phi$ normal to the face and V is the cell volume. FLUENT stores discrete values of ϕ at the centre of each cell, however equation 20 requires values of ϕ at the faces of the cell. These face values are interpolated from the cell centre values using an upwind scheme which is discussed later.

Equation 20 is, in general, non-linear with respect to these variables. A linearized form may be written as:

$$a_p\phi = \sum a_{nb}\phi_{nb} + b \quad (21)$$

Where the subscript nb refers to neighbouring cells and a_p and a_{nb} are the linearized coefficients for ϕ and ϕ_{nb} .

Because of the non-linearity of the equation set being solved, it is necessary to control the change of ϕ through the use of under-relaxation factors. The new value of ϕ depends on the previous value, ϕ_{old} , the computed change, $\Delta\phi$ and the under-relaxation factor, α . The new value of ϕ is calculated as:

$$\phi = \phi_{old} + \alpha\Delta\phi \quad (22)$$

Under-relaxation factors for the various equations are shown in table 2. In certain situations where the solution would not converge stably, these values were slightly reduced, although higher values resulted in faster convergence.

Table 2: Under-relaxation factors

Pressure	0.3
Momentum	0.4
Energy	1.0
Turbulence Kinetic Energy	0.8
Turbulence Dissipation Rate	0.8
Turbulence Dissipation Rate	0.8
Viscosity	1.0
Body Forces	1.0

4.4.3 Momentum equation

FLUENT obtains a solution for the velocity field by solving the steady-state continuity and momentum equations. The momentum equation can be expressed in integral form as:

$$\oint \rho \mathbf{v} \mathbf{v} \cdot d\mathbf{A} = - \oint p \mathbf{I} \cdot d\mathbf{A} + \oint \boldsymbol{\tau} \cdot d\mathbf{A} + \oint_V \mathbf{F} dV \quad (23)$$

Where $\mathbf{I}$ is the identity matrix, $\boldsymbol{\tau}$ is the stress tensor and $\mathbf{F}$ is the force vector. Equation 23 is linearized using the scheme described in section 4.4.2. The x -momentum equation becomes:

$$a_P u = \sum_{nb} a_{nb} u_{nb} + \sum p_f \cdot \hat{\mathbf{i}} A + S \quad (24)$$

This equation can be solved to yield a velocity field provided that the pressure field and face mass fluxes are known. FLUENT uses a co-located scheme where fluids properties are stored at the centre of each cell. In order to determine the mass flux and CO_2 concentrations along the walls of the cell, the second-order upwind scheme was used. This scheme uses a Taylor expansion series of the cell-centred solution about the cell centroid. The face value of a given property, ϕ_f is given as:

$$\phi_f = \phi + \nabla \phi \cdot \Delta \mathbf{s} \quad (25)$$

Where ϕ and $\nabla \phi$ are the cell-centred value and its gradient in the upstream cell, and $\Delta \mathbf{s}$ is the displacement vector from the upstream cell centroid to the face centroid. The gradient is determined using the divergence theorem which is written in discrete form as:

$$\nabla \phi = \frac{1}{V} \sum_f^{N_{faces}} \bar{\phi}_f \mathbf{A} \quad (26)$$

Where $\bar{\phi}_f$ is computed by averaging ϕ from the from the two cells adjacent to the face.

Turbulence and energy parameters were computed at the cell walls using the first-order upwind scheme. This scheme assumes that the value on the cell wall is the same as the value at the centre of the cell and results in only a small difference when used for these parameters compared to the second-order upwind scheme.

The pressure values at the cell faces are determined through an interpolation scheme that uses the momentum equation coefficients. This scheme works well as long as the pressure variation between cells is smooth.

4.4.4 Continuity equation

The continuity equation may be expressed in integral form as:

$$\oint \rho \mathbf{v} \cdot d\mathbf{A} = 0 \quad (27)$$

Integrating equation 27 over a control volume yields:

$$\sum_f^{N_{faces}} \rho v_n A_f = 0 \quad (28)$$

Equations 24 and 28 are solved sequentially by the segregated solver. In this procedure the continuity equation is used as an equation for pressure since density is directly related to pressure. To solve the continuity equation it is necessary to evaluate the face velocities, v_n , from the velocity values at the cell centres. This is done through weight averaging which uses weighting factors based on the a_p coefficient in equation 24. In this scheme the face flow rate, J_f is evaluated as:

$$J_f = \hat{J}_f + \frac{\rho A_f^2}{\bar{a}_P} (p_{c0} - p_{c1}) \quad (29)$$

Where p_{c0} and p_{c1} are the pressures at the centres of the cells on either side of the face, $\hat{J}_f$ contains the influence of velocities in these cells, and $\bar{a}_P$ is the average of the coefficients a_P for the cells on either side of the face.

FLUENT uses an algorithm known as the semi-implicit method for pressure linked equations (SIMPLE) to provide a relationship between velocity and pressure corrections in order to enforce mass conservation and obtain the pressure field. If a guessed pressure field, p^* , is used in equation 29, the resultant face flow rate, J_f^* , will not satisfy continuity. As a result, a correction, $\acute{J}_f$, is added to the face flow rate, J_f^* , so that the corrected face flow rate, J_f , satisfies the continuity equation. The SIMPLE algorithm calculates the correction through:

$$\acute{J}_f = d_f(\acute{p}_{c0} - \acute{p}_{c1}) \quad (30)$$

Where $\acute{p}$ is the cell pressure correction. The SIMPLE algorithm substitutes the flux correction equations into the discrete continuity equation to obtain a discrete form of the pressure correction in the cell.

$$a_P \acute{p} = \sum_{nb} a_{nb} \acute{p}_n b + \sum_f^{N_{faces}} J_f^* \quad (31)$$

Where the last term in equation 31 represents the net flow rate into the cell. Equation 31 is solved and the cell pressure and face flow rate are then corrected using:

$$p = p^* + \alpha_p \acute{p} \quad (32)$$

$$J_f = J_f^* + d_f(\acute{p}_{c0} - \acute{p}_{c1}) \quad (33)$$

Where α_p is the under-relaxation factor for pressure. The continuity equation is then satisfied identically by the corrected face flow, J_f , during each iteration.

4.4.5 Turbulence modeling

Turbulence modeling is the most difficult part of computation fluids dynamics simulation. Turbulent flows are characterized by random, three dimensional vortical fluctuations which cause momentum, energy and species to be diffused and create fluctuations in their values as well. The randomness, small size and high frequency of these fluctuations preclude them from being simulated directly in computations, so the instantaneous governing equations are manipulated to remove the small scales. This gives a modified set of equations that requires less computational resources to solve but contain unknown variables which require the use of turbulence models.

FLUENT offers a variety of different turbulence models that are appropriate for different types of flows and require different amounts of computational time.

The realizable k - ϵ model was used in the current simulations. This model was chosen since it does not require excessive computational time and provides several improvements over the standard k - ϵ model. It has also performed well in simulations conducted on swirler simulations at ALSTOM Power Ltd.[28] The main drawback to the k - ϵ model is that it assumes that the turbulence level is identical in all directions. Other turbulence models, such as the Reynolds Stress Model, evaluate each component of the Reynolds stress tensor and therefore allow for anisotropic turbulence, but take considerably more time to evaluate.

The k - ϵ models are used in conjunction with the Reynolds-averaged Navier-Stokes equations (RANS). The RANS equations represent transport equations for the mean flow quantities only, and all scales of turbulence are modeled. This greatly reduces the amount of

time required since the governing equations contain no time derivatives and a steady-state solution can be obtained without a great computational effort. In Reynolds averaging, the variables in the instantaneous Navier-Stokes equations are decomposed into the mean and fluctuating components. Each velocity component, pressure and any other scalar quantity takes the form:

$$\phi = \bar{\phi} + \phi' \quad (34)$$

Where $\bar{\phi}$ denotes the mean quantity and ϕ' denotes the fluctuating quantity. Substituting expressions of this form for the flow variables into the instantaneous continuity and momentum equations and performing a time average yields the time-averaged momentum equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0 \quad (35)$$

$$\rho \frac{D\bar{u}_i}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \bar{u}_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \quad (36)$$

Equations 35 and 36 are the Reynolds-averaged Navier-Stokes equations and have the same general form as the instantaneous Navier-Stokes equations, except that the solution variables are time-averaged values. The Reynolds stress term (the last term in equation 36 on the right hand side) represents the effect of turbulence and must be modeled.

In the k - ϵ models the Reynolds stress is modeled using the Boussinesq hypothesis which relates the Reynolds stresses to the mean velocity gradients.

$$-\overline{\rho u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_i}{\partial x_i} \right) \delta_{ij} \quad (37)$$

The turbulent kinetic energy, k , and the turbulence dissipation rate, ϵ , are solved for, and

the eddy viscosity, μ_t , is calculated as a function of k and ϵ . The advantage of this model is that the computational cost is reduced in the computation of μ_t . The main disadvantage of this model is that it assumes that μ_t is an isotropic scalar quantity, which is not true in many cases. Often times, the k - ϵ model performs well, and the use of more computationally expensive models such as the Reynolds stress model is not justified.

The k - ϵ model is a semi-empirical model based on model transport equations for k and ϵ . The model transport equation for k is derived from the exact equation while the model transport equation for ϵ is obtained from physical reasoning. The realizable k - ϵ model differs from the standard k - ϵ model in that the model satisfies certain mathematical constraints on the normal stresses, consistent with the physics of turbulent flows. In both the standard and realizable k - ϵ models, the eddy viscosity is calculated as:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (38)$$

In the standard k - ϵ model C_μ is a constant, although in certain situations, the normal stress, $\overline{u^2}$, can become negative, i.e. non-realizable. In the realizable k - ϵ model, C_μ is a variable that is sensitive to the mean flow and turbulence. The modeled transport equations for k and ϵ are:

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M \quad (39)$$

$$\rho \frac{D\epsilon}{Dt} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu} \epsilon} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b \quad (40)$$

where

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right] \quad (41)$$

and

$$\eta = \frac{Sk}{\epsilon} \quad (42)$$

In these equations G_k and G_b are the generation of turbulent kinetic energy due to the mean velocity gradients and buoyancy respectively, Y_M is the contribution of fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_{1\epsilon}$ and C_2 are constants, and σ_k and σ_ϵ are the turbulent Prandtl numbers for k and ϵ respectively.

The eddy viscosity is given by equation 38 above. As was mentioned previously, the value C_μ is not constant as it is in the standard and renormalization group k - ϵ models, but is calculated from:

$$C_\mu = \frac{1}{A_0 + A_s \frac{U^* k}{\epsilon}} \quad (43)$$

Where

$$U^* \equiv \sqrt{S_{ij}S_{ij} + \tilde{\Omega}_{ij}\tilde{\Omega}_{ij}} \quad (44)$$

and

$$\tilde{\Omega}_{ij} = \Omega_{ij} - 2\epsilon_{ijk}\omega_k \quad (45)$$

$$\Omega_{ij} = \overline{\Omega_{ij}} - \epsilon_{ijk}\omega_k \quad (46)$$

Where $\overline{\Omega_{ij}}$ is the mean rate of rotation tensor viewed in a rotating reference frame with the angular velocity ω_k . The model constants are defined as:

$$\begin{aligned} A_0 &= 4.04 \\ A_s &= \sqrt{6} \cos \phi \end{aligned}$$

Where

$$\phi = \frac{1}{3} \arccos(\sqrt{6}W) \quad (47)$$

$$W = \frac{S_{ij}S_{jk}S_{ki}}{\tilde{S}} \quad (48)$$

$$\tilde{S} = \sqrt{S_{ij}S_{ij}} \quad (49)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (50)$$

From equations 43 through 50 it is seen that C_μ is a function of the mean strain and rotation rates, the angular velocity of the system rotation and the turbulence fields (k and ϵ).

The constants in the modeled transport equations have been established to ensure that the model performs well for certain flows and are given as:

$$\begin{aligned} C_{1\epsilon} &= 1.44 \\ C_2 &= 1.9 \\ \sigma_k &= 1.0 \\ \sigma_\epsilon &= 1.2 \end{aligned}$$

The term G_k , which represents the production of turbulent kinetic energy is computed in a manner consistent with the Boussinesq hypothesis:

$$G_k = \mu_t S^2 \quad (51)$$

Where S is the modulus of the mean rate of strain tensor:

$$S \equiv \sqrt{2S_{ij}S_{ij}} \quad (52)$$

With the mean strain rate, S_{ij} given by equation 50.

The term G_b , which represents generation of turbulence due to buoyancy, is important in situations with a nonzero gravity field and a temperature field. In the current simulations

neither of these conditions exist and this term is negligibly small. It is, however, defined in FLUENT as:

$$G_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (53)$$

Where g_i is acceleration of gravity, Pr_t is the turbulent Prandtl number for energy and the coefficient of thermal expansion is defined as:

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p \quad (54)$$

Finally, the term Y_M represents the dilatation dissipation term. This term is particularly important in high Mach number flows and accounts for the effect of compressibility on turbulence. Neglecting this term causes the model to fail to predict the decreased spreading rate in shear layers that has been observed experimentally. This value is modeled as:

$$Y_M = 2\rho\epsilon M_t^2 \quad (55)$$

Where the turbulent Mach number is defined as:

$$M_t = \sqrt{\frac{k}{a^2}} \quad (56)$$

4.4.6 Convergence of a solution

After discretization, the conservation equation for variable ϕ can be written as shown in equation 21. Where a_P is the coefficient at the centre of the cell, a_{nb} are the coefficients for the neighbouring cells, and b is the contribution of the constant part to the source term S_c in:

$$S = \sum_{nb} S_c + S_{p\phi} \quad (57)$$

Rewriting equation 21:

$$a_P = \sum_{nb} a_{nb} - S_P \quad (58)$$

The unscaled residual, R^ϕ computed by the segregated solver is the imbalance in equation 21 summed over all the computational cells P .

$$R^\phi = \sum_{\text{cells } P} \left| \sum_{nb} a_{nb} \phi_{nb} + b - a_P \phi_P \right| \quad (59)$$

Since it is difficult to judge convergence by examining the residuals given in equation 59, they are usually scaled by a factor representative of the flow rate of ϕ through the domain. The scaled residual of ϕ is given as:

$$R^\phi = \frac{\sum_{\text{cells } P} \left| \sum_{nb} a_{nb} \phi_{nb} + b - a_P \phi_P \right|}{\sum_{\text{cells } P} |a_P \phi_P|} \quad (60)$$

The scaled residual is a more appropriate indicator of convergence for most cases.

The residual for the continuity equation is defined as:

$$R_c = \sum_{\text{cells } P} |\text{rate of mass creation in cell } P| \quad (61)$$

The scaled residual for continuity is:

$$R_c = \frac{R_{\text{iteration } N}^c}{R_{\text{iteration } 5}^c} \quad (62)$$

Where the denominator is the largest absolute value of the continuity residual in the first five iterations.

In the current simulations the solution was considered to have converged once the residuals had leveled off and had dropped at least four orders of magnitude.

5 Results and discussion of water channel tests

An experimental burner with design features similar to ALSTOM's machine burners was considered as the baseline case for tests conducted in the water channel. The baseline burner had an outlet similar to that shown in figure 29, and its swirl number was measured to be $S_N = 0.5$. LDA measurements were made in one of the two planes shown in this figure, denoted as being either parallel or perpendicular to the burner slots. LIF measurements were conducted with the laser sheet aligned with these two planes, as well as in a plane perpendicular to the burner outlet. Several different modifications were made to the baseline burner to determine how they affected the instability and flow structure.

Figure 29: Measuring planes on the outlet of the experimental burner

The first modification involved inserting a pair of shells into the burner cone which gave the burner an elliptic outlet with an eccentricity of $e = 0.7$ (aspect ratio of $AR = 1.429$). The plane parallel with the slots was the major axis and the plane perpendicular to the slots was the minor axis. The second modification was to use a lengthened burner lance that extended inside of the burner cone. The long lance, or LoLa as it is commonly called, is

positioned such that its tip is approximately at the upstream end of the vortex breakdown bubble. The final modification was to mount a set of miniature vortex generators ($L_{vg}/D_b = 0.029$) around the burner outlet such that they protruded into the flow leaving the burner.

Two different instability modes were investigated in the water channel at ALSTOM Power Ltd. The first instability mode was the natural instability of the swirling flow and was observed simply by forcing water through the burner model. The second instability simulated a thermoacoustic instability and was excited by pressure pulsations in the flow which were generated by displacing 10% of the bulk flow at a single frequency.

The instability modes are characterized by the Strouhal number, St , which is defined as:

$$St = \frac{f D_{sw}}{u} \quad (63)$$

Where f is the instability frequency, D_{sw} is the burner diameter and u is the average velocity of the water through the burner, defined as:

$$u = \frac{4Q}{\pi D_{sw}^2} \quad (64)$$

Where Q is the volumetric flow rate of water through the test section.

The flow conditions are characterized by the Reynolds number defined as:

$$Re = \frac{u D_{sw}}{\nu} \quad (65)$$

Where ν is the kinematic viscosity of the water. The flow rate used for LDA measurements was $Q = 15$ L/s which gave a Reynolds number of $Re = 83,200$. During LIF measurements, the flow rate was reduced to $Q = 10$ L/s, giving a Reynolds number of $Re = 55,500$. This change in Reynolds number did not significantly alter the structure of the flow, but only changed the magnitude of the flow velocity.

When the forcing mechanism was not activated, an instability frequency of approximately 3.2 Hz was consistently measured with a hot film probe downstream of the burner exit for a flow rate of $Q = 15$ L/s. Frequency spectra of velocity time traces at a point a distance of $y = 0.17D_{sw}$ downstream of the outlet are shown in figures 30 and 31 for the baseline burner. The velocity spectrum shown in figure 30 was acquired with the forcing mechanism deactivated and the spectrum shown in figure 31 was acquired with the forcing mechanism activated. Figure 30 shows that the natural flow instability is the only instability mode, and has a frequency corresponding to $St = 1.33$. This instability relates well to the helical instability identified by Paschereit et al. in atmospheric combustion tests conducted on a similar experimental burner.[29] When the forcing mechanism is activated, the natural flow instability is still clearly seen, although its amplitude is reduced to approximately one third of the original level and is dominated by an instability at the same frequency as the forcing mechanism, corresponding to $St = 0.58$. The amplitude of this instability was dictated by the amplitude of the forcing mechanism and had a level approximately 2.6 times greater than the $St = 1.33$ instability when the forcing mechanism is not activated.

5.1 Phase-locked LIF measurements

The signal from the hot film probe was used as described in section 3.1 to trigger the CCD camera for the unforced case. A series of phase-locked images recorded every 45° through the instability cycle is shown in figure 32 for the unmodified burner. The images are recorded immediately downstream of the burner outlet with the flow propagating toward the right

side of the image. From this figure it can be seen that vortices are shed alternately from either side of the burner. The final image in the sequence was obtained by averaging the eight phase-locked images together to obtain an unbiased non-phase-locked image. From this image it is seen that on average the flow is axisymmetric, and that the vortex breakdown bubble extends upstream inside the burner cone. The upper half of each image is brighter than the lower half since the laser is projected from the upper side.

Figure 33 shows a second series of phase-locked images of this instability recorded with the laser sheet oriented in a plane parallel with the outlet of the burner, positioned at approximately $y = 0.054D_{sw}$ downstream of the sudden expansion. The flow direction is out of the page and the swirl direction is clockwise. From this set of images it can be seen that the instability propagates azimuthally around the perimeter of the burner outlet in the direction of swirl. Comparing figures 32 and 33, it is seen that this instability has a helical structure.

The forcing mechanism was programmed to operate at a frequency giving a Strouhal number of $St = 0.58$, in order to simulate the axisymmetric instability identified by Paschereit et al. in atmospheric combustion tests.[29] For a volumetric flow rate of $Q = 15$ L/s the forcing frequency was 2.05 Hz and for $Q = 10$ L/s the frequency was 1.38 Hz.

A series of phase locked images of the forced flow is shown in figure 34. For this image set, the laser sheet passes through the plastic window in the side of the burner cone and illuminates the flow downstream of the burner outlet as well as. The flow direction is from bottom to top. Vortices are seen forming simultaneously on both sides of the burner. More

striking in these images is the drastic axial oscillation of the vortex breakdown bubble inside the burner cone. Shedding of the vortices from the burner outlet is in phase with oscillation of the vortex breakdown bubble. That is, formation of the vortices begins as the breakdown bubble is at its furthest point upstream. The vortices grow as the breakdown bubble moves downstream, and are shed as the breakdown bubble reaches its furthest downstream position. Helical structures can also be seen inside the burner cone upstream of the vortex breakdown bubble.

A second set of phase-locked images of this instability is shown in figure 35. The flow direction is out of the page and the swirl direction is clockwise. This set of images clearly shows the axisymmetric nature of the instability. The ring structure of the vortex can be seen forming and shedding, followed by the flow in the centre collapsing inwards. In this set of images, the helical instability can also be seen as a bright spot on the ring vortex propagating around the circumference of the burner in the direction of swirl.

Since the elliptic inserts reduced the outlet area of the burner by a factor of 0.70, they also increased the burner exit velocity by a factor of 1.429. The hydraulic diameter of the elliptic burner, which was approximately 81% of the diameter of the circular burner, was used to calculate the Strouhal and Reynolds numbers. As expected, the increased exit velocity resulted in an increased instability frequency of approximately 5.3 Hz for a flow rate of $Q = 10$ L/s and about 7.95 Hz for $Q = 15$ L/s. Both of these values correspond to a Strouhal number of 1.27.

A visualization of the $St = 1.27$ instability for the elliptic burner is shown in figure 36.

The flow direction is toward the right side of the images. Here it can be seen that the presence of the elliptic shells has little effect on the overall structure of the instability: vortices are shed alternately from either side of the burner outlet. Comparing this plot to figure 32, it is seen that the main difference is that the elliptic shells accelerate the flow and force the vortex breakdown bubble downstream and out of the burner cone. This is verified by the velocity measurements which are discussed later.

The elliptic burner was tested with the forcing mechanism operating at a frequency corresponding to a Strouhal number of $St = 0.58$. For a flow rate of $Q = 10$ L/s the forcing frequency was $f = 2.2$ Hz and for a flow rate of $Q = 15$ L/s it was $f = 3.3$ Hz. With the forcing mechanism activated, the elliptic burner was observed to shed axisymmetric vortices from its outlet in a manner similar to that of the standard burner (fig. 37). From the non-phase-locked image at the end of this sequence it is apparent that the average position of the vortex breakdown bubble is outside of the burner cone. A Perspex elliptic shell was fabricated and used to observe the flow field inside the burner cone. A phase-locked visualization of the flow field inside the elliptic burner cone is shown in figure 38. The flow direction is from left to right. From these images it is seen that the vortex breakdown bubble is outside of the burner cone for most of the instability cycle. For phase angles of 225° , 270° , 315° and 0° it can be seen that while the breakdown bubble enters the burner cone, its movement is not nearly as drastic as it is for the standard burner. Since the elliptic shells decrease the outlet area of the burner, the exit flow is accelerated and the vortex breakdown bubble is forced outside of the burner cone. Since there is a higher dynamic pressure inside the burner cone,

pressure pulsations in the combustion chamber would require a much greater amplitude to disturb the vortex breakdown bubble to the same extent as for the standard burner. This would damp the oscillation of the breakdown bubble and stabilize the combustion process.

The extended lance has achieved a large degree of success in testing and in actual operation.[21] The lance is positioned such that its tip is approximately at the upstream end of the vortex breakdown bubble. The outlet area for this configuration is unchanged from the standard burner, and therefore the average flow velocity and instability frequency values remain unchanged compared to the standard burner.

Figure 39 shows a visualization of the helical instability for the burner with the LoLa installed. The flow inside the burner cone and downstream of the burner outlet is shown in this figure. The flow direction is toward the right side of the images. It is seen that the lance stabilizes the vortex breakdown just upstream of the burner outlet. Helical vortices can be seen forming and shedding from the outlet of the burner, similar to that in figure 32. The flow inside the burner cone immediately downstream of the lance exhibits a lateral flapping motion in phase with the shedding of the helical vortices.

The most significant effect on the flow was observed when the forcing mechanism was activated. This is shown in figure 40. In this figure, an axisymmetric ring vortex is seen forming and shedding from the burner outlet. Inside the burner, however, there is only slight movement of the vortex breakdown bubble. The extended lance provides an anchoring point for the vortex breakdown bubble and physically impedes its movement.

5.2 Velocity profile measurements

Measurements of the axial and tangential velocity components were conducted with a two component LDA system downstream of the burner outlet for several different burner configurations. Velocity profiles were obtained by making measurements at several downstream locations along radial lines passing through the axis of the burner. A flow rate of $Q = 15$ L/s was used while conducting LDA measurements.

Initially, several different velocity profiles were measured for the unmodified burner at distances of $0.17D_{sw}$, $0.29D_{sw}$ and $0.5D_{sw}$ downstream of the burner to determine how the velocity field changed in the downstream direction. Measurements were made parallel with and perpendicular to the burner slots, and all variations were tested with and without the forcing mechanism activated.

Figure 41 shows axial velocity profiles for the unmodified burner at the three different downstream locations, parallel and perpendicular to the burner slots, with the forcing mechanism deactivated. The velocity profiles are normalized by the average exit velocity of the burner. Looking at the three solid lines which represent the velocity profiles parallel to the slots, it can be seen that as the flow propagates downstream, it splits into a bifurcated jet that spreads, widens and slows as it travels around the vortex breakdown bubble in the centre of the flow. It is also seen that both the inner and outer shear layers move outwards from the centre of the burner and the velocity of the backflow in the centre of the flow increases. Looking at the dashed lines, a similar trend is seen for the velocity profiles perpendicular to the burner slots, however the movement of the shear layers outward and the slowing of the

bifurcated jet is more marked. Initially the jet has its highest value in a plane perpendicular to the slots, but the axial velocity in this plane decays quickly and beyond a distance of $0.29D_{sw}$ downstream of the outlet, the jet has a higher velocity in a plane parallel to the burner slots. At all downstream positions, the jet has a higher spreading rate in the plane perpendicular to the slots.

Figure 42 shows the tangential velocity profiles for the standard burner at the same locations as figure 41. The three solid lines represent the velocity profiles parallel to the slots, and it is seen that the tangential component decreases in magnitude moving downstream. The velocity profiles perpendicular to the burner slots, represented by the dashed lines, show a slight decrease in the magnitude of the tangential velocity relative to the profiles parallel to the burner slots. At locations close to the burner outlet, the tangential velocity component increases from a zero value along the axis of the burner, reaches a local maximum value and then drops sharply near the edge of the burner outlet before increasing in magnitude again. Further downstream, near $0.5D_{sw}$, the tangential velocity component reaches a value which remains nearly constant along the remainder of the profile. Close to the burner outlet, there is a higher tangential velocity in the plane parallel with the burner slots, but further downstream the velocity profiles show less difference.

Figure 43 shows axial RMS velocity profiles. This plot shows that the turbulence intensity is strongest in the plane perpendicular to the burner slots, although its level in this plane decreases quickly in the downstream direction. The turbulence intensity is strongest in the inner shear layer and is weaker in the centre of the flow and in the outer shear layer.

Figure 44 shows axial velocity profiles for the standard burner for the same locations as before with the forcing mechanism activated. A side by side comparison of figures 41 and 44 shows that the forcing mechanism causes only slight changes in the velocity profiles. Activation of the forcing mechanism causes the jet parallel to the burner slots to move slightly inwards toward the centreline of the burner, and causes the maximum axial velocity in the flow perpendicular to the slots to increase slightly. Figure 45 shows the tangential velocity profiles for the same conditions as figure 44. Little difference is observed in the tangential velocity component whether the forcing mechanism is activated or not.

Figure 46 shows axial RMS velocity profiles for the standard burner with the forcing mechanism activated. The same general trend is seen as in figure 43, except that the turbulence intensity is approximately 40% higher in the centre of the flow. This is a result of the oscillation of the vortex breakdown bubble, caused by the pressure pulsations in the flow.

Figure 47 shows a set of axial velocity profiles for the burner with the $e = 0.7$ elliptic shells inserted. This figure shows that the bifurcated jet widens and slows as it moves downstream, similar to the case for the standard burner. In the plane perpendicular to the burner slots, the jet has a significantly higher velocity than in the parallel plane. The jet along the minor axis has a much higher spreading rate than along the major axis, which is an indication that axis switching is occurring. A significant difference between the standard and elliptic burners is that the vortex breakdown bubble of the elliptic burner is downstream of the burner cone. The velocity profiles show that the upstream tip of the vortex breakdown bubble is positioned somewhere between $y = 0.17D_{sw}$ and $y = 0.29D_{sw}$.

Figure 48 shows tangential velocity profiles for the elliptic burner. The location of maximum velocity moves radially outward when moving downstream in both planes. The magnitude of the tangential velocity component is similar in both planes, and the velocity shows a sharp increase in the plane perpendicular to the burner slots beyond the outlet of the burner.

Axial RMS velocity profiles are shown for the elliptic burner in figure 49. Near the outlet, the turbulence intensity is highest in the plane parallel to the burner slots, however this level quickly decreases moving downstream and the turbulence intensity becomes higher in the plane parallel to the burner slots, where the maximum turbulence intensity maintains a nearly constant level.

Figure 50 shows a comparison of axial velocity profiles parallel to the slots between the standard, elliptic, LoLa and vortex generator burners. The most drastic change occurs when the elliptic shells are installed. In addition to the vortex breakdown bubble being pushed outside of the burner cone, it is also seen that the bifurcated jet widens and slows, and both shear layers move outward. The LoLa has little effect on the velocity profile, and the vortex generators cause the shear layers to move slightly inward.

A comparison of the tangential velocity profiles is shown in figure 51. The elliptic burner shows the most significant changes compared to the other burners. It shows a nearly linear increase in velocity moving out from the centre of the flow, and the location of maximum velocity is further away from the centre of the flow. The LoLa burner shows little difference from the standard burner and the burner with vortex generators shows that the point of maximum velocity is slightly closer to the centre of the burner.

Axial RMS velocity profiles are compared for the various burners in figure 52. Again, the elliptic burner shows the greatest changes, with turbulence intensity values that are approximately double those of the standard burner at all locations across the flow. The LoLa burner showed little difference compared to the standard burner, and the burner with vortex generators showed slightly reduced turbulence away from the centre of the flow.

Figure 53 shows that similar trends appear further downstream in the axial velocity profiles for all three modifications. The tangential velocity profiles are shown in figure 54. The location of maximum velocity for the elliptic swirler again occurs further away from the centre of the flow. The tangential velocity of the LoLa burner increases compared to the standard burner moving downstream, and the tangential velocity of the burner with vortex generators decreases to the point that it is little different from the standard burner at a distance of $y = 0.5D_{sw}$ downstream of the swirler outlet. At $y = 0.5D_{sw}$, all burners show a nearly linear increase in velocity from the axis of the burner to the point of maximum velocity. Profiles of axial RMS velocity for the various burners are shown in figure 55. Here it is seen that the turbulence of the elliptic burner has dissipated further downstream. The LoLa burner shows little difference compared to the standard burner and the burner with vortex generators shows slightly reduced axial turbulence across the entire width of the flow.

Figure 56 shows the velocity profiles for the same burners and locations as figure 50 with the forcing mechanism activated. Again it is seen that the LoLa has little effect on the velocity profile, and that the vortex generators cause the shear layers to move inwards. With the forcing mechanism activated, the vortex breakdown bubble for the elliptic burner

has an average position that is further upstream compared to the case without forcing. It is also seen that with the forcing mechanism activated, the bifurcated jet burner moves inward and slows.

Tangential velocity profiles for the different burners with forcing are shown in figure 57. Both the elliptic burner and the burner with vortex generators showed a small increase in the tangential velocity. Figure 58 shows the axial RMS velocity profiles for the different burners. Little difference is seen between the standard burner and the burner with the vortex generators, however the elliptic burner shows a much higher turbulence intensity near the centre of the flow. Comparing this to the case where the forcing mechanism is deactivated (fig. 52) it is seen that the turbulence intensity in the centre of the flow is approximately twice as strong for the standard burner and the burner with vortex generators, but only slightly increased for the elliptic burner.

Figure 59 shows axial velocity profiles for the burner configurations further downstream with forcing. The vortex generators cause a slight increase in the maximum axial velocity, and at $y = 0.29D_{sw}$ they cause the jet to move in toward the centre of the burner. The elliptic burner also increases the maximum velocity but causes the outer shear layer to move outward. Tangential velocity profiles are shown in figure 60. At $y = 0.29D_{sw}$, both the elliptic burner and the burner with the vortex generators cause a slight increase in the tangential velocity, but at $y = 0.5D_{sw}$, the velocity profile for the burner with vortex generators is little different from that of the standard burner. Axial RMS velocity profiles are shown in figure 61. Similar trends are seen between the profiles for the different burners as are

seen in figure 58. Comparing the turbulence intensity to the unforced case (fig. 55), it is seen that at $y = 0.29D_{sw}$ the turbulence intensity is approximately doubled, but further downstream there is little difference in its value between the forced and unforced cases. The elliptic burner shows some damping of the turbulence further downstream, however not to the extent that was seen for the unforced case.

Figure 30: Velocity spectrum of standard burner, forcing mechanism deactivated, $Q = 15$ L/s, $y = 0.17D_{sw}$

Figure 31: Velocity spectrum of standard burner, 10% forcing, $Q = 15$ L/s, $y = 0.17D_{sw}$

Figure 32: Phase-locked LIF images of the unforced flow, standard burner, perpendicular to slots, $St=1.33$, $Re=55,500$

Figure 33: Phase-locked LIF images of the unforced flow, standard burner, plane parallel to burner outlet, $\sim 0.55D_{sw}$ downstream, $St=1.33$, $Re=55,500$

Figure 34: Phase-locked LIF images of the flow with forcing, standard burner, flow field within the burner cone and downstream of the dump plane, $St=0.58$, $Re=55,500$

Figure 35: Phase-locked LIF images of the flow with forcing, standard burner, plane parallel to burner outlet, $\sim 0.55D_{sw}$ downstream, $St=0.58$, $Re=55,500$

Figure 36: Phase-locked LIF images of the unforced flow, elliptic burner, perpendicular to slots, $St=1.27$, $Re=65,200$

Figure 37: Phase-locked LIF images of the flow with forcing, elliptic burner, flow field downstream of the burner cone, $St=0.58$, $Re=65,200$

Figure 38: Phase-locked LIF images of the flow with forcing, elliptic burner, flow field within the burner cone, $St=0.58$, $Re=65,200$

Figure 39: Phase-locked LIF images of the unforced flow, burner with LoLa, flow field within the burner cone and downstream of the dump plane, $St=1.33$, $Re=55,500$

Figure 40: Phase-locked LIF images of the flow with forcing, burner with LoLa, flow field within the burner cone and downstream of the dump plane, $St=0.58$, $Re=55,500$

Figure 41: Averaged axial velocity profiles with forcing mechanism deactivated, standard burner, $Q = 15$ L/s, $Re=83,200$

Figure 42: Averaged tangential velocity profiles with forcing mechanism deactivated, standard burner, $Q = 15 \text{ L/s}$, $Re=83,200$

Figure 43: Axial RMS velocity profiles with forcing mechanism deactivated, standard burner, $Q = 15 \text{ L/s}$, $Re=83,200$

Figure 44: Averaged axial velocity profiles with 10% forcing, standard burner, $Q = 15$ L/s, $Re=83,200$

Figure 45: Averaged tangential velocity profiles with 10% forcing, standard burner, $Q = 15$ L/s, $Re=83,200$

Figure 46: Axial RMS velocity profiles with 10% forcing, standard burner, $Q = 15$ L/s, $Re=83,200$

Figure 47: Averaged axial velocity profiles with forcing mechanism deactivated, elliptic burner, $Q = 15$ L/s, $Re=97,800$

Figure 48: Averaged tangential velocity profiles with forcing mechanism deactivated, elliptic burner, $Q = 15 \text{ L/s}$, $Re=97,800$

Figure 49: Axial RMS velocity profiles with forcing mechanism deactivated, elliptic burner, $Q = 15 \text{ L/s}$, $Re=97,800$

Figure 50: Averaged axial velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.17D_{sw}$, parallel to slots

Figure 51: Averaged tangential velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.17D_{sw}$, parallel to slots

Figure 52: Axial RMS velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15$ L/s, $y = 0.17D_{sw}$, parallel to slots

Figure 53: Averaged axial velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15$ L/s, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

Figure 54: Averaged tangential velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

Figure 55: Axial RMS velocity profiles with forcing mechanism deactivated, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

Figure 56: Averaged axial velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.17D_{sw}$

Figure 57: Averaged tangential velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.17D_{sw}$

Figure 58: Axial RMS velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.17D_{sw}$

Figure 59: Averaged axial velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

Figure 60: Averaged tangential velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

Figure 61: Axial RMS velocity profiles with 10% forcing, various burner modifications, $Q = 15 \text{ L/s}$, $y = 0.29D_{sw}$, $0.50D_{sw}$, parallel to slots

6 Results and discussion of cold flow tests

The XEVa was designed as the baseline burner and was first tested with the transition piece absent, the burner outlet flush with the sudden expansion (i.e. zero mixing tube length), and no extended lance. This configuration is shown in figure 62, and was considered the baseline condition. Stereo PIV measurements were made on the flow field in streamwise planes passing through the axis of the combustion chamber.

The circular XEV burners have outlets similar to that shown in figure 63. Measurements were first made in a plane parallel with the burner slots, labeled as 0° in figure 63. These measurements were repeated for each of the circular burners in planes with azimuthal angles of 10° , 20° , 30° , 40° and 50° in order to determine whether the flow was axisymmetric. Measurements were further made in the plane with an angle of 180° to verify that the flow was symmetric in a single plane.

It was expected that the flow field for the elliptic swirler would be very asymmetric, so the flow field was measured for the baseline condition at angles of 0° , 30° , 60° , 90° , 120° , 150° and 180° , as shown in figure 64. Note that the direction of swirl of the elliptic burner is opposite that of the four circular burners. This was the result of a design oversight and served no specific purpose.

After the flow field of the XEVa had been explored in the baseline condition, the XEVc, XEVd and XEVb were tested to determine the effect of altering the cone angle and slot width in various combinations while leaving the outlet area the same. All four of the circular burners were then tested with the long lance (LoLa) length varied from zero to the length of

the swirler cone in four equal increments. The final test performed on the circular swirlers was to introduce a cylindrical mixing section between each swirler's outlet and the sudden expansion. The mixing tube was varied up to a length of 2.0" in 0.5" increments, and its length was measured from the downstream tip of the transition piece to the sudden expansion.

After testing the circular swirlers, the elliptic XEVe-6 was tested in the baseline condition and with similar LoLa and mixing tube lengths.

As with the experimental burner model tested at ALSTOM Power Ltd, the flow rate of the XEV swirlers was characterized by the Reynolds number based on the diameter of the swirler outlet without the transition piece. As before, the Reynolds number is defined as:

$$Re = \frac{uD_{sw}}{\nu} \quad (66)$$

In order to match flow conditions from the tests at ALSTOM Power Ltd, a Reynolds number of 100,000 was selected.

6.1 Results from the baseline burner

The XEVa was first tested in the baseline condition with a Reynolds number of 100,000. At these conditions, the XEVa caused a 6.4% drop in static pressure, corresponding to a discharge coefficient of $C_D = 0.35$. The swirl number was estimated for this swirler to be $S_N \simeq 0.64$. Figure 65 shows a typical particle image acquired for the XEVa. Good seeding was attained over the entire field of view, although there is a small region immediately downstream of the burner outlet where seeding was sporadic. Due to the extremely turbulent

Figure 62: XEVA mounted in the baseline condition.

flow in this region, certain captures showed little seeding in this area, though most gave a satisfactory particle distribution. A narrow region of high turbulence was observed in the centre of the flow. This turbulent core extended far downstream and exhibited slight radial oscillation from one particle image to the next. Figure 65 is typical of the particle images acquired for most swirler configurations.

Figure 66 shows a three dimensional velocity vector field for the XEVA. This image is the average of 100 single captures acquired by the PIV system. The laser sheet is in the same plane as the page, propagating from left to right as shown by the green arrow. The flow direction is towards the bottom of the page as indicated by the blue arrow, and the location of the swirler outlet is indicated by the white rectangle at the top of the image. The vectors are coloured according to vorticity about the axis normal to the plane of the laser sheet.

Figure 63: Measuring planes on the XEV swirlers.

Vorticity about this axis is defined as:

$$\Omega_z = \frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \quad (67)$$

Positive vorticity represents counter-clockwise rotation and negative vorticity represents clockwise rotation. Four regions of strong vorticity are identified in counter-rotating pairs in this image.

Figure 66 shows that the flow from the baseline burner enters the combustion chamber as a bifurcated jet. The jet recirculates at the sudden expansion in two counter-rotating vortices on the outside of the flow. The swirling flow undergoes vortex breakdown and recirculates inside the bifurcated jet in a pair of elongated vortices that converge near their upstream ends, at approximately $y = 0.7D_{sw}$ downstream of the swirler outlet. The point

Figure 64: Measuring planes on the XEVe-6 swirler.

at which the elongated vortices converge is a stagnation point where flow upstream of this point propagates upstream towards the swirler and flow downstream of this point continues downstream towards the combustion chamber outlet. Since the elongated vortices remain very close to the bifurcated jet instead of moving closer to the burner axis, there is high shear in this area which results in very good fuel-air mixing. Close examination of the velocity vectors near the swirler outlet show that the backflow velocity is very low in this region, and that the upstream tip of the vortex breakdown bubble is positioned at the exit of the swirler cone of the XEVa.

Figure 67 shows three samples of single captures of three dimensional velocity vector fields for the XEVa. These plots show a picture of the velocity vector field at an instant in time. Near the outlet of the swirler, the bifurcated jet can be seen in each of the individual images

as well as recirculation in the centre of the flow. The unaveraged images, however, show very turbulent flow everywhere in the field of view, especially in the region immediately downstream of the swirler outlet. Averaging a series of 100 of these individual captures eliminates the small turbulent fluctuations and allows the average structure of the flow to be seen more clearly.

Figure 68 shows the three dimensional velocity vector field as viewed from the bottom of the combustion chamber, looking into the swirler cone. This is a different view of figure 66 with the vectors coloured according to the tangential velocity component. This figure shows the strong swirl induced by the swirler. No counter-swirl is observed in this figure, except for a few spurious vectors which are not physically possible. The highest tangential velocity is observed near the axis of the burner and an approximately linear decrease is seen moving radially outwards.

Contours of axial velocity are shown in figure 69. This is the same view as shown in figure 66. The bifurcated jet is seen clearly in this figure as the dark blue v-shaped region, and locations of zero axial velocity are identified by the thin black contour. The flow seen in this image is not perfectly symmetric as a result of the setup of the PIV system; unavoidable laser reflections and poor contrast on the right hand side of the image resulted in poorer data quality on this side of the image. This was true for all PIV measurements made in this project, and data on the left side of the image is generally regarded as more reliable. The small recirculation zone at the sudden expansion is seen as a pair of triangular red regions immediately downstream of the burner outlet. The vortex breakdown bubble is seen

as the red v-shaped region in the centre of the flow. It appears from this image that the upstream stagnation point of the vortex breakdown bubble is positioned near the swirler exit. A secondary downstream propagating flow is observed emanating from the centre of the vortex breakdown bubble, which gives it its unusual hollow-cone shape. This is an unexpected flow feature since at high Reynolds numbers, most swirling flows break down into an axisymmetric egg-shaped bubble.[11, 12] The furthest downstream point of this hollow-cone vortex breakdown bubble is seen to extend approximately $y = 2.5D_{sw}$ downstream from the swirler outlet.

Single captures of the axial velocity contours are shown in figure 70. The bifurcated jet and hollow-cone structure of the vortex breakdown bubble are clearly seen in each of these images. Averaging many of these single captures smooths the profiles and gives a more clear picture of what is actually happening in the flow.

Figure 71 shows the evolution of the axial velocity profiles moving downstream. Immediately at the burner outlet the bifurcated jet has its highest velocity and the central backflow has a low negative velocity. Moving downstream the jet spreads, widens and slows, and the vortex breakdown bubble splits into a cone shape. The stagnation point in the centre of the cone is located approximately $y = 0.64D_{sw}$ downstream of the swirler outlet, and the outer recirculation zone disappears about $0.90D_{sw}$ from the outlet. The inner recirculation disappears at $2.18D_{sw}$ downstream, and beyond this point the velocity profiles become progressively flatter.

Figure 100 shows the axial velocity at the centreline of the flow moving in the downstream

direction. For the XEVa, the axial velocity is negative in the region immediately downstream of the swirler outlet. The upstream tip of the breakdown bubble occurs at approximately $y = 0.1D_{sw}$ downstream of the swirler outlet, and the downstream stagnation point in the centre of the hollow-cone vortex breakdown occurs at $y = 0.6D_{dw}$. Downstream of this location there is a low positive velocity of the flow propagating towards the combustion chamber outlet.

Contours of radial velocity are shown in figure 72. Blue regions indicate flow toward the left side of the image and red regions indicate flow toward the right. It is seen that the region of flow corresponding to the bifurcated jet diverges strongly, while flow in the outer recirculation zone and inside of the jet converges more weakly. Downstream of the vortex breakdown bubble the radial velocity is nearly zero across the entire width of the flow. Figure 73 shows contours of radial velocity for single image captures. The diverging of the bifurcated jet and the converging of the flow in the recirculation zones can clearly be seen in each of these averaged contour plots.

Contours of tangential velocity are shown in figure 74. There is a region of high tangential velocity immediately downstream of the burner outlet corresponding to the base of the bifurcated jet. Tangential velocity further downstream is strongest near the burner axis and decays moving outwards. Figure 75 shows unaveraged contours of tangential velocity for the XEVa. The strong, coherent swirl for this burner is seen in these plots. In the region immediately downstream of the swirler outlet, small regions of counter-rotating flow are seen which indicate that the flow is very turbulent in the tangential direction in this region of the

flow.

Figure 76 shows the evolution of the tangential velocity component in the downstream direction. Nearest to the burner outlet, a peak in the velocity profile is seen along the edge of the burner outlet. Further downstream, the flow stabilizes into a profile that shows little change in the downstream direction. The swirl is seen to remain very strong moving downstream, with no slowing of the tangential velocity upstream of $y = 2.5D_{sw}$.

Contours of total turbulence are shown in figure 77. It is seen that the turbulence is strongest in the region of the flow corresponding to the bifurcated jet and inner shear layer. A slightly weaker region of turbulence is seen along the axis of the swirler. The region of high turbulence along the far right side of the flow corresponds to a region where strong laser reflections existed. Data here is considered unreliable.

Profiles of total turbulence for this XEVa are shown in figure 78. It is seen that in the region of the bifurcated jet and the vortex breakdown bubble that turbulence is lower in the centre of the flow and is highest in the region of the jet. Further downstream, the turbulence level decreases and beyond the vortex breakdown bubble, the turbulence profile is flat with only a small peak in the centre. Figure 109 shows profiles of total turbulence along the centreline of the burner. This figure shows that the turbulence level is slightly increased at the outlet of the swirler but decays steadily moving downstream.

It is interesting with this flow to investigate the turbulence in its three components. The axial, radial and tangential components are shown in figures 79–81 respectively and show that the turbulence from this burner is very anisotropic. The axial component is weakest along

the axis of the swirler. Figure 71 shows that this is because there is no shear in this region of the flow at all downstream locations. Radial turbulence is highest in the region of the jet where high spreading is observed and also along the axis of the burner where lateral flapping of the core in the centre of the flow was observed. The tangential turbulence component was clearly the highest of the three. This was a result of the strong shear generated by the swirling jet entering the combustion chamber near the swirler outlet. Further downstream, the high shear observed in the tangential velocity profiles caused a region of high turbulence along the axis of the burner.

Figure 82 is a plot of the three turbulence components at a distance of $y = 0.13D_{sw}$ downstream of the swirler outlet. The dashed lines in this plot show the anisotropy of the radial and tangential anisotropy of the turbulence, relative to the axial turbulence. These value are calculated as:

$$\begin{aligned} R_{ani} &= \frac{v'}{u'} \\ T_{ani} &= \frac{w'}{u'} \end{aligned} \tag{68}$$

Where R_{ani} is a measure of the anisotropy of the radial turbulence relative to the axial turbulence, T_{ani} is a measure of the anisotropy of the tangential turbulence relative to the axial turbulence, and u' , v' and w' are the RMS velocity components in the axial, radial and tangential directions.

This figure shows that close to the swirler outlet, the axial and radial velocity components are of similar magnitude, and that the radial anisotropy has a value close to one. Tangential turbulence is much higher, having an anisotropy value ranging between 1.5 along the centre

of the flow to 2.0 further out from the centre.

Figures 83 and 84 show a similar trend slightly further downstream. The axial and radial components are of similar magnitude, and the radial anisotropy has a value of approximately one. The tangential turbulence is clearly the strongest component, and the tangential anisotropy is in the range of 2.0.

Downstream of the breakdown bubble at $y = 1.15D_{sw}$ (fig. 85), the turbulence profiles are flatter with a small peak along the axis of the swirler. In this region, the radial anisotropy has a value of approximately 1.5, as a result of the lateral oscillation of the turbulent core. Tangential anisotropy is in the range of 2.5 to 3.5 since the axial turbulence is damped downstream of the jet, but the tangential turbulence is still large due to the high shear in the centre of the flow.

Figure 86 compares the three dimensional velocity vector fields for the XEVa at different azimuthal angles. The same basic flow structure is seen in each figure, indicating that for the most part, the flow is axisymmetric. The vectors are coloured by vorticity, and show similar levels at all azimuthal angles. A comparison of the axial velocity contours is shown in figure 87, where again, it appears that the flow is axisymmetric. Figures 88 and 89 compare the axial velocity profiles at different azimuthal angles at a distances of $y = 0.38D_{sw}$ and $y = 1.92D_{sw}$ downstream of the outlet. These plots show that there are only minor variations in the axial velocity profiles from one azimuthal location to the next.

Radial velocity contours (fig. 90) and tangential velocity contours (fig. 91) also show little variation with azimuthal angle. This trend is further confirmed by the azimuthal velocity

profiles (fig. 92).

Based on the plots seen in figures 86 through 92, it is seen that there is very little difference in the flow structure with azimuthal angle. The remaining circular swirlers were tested over the same azimuthal angles, and it was discovered that their flow fields were similarly axisymmetric. As a result, the remainder of the tests on the circular swirlers were conducted with the laser sheet oriented parallel with the burner slots.

6.2 Changes in cone angle and blade spacing

6.2.1 Effect of changing the blade spacing

After testing the XEVa swirler, the XEVc swirler was tested in the baseline condition. The XEVc had the same outlet area and cone angle as the XEVa, but its slot area was increased by a factor of 2.25. It was expected that the increased slot area would decrease the velocity of the flow entering the swirler and thereby reduce the swirl. It was anticipated that this would reduce the strength of the vortex breakdown relative to the XEVa.

The XEVc was tested at the same azimuthal angles as the XEVa and it was determined that its flow was essentially axisymmetric. A pressure drop of 2.2% was measured across the XEVc, corresponding to a discharge coefficient of $C_D = 0.61$. The swirl number was estimated for this swirler to be $S_N \simeq 0.23$.

Figure 93 shows a comparison of the velocity vector fields coloured by vorticity for all four circular burners and the elliptic burner in the baseline condition. The vector field for the XEVc is seen in the lower left corner of this image. Here it is seen that the flow exits

the swirler across its entire width as a single slow moving jet. While the vector plot for the XEVa shows contours of strong vorticity in regions corresponding to the recirculation zones, this is not seen for the XEVc. The vectors show weak recirculation on either side of the swirler outlet, but the swirling flow does not undergo vortex breakdown and recirculate in its centre. The outer recirculation zone ends at approximately $1.5D_{sw}$ downstream of the outlet, and the flow continues downstream from this point towards the combustor exit.

Figure 118 shows samples of single instantaneous velocity vector fields for the XEVc and figure 119 shows the average of 100 of these single images. These plots show that the main velocity component of the jet exiting the swirler is in the downstream direction, but that there are violent fluctuations in the radial velocity component. These plots also show that there is a tendency of the flow to rotate about an axis normal to the laser sheet in the centre of the field of view. This indicates that although a backflow region does not exist, there is a tendency of the flow to begin the vortex breakdown process.

Figure 94 shows a comparison of the vector fields of the different swirlers viewed from the bottom of the combustion chamber. This burner shows a clear rotation of the flow with no counter-rotation, however the tangential velocity is significantly reduced compared to the XEVa.

Contours of axial velocity are shown in figure 95. The outer recirculation zone occurring at the sudden expansion appears as a pair of rectangular zones extending $1.25D_{sw}$ downstream of the swirler outlet. This figure clearly shows the absence of a recirculation zone in the centre of the flow. Figure 120 shows instantaneous contours of axial velocity for the XEVc

and figure 121 shows the average of 100 single captures. The single jet exiting the swirler outlet can be clearly identified in each of these images, as well as the recirculation zone at the sudden expansion. Small regions of backflow can be seen in the centre of the flow indicating that there is a tendency of the flow to undergo vortex breakdown, although recirculation in this region is not stable.

A comparison of the axial velocity profiles is shown in figure 96. It is seen from this figure that the magnitude of the maximum velocity is similar between the XEVa and XEVc, but the axial flow of the XEVc exists as a single jet that does not recirculate in its centre. The outer recirculation zone for the XEVc is the widest of the four swirlers and its velocity magnitude is similar to those of the other swirlers. Moving further downstream (figs. 97–99), it is seen that the outer recirculation zone disappears around $y = 1.28D_{sw}$, and the velocity profiles quickly begin to flatten. Figure 100 compares the axial velocity values along the centreline of the flow for the different burners. The velocity at the exit of the swirler has a low positive value at the swirler outlet which increases moving downstream. Beyond the outer recirculation zone, the velocity on the centreline drops off. Negative velocities are not seen at any location along the swirler axis.

Radial velocity contours (fig. 101) show that the jet spreads weakly as it leaves the swirler and converges further downstream. Instantaneous contours of radial velocity (fig. 122) show that the flow exhibits a violent lateral flapping motion as it exits the swirler. The time averaged flow structure (fig. 123) cannot be discerned from the individual images.

Tangential velocity contours (fig. 102) show that the swirl is strongest for this swirler

immediately downstream of the swirler outlet. The swirl remains strong as the flow propagates downstream, but downstream of $D_{sw} = 1.4$ the tangential velocity drops off drastically, especially along the swirler axis. Profiles of tangential velocity near the swirler outlet are shown in figure 103. As the flow leaves this swirler, its tangential velocity is slightly greater than that of the XEVa, and its point of maximum velocity is at a similar radial location in the flow. Moving downstream, the magnitude of the tangential velocity quickly drops off, and beyond $y = 1.28D_{sw}$ the flow has very weak swirl (figs. 104–106). Single captures of tangential velocity contours are shown in figure 124 and the average of 100 single captures is shown in figure 125. This figure shows a coherent tangential velocity distribution at the outlet of the swirler, followed by reduced tangential velocity further downstream. This is the same trend observed in the time-averaged flow.

Contours of total turbulence are shown in figure 107. Again, bad reflections caused an area on the right hand side of the image to register inaccurately high turbulence. This figure shows that the highest turbulence from this burner occurs in a wide region extending approximately one swirler diameter downstream of the swirler outlet. Turbulence for this swirler is much higher than that for the XEVa. This is due to the fact that the XEVc does not have a coherent recirculating flow structure, but rather exists as a region of high turbulence. Profiles of total turbulence for the different swirlers (fig. 108) show that the turbulence for the XEVc is approximately twice that of the other swirlers in the centre of the flow, and decreases moving radially outwards. Profiles of total turbulence along the centreline of the swirler (fig. 109) show very high turbulence in the region immediately

downstream of the swirler outlet. Moving downstream the turbulence level decreases and becomes very low as the flow propagates toward the combustion chamber outlet.

Contours of axial turbulence for the XEVc (fig. 110) show that the region of high turbulence immediately downstream of the swirler outlet extends further downstream for the XEVc than for the XEVa, although its maximum value is similar. Profiles of axial turbulence are shown in figure 111. It is seen that axial turbulence is highest in the centre of the flow, and its magnitude is approximately twice that of the other swirlers.

Figure 112 shows contours of radial turbulence. The XEVc shows an approximately spherical region of high radial turbulence in the centre of the flow. Figure 113 shows that the level of radial turbulence is nearly twice as high as for the other swirlers. The fact that the radial turbulence is very high is an indication that the flow of this swirler has a tendency to undergo vortex breakdown. The anisotropy of the radial turbulence relative to the axial turbulence is shown in figure 114. This figure shows that the radial turbulence is most anisotropic in the centre of the flow, but the radial anisotropy is approximately one outside of the jet.

Tangential turbulence (fig. 115) is also very high in the region immediately downstream of the swirler outlet. Profiles of tangential velocity showed high shear in this region of the flow that tapered off moving downstream. Profiles of tangential turbulence (fig. 116) also showed that this turbulence component had a maximum value that was twice that for the other swirlers. The tangential turbulence was very anisotropic (fig. 117), and showed velocity fluctuation levels 2–2.5 times greater than those of the axial component.

It has been shown that widening the slots of the swirler while leaving other geometric parameters unchanged caused the tangential velocity to decay very quickly moving downstream. This occurred to such a large degree that the swirling flow was unable to undergo vortex breakdown and single highly turbulent jet was observed instead of a central recirculation zone. As a result, this swirler would perform very poorly in combustion tests since it would be unable to stabilize a flame in the centre of the flow. It is possible that the recirculation caused by the sudden expansion would be able to adequately anchor the flame under certain operating conditions, but this would be less stable and defeat the purpose of using a swirler. It is expected that a less severe widening of the slots would cause the swirling flow to undergo a weaker vortex breakdown than was observed for the XEVa, and narrowing the slots would cause a stronger vortex breakdown.

6.2.2 Effect of changing the cone angle

The next swirler to be tested was the XEVd, which had the same outlet and slot area as the XEVa but a cone angle that was widened by a factor of 1.64. It was expected that widening the cone would force the vortex breakdown bubble downstream as a result of the reduced volume inside of the cone, and that the transition to a more axial type of flow would increase the swirl and cause a stronger vortex breakdown.

The XEVd was tested at the same azimuthal angles as the XEVa and it was determined that its flow was basically axisymmetric. A pressure drop of 9.0% was measured across the XEVd, corresponding to a discharge coefficient of $C_D = 0.29$. The swirl number was

estimated for this swirler to be $S_N \simeq 1.17$. A typical particle image for the XEVd is shown in figure 126. This image is similar to those observed for the other swirler configurations, except that a core with no seeding particles exists along the axis of the combustion chamber. Further investigation showed that this core extended all the way downstream to the combustion chamber outlet, and appeared to be entraining air into the vortex breakdown from outside the combustion chamber. While measurements conducted in the centre of the core yielded unreliable data, measurements along its edge verified that it was a region of strong backflow.

The velocity vector field for this swirler is shown in figure 93 as the image in the top row, middle column. This figure shows that the flow exits the swirler as a bifurcated jet. As with the XEVa, the jet recirculates in a pair of vortices at the sudden expansion and in a second set of elongated vortices on the inside of the flow. These vortices form along the bifurcated jet and converge near their upstream ends, at approximately $y = 0.55D_{sw}$ downstream of the burner outlet. The long vectors seen in the centre of this figure were calculated in the region of the central core, and are considered to be unreliable due to their discontinuity with surrounding data. Because this core extended all the way to the combustion chamber outlet, no stagnation point was observed in the centre of the flow. Examination of the velocity vectors at the outlet of the swirler show that the vortex breakdown bubble ends slightly inside the swirler cone.

Figure 94 shows the velocity vectors viewed from the bottom of the combustion chamber. The increased tangential velocity relative to the other swirlers can be seen. The unreliable velocity vectors calculated in the swirling core are also clearly visible in this figure. A few

counter-rotating vectors are seen in this image near the walls of the combustion chamber. Because of the strong tangential velocity of the flow exiting the swirler, these vectors are deemed inaccurate.

Figure 95 shows that the axial velocity field of the XEVd shows some of the same basic flow features of the XEVa. The bifurcated jet is slightly narrower for this swirler, but the outer recirculation zone is approximately the same size. The main difference is that a recirculating swirling core has formed in the centre of the flow and is joined to the hollow-cone vortex breakdown in its centre. The width of the annular section of the hollow cone breakdown is slightly thicker, but its overall size is similar to that of the XEVa. Axial velocity profiles at $y = 0.38D_{sw}$ downstream of the burner outlet are shown in figure 96. It is seen that the velocity of the bifurcated jet is reduced for this swirler, and the velocity of the backflow is slightly higher, indicating that the breakdown bubble is slightly upstream compared to the XEVa. At $y = 0.77D_{sw}$ (fig. 97), the same trend appears, and it can also be seen that recirculating core has begun to form. Beyond $y = 1.28D_{sw}$ (figs. 98 and 99), the axial velocity profile is very similar to that of the XEVa, except for the high backflow velocity in the centre of the combustion chamber caused by the recirculating core. Figure 100 shows that the upstream tip of the vortex breakdown bubble for the XEVd is located very near the swirler outlet. Moving downstream, the magnitude of the backflow velocity increases in the centre of the vortex breakdown bubble. The magnitude of the backflow decreases in the recirculating core, but maintains a strong recirculation moving downstream. No stagnation point forms in the centre of the hollow-cone.

Radial velocity contours (fig. 101) show that the flow behaves in a manner similar to that of the XEVa; the flow diverges along the bifurcated jet, and converges inside the jet. Further downstream, the radial velocity decreases as the flow propagates towards the exit of the combustion chamber.

Contours of tangential velocity are shown in figure 102. A high tangential component is seen in region of flow corresponding to the bifurcated jet. Further downstream the swirl is strongest immediately adjacent to the central core. A few regions of counter-rotating flow are observed in this plot, but these are considered questionable due to the strong clockwise rotation throughout the rest of the flow. Tangential velocity profiles near the swirler exit (figs. 103 and 104) show that the XEVd has a tangential profile similar to that of the XEVa. Downstream of $y = 1.28D_{sw}$ (figs. 105 and 106), it is seen that the tangential velocity of the XEVd increases and remains higher than that of the XEVa.

Contours of total turbulence are shown in figure 107. Laser reflections caused the system to calculate a small region of high turbulence on the right hand side, which is considered unreliable. Similar to the XEVa, turbulence is highest in the region corresponding to the bifurcated jet and is lower further downstream. Profiles of total turbulence (fig. 108) show that the turbulence is slightly increased for the XEVd along the entire width of the combustion chamber. Profiles of turbulence (fig. 109) along the centreline of the swirler show relatively constant turbulence along the centreline of the swirler. This level is increased relative to all other swirlers except the XEVc as a result of the high turbulence generated by the recirculating core in the centre of the flow.

Contours of axial turbulence (fig. 110) show very little difference between the XEVd and the XEVa. Profiles of axial turbulence (fig. 111) indicate that the only significant difference between the two is that the XEVd exhibits higher axial turbulence along its centreline as a result of the recirculating core.

Contours of radial turbulence are very similar to those for the XEVa. Figures 113 and 114 show that the radial turbulence of the XEVd is slightly reduced compared to the XEVa, and that its radial turbulence level is very similar to its axial turbulence level.

Figure 115 shows that the tangential turbulence of the XEVd is greater than that of the XEVa in the region immediately downstream of the swirler outlet. Profiles of tangential turbulence (fig. 116) show that the tangential turbulence is increased across the entire flow compared to the XEVa. Figure 117 shows that the tangential turbulence component is approximately 2.5 times greater than the axial component for this flow.

It was seen that increasing the swirler's cone angle increased the tangential velocity of the flow. This, in turn, caused an increase in the strength of the vortex breakdown, which caused the thickness of the annular region of the hollow cone breakdown to slightly increase and the recirculating core to form downstream of the breakdown bubble. The velocity vector plot and axial velocity contours also indicated that the vortex breakdown bubble had moved upstream. It is likely that this swirler would perform poorly in combustion tests. While the higher swirl generates a strong vortex breakdown, the strong recirculating core in the centre of the flow would tend to continually draw combustion products from far downstream back into the combustion zone. Additionally, the 9.0% pressure drop across the burner is

unacceptably high and would result in large losses and reduced efficiency.

6.2.3 Effect of changing the blade spacing and cone angle

The final circular swirler to be tested was the XEVb. It had the same cone angle as the XEVd and the same slot area as the XEVc. Compared to the XEVa, its cone angle was 1.64 times wider, and its slot area was 2.25 times greater. It was expected that the greater slot area would weaken the vortex breakdown and that the widened cone would strengthen it. It was difficult to estimate whether the overall effect would be to weaken or strengthen the breakdown, but it was expected that the overall strength of the breakdown would be similar to that of the XEVa.

The XEVb was tested at the same azimuthal angles as the rest of the circular swirlers and its flow field was seen to be essentially axisymmetric. A pressure drop of 3.3% was measured across the XEVb, corresponding to a discharge coefficient of $C_D = 0.50$. The swirl number for this swirler was estimated to be $S_N \simeq 0.55$.

The velocity vector field for the XEVb is shown in figure 93 as the middle image on the bottom row. The same basic flow features that were observed for the XEVa are seen in this vector field, although there are a few differences. First, the bifurcated jet exits the swirler at less of an angle than for the XEVa and XEVd. The elongated vortices formed on the inside of the jet are shorter for this swirler and do not extend downstream of the end of the jet. The recirculation zone created at the sudden expansion is slightly larger than that observed for the XEVa. The stagnation point in the centre of the vortex breakdown bubble is located

further downstream at about $y = 1.4D_{sw}$ from the outlet.

Looking at the velocity vector fields from the bottom of the combustion chamber (fig. 94), it is seen that this swirler has a low tangential velocity except for a couple of isolated regions where the velocity is higher. As with the other swirlers, the XEVb displays a strong clockwise swirl, with only a few spurious counter-rotating vectors.

Contour plots of axial velocity (fig. 95) show that the flow field for this swirler is different from those of the XEVa and XEVd. The width of the bifurcated jet is about the same as that of the XEVa, but the outer recirculation zone is slightly longer as a result of the jet exiting the swirler at a less of an angle. The vortex breakdown bubble has the basic hollow-cone structure, although the stagnation point is further downstream and the hollow cone is narrower and more closed. The solid region of this breakdown is larger compared to the XEVa and XEVd, and its annular region is shorter and smaller in diameter. Axial velocity profiles (fig. 96) show that velocity of the bifurcated jet is considerably higher for this swirler, and the vortex breakdown bubble is narrower. Moving downstream, the jet's axial velocity decreases rapidly and the vortex breakdown bubble eventually splits into the hollow-cone structure. The furthest downstream tip of the vortex breakdown bubble is near $y = 1.92D_{sw}$ downstream of the outlet, and at this location it can be seen that the flow in the centre of the combustion chamber has increased in velocity. Figure 100 shows a similar trend for the XEVb compared to the XEVa. The vortex breakdown bubble of the XEVb appears to stabilize slightly further upstream than for the XEVa, and its downstream stagnation point is further downstream because the vortex breakdown bubble splits into its hollow-cone

shape further downstream. The axial velocity shows a steady increase moving downstream from the stagnation point.

Contour plots of radial velocity are shown in figure 101. The basic structure is seen for this swirler as was seen for the XEVa, however the spreading region corresponding to the jet extends slightly further downstream as a result of the jet's reduced angle exiting the swirler.

Contour plots of tangential velocity are shown in figure 102. It is seen that this swirler induces a high tangential velocity in the region corresponding to the bifurcated jet, and that there is very low swirl in the centre of the flow immediately downstream of the swirler. Profiles of tangential velocity near the swirler outlet are shown in figure 103. It is seen that the location of maximum tangential velocity is further away from the axis of the combustion chamber than for the other burners. At $y = 0.77D_{sw}$ downstream (fig. 104), the tangential velocity has slightly decayed, and further downstream (figs. 105 and 106) the location of maximum velocity has moved closer to the axis of the swirler.

Contours of total turbulence are shown in figure 107. As before, the region of highest turbulence corresponds to the region of the bifurcated jet. The magnitude of the turbulence for this swirler is lower than for the XEVa and XEVd, but its region of highest turbulence extends slightly further downstream. Profiles of total turbulence (fig. 108) show that turbulence is lowest for this swirler in the centre of the flow, but is approximately 40% higher in the region of the bifurcated jet. The overall turbulence level is similar to that of the XEVa and XEVd. Profiles of turbulence along the centreline of the swirler (fig. 109) show turbulence levels identical to that of the XEVa.

Contours of axial turbulence (fig. 110) show highest axial turbulence in the region of the jet. Profiles of axial turbulence (fig. 111) show that in this region the XEVb has a higher magnitude than the XEVa and XEVd. This is due to the fact that the region of high turbulence for the XEVb extends further downstream. Contours of radial turbulence (fig. 112) are similar to those for the XEVa, showing highest turbulence in the bifurcated jet and also in the region of the turbulent core along the burner's axis.

Profiles of radial turbulence (fig. 113) show reduced radial turbulence compared to the XEVa in the centre of the flow, but similar levels further away from the centre. Profiles of radial turbulence anisotropy (fig. 114) show that the radial turbulence is considerably lower for this burner relative to the axial turbulence for this burner, resulting in anisotropy values ranging from 0.6–0.9 near the centre of the flow.

Contours of tangential turbulence (fig. 115) show that the turbulence level is reduced compared to the XEVa and XEVd, but the region of highest turbulence extends further downstream. Profiles of tangential turbulence (fig. 116) show a similar turbulence level between the XEVa and XEVb in the centre of the flow, but higher turbulence for the XEVb moving radially outwards. This was because the region of highest turbulence for the XEVb persisted further downstream. As with the other swirlers, the tangential turbulence was very anisotropic relative to the axial velocity. This is shown in figure 117, where it is seen that the anisotropy is slightly reduced for this swirler in the centre of the flow, compared to the other circular swirlers.

It was seen that the opposing effects of increasing both the slot area and the cone angle

caused an overall reduction in swirl and decreased the strength of the vortex breakdown bubble. The weaker vortex breakdown bubble was narrower than that of the XEVa and XEVd and appeared to be making a transition from a solid structure to the hollow-cone structure. It is likely that this swirler would perform well in combustion tests. It generates an adequate vortex breakdown bubble and outer recirculation while causing a pressure loss of approximately 3.3%.

6.3 Effect of long lance position

All four circular swirlers were tested with the long lance varied to a maximum length of $L_{La} = L_{sw}$ in steps of $0.25L_{sw}$. It was expected that the long lance positioned near the upstream end of the vortex breakdown bubble would physically anchor the breakdown bubble and result in stable combustion. Shorter lances were expected to draw the vortex breakdown bubble further inside of the burner cone and longer lances were expected to force the vortex breakdown further downstream.

6.3.1 The XEVa with different lance lengths

The long lance was seen to have a significant effect on the flow field of each swirler, and was also observed to have an effect on the pressure drop across the swirlers. The pressure drop across the XEVa increased from 6.4% at the baseline condition, to a maximum of 8.1% for a lance length of $L_{La} = 0.50L_{sw}$, and 7.3% at $L_{La} = L_{sw}$. The other swirlers also showed a similar trend of increasing pressure drop for intermediate lance lengths followed by

a decreasing pressure drop for longer lances.

Figure 127 shows velocity vector fields for the XEVa with different lance lengths. Shorter lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.50L_{sw}$ are seen have the greatest effect on the flow field. At these positions, it is seen that the lance widens the angle of the bifurcated jet at the swirler's exit and slightly reduces the strength of the vortices. The flow fields for the burners with lance lengths of $L_{La} = 0.75L_{sw}$ and $L_{La} = L_{sw}$ are seen to have the least difference from the baseline case.

Contours of axial velocity are shown in figure 128 for the XEVa with different lance lengths. The most marked changes were seen for $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.50L_{sw}$. The wall of the hollow-cone vortex breakdown bubble became thicker and a strong recirculating core, similar to that observed in the flow of the XEVd, formed. The recirculating core appears to weaken for $L_{La} = 0.50L_{sw}$, and disappears entirely for longer lance lengths, although the vortex breakdown bubble remains large. Velocity profiles for the XEVa at $y = 0.38D_{sw}$ downstream of the swirler outlet are shown in figure 129. At this position, the overall shape of the axial velocity profiles is similar for all cases, however the recirculation inside the jet is reduced, particularly along the centreline of the swirler, and the velocity of the jet is reduced for short lances. A more significant change in the axial velocity profiles is seen at $y = 0.77D_{sw}$. Lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.50L_{sw}$ show the greatest difference compared to the baseline. As the bifurcated jet slows, the inner shear layer moves outwards, and the recirculating core begins to form. Longer lance positions of $L_{La} = 0.75L_{sw}$ and $L_{La} = L_{sw}$ show less differences in the overall flow structure, although

there is a significant increase in the axial velocity in the centre of the flow. Velocity profiles at $y = 1.92D_{sw}$ (fig. 131) show that the flow has the same basic structure in each configuration. This figure also shows that the velocity inside the recirculating core generated by the XEVa with a lance length of $L_{La} = 0.25L_{sw}$ is much lower compared to the velocity inside the recirculating core generated by the XEVd in the baseline condition.

Figure 132 shows profiles of axial velocity with downstream direction. This figure shows that the shortest lance length generates a very high backflow in the centre of the flow that decreases in magnitude moving downstream. For this configuration, no stagnation point is observed in the centre of the hollow-cone breakdown. Increased lance lengths cause the magnitude of the backflow to decrease, and for a lance length of $L_{La} = 0.50L_{sw}$ it is seen that the backflow in the recirculating core begins to break up. Longer lances show a smaller backflow region at the outlet of the swirler and a higher positive velocity in the centre of the cone. This indicates that a very short lance increases the strength of the vortex breakdown bubble, but increases in length cause it to weaken.

Contours of radial velocity for the XEVa show that the angle of the bifurcated jet widens slightly for lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.50L_{sw}$. Except for this, the radial flow structure for all lance configurations is very similar to that for the baseline case.

Contours of tangential velocity for the XEVa are shown in figure 134. These figures indicate that there is very little difference in the level of the tangential velocity distribution, regardless of the lance position. The tangential velocity is highest immediately adjacent to the swirling core, and maintains a strong coherence moving downstream. Figures 135–137

also show that there is little change in the tangential velocity with different lance positions. The only noticeable difference is that long lances cause the point of maximum tangential velocity to move very slightly outwards from the swirler axis.

Contours of total turbulence are shown in figure 138 for the XEVa. It is seen in this figure that all lances cause an increase in the magnitude of the turbulence downstream of the swirler outlet, and that the region of high turbulence extends further downstream for shorter lances. Figure 139 shows profiles of total turbulence for the XEVa with different lance lengths. This figure shows that shorter lances cause an increase in turbulence relative to the baseline. A lance length of $L_{La} = L_{sw}$ showed little different from the baseline case. A lance length of $L_{La} = 0.75L_{sw}$ shows a slight increase in turbulence in the region of the jet but no change in the centre of the flow.

Figure 140 shows profiles of total turbulence along the centreline of the swirler for different lance configurations. This figure shows that the lance with a length of $L_{La} = 0.25L_{sw}$ increases the turbulence level relative to the other swirler configurations as a result of the formation of the recirculating core. Moderate lance lengths show little change relative to the baseline. The configuration with a lance length of $L_{La} = L_{sw}$ shows a significant increase in the turbulence level immediately downstream of the swirler outlet, as the vortex breakdown bubble is forced to a location where it is unstable.

Figure 141 shows contours of axial turbulence for the XEVa with different lance lengths. It is seen from these plots that the long lance has very little effect on the axial turbulence, and this is confirmed by profiles of axial turbulence shown in figure 142.

Contours of radial turbulence (fig. 143) show similar turbulence levels in the region of the bifurcated jet and increased turbulence in the outer recirculation zone. High radial turbulence is seen along the axis of the flow for the baseline condition and for shorter lances as a result of lateral oscillation of the turbulent core. Longer lances stabilized this oscillation, and radial turbulence in the centre of the flow became very low. Figure 144 shows that downstream of the jet, the radial turbulence level is very similar for all configurations, that is, the lance has the greatest effect on the radial turbulence close to the swirler outlet and along the swirler's centreline. Figure 145 shows that the anisotropy of the radial turbulence relative to the axial turbulence is highest in the centre of the flow. Anisotropy of the radial component was greatest in the centre of the flow for the baseline burner, but was little different from the other configurations at other locations. Radial turbulence is stronger than axial turbulence in the centre of the flow for all configurations, but weaker in the region of the jet.

Figure 146 shows contours of tangential turbulence. It is seen that short to moderate lance lengths cause increased tangential turbulence approximately one swirler diameter downstream of the outlet, and that the regions of highest turbulence are in the region of the jet. Tangential turbulence is reduced for a lance length of $L_{La} = L_{sw}$, and has a similar level to that of the baseline swirler. Figure 147 shows profiles of tangential turbulence. This figure shows that the tangential turbulence is slightly increased for the shorter lances. A lance length of $L_{La} = L_{sw}$ shows no difference from the baseline configuration and a lance length of $L_{La} = 0.75L_{sw}$ shows an increase only in the region of the jet. Figure 148 shows that

the tangential turbulence component is the greatest of the three, having a level 1.5–3 times greater than the axial component. Anisotropy of the tangential component is approximately constant across the width of the flow for the two shortest lances and has a value between 2.5 and 3.0. The anisotropy is slightly reduced for a lance length of $L_{La} = 0.75L_{sw}$, but still maintains a nearly constant level across the flow. A lance length of $L_{La} = L_{sw}$ shows a similar trend to the baseline case of highest anisotropy in the centre of the flow and near the wall and lowest anisotropy in the region of the jet.

6.3.2 The XEVc with different lance lengths

The XEVc exhibited the most dramatic change between the baseline configuration and the long lance configurations. Figure 149 shows velocity vector fields for the XEVc swirler with the long lance. The baseline condition shows a non-recirculating flow exiting the swirler as a single slow moving jet. All configurations with the lance, however, clearly show a recirculating flow field similar to that of the XEVa. Configurations with shorter lances show the bifurcated jet leaving the swirler with a moderate spreading angle, while the configuration with a lance length of $L_{La} = L_{sw}$ shows the flow exiting the swirler as a single jet which then splits in two and spreads with a very high angle. Recirculation zones on the either side of the bifurcated jet can be identified as symmetric regions of opposite vorticity for all configurations except the baseline.

Contours of axial velocity for the XEVc (fig. 150) show that the axial velocity field for this swirler is very dependent on the position of the lance. For a lance position of $L_{La} = 0.25L_{sw}$

it is seen that the jet leaving the swirler splits in two, and a hollow-cone vortex breakdown bubble forms between the two jets. The structure of the breakdown is similar to that of the XEVa, but is narrower and has a larger solid region near the outlet of the swirler. The vortex breakdown bubble at $L_{La} = 0.50L_{sw}$ shows slight opening of hollow-cone structure as its annular region increases in size. The same trend is seen for $L_{La} = 0.75L_{sw}$, and for $L_{La} = L_{sw}$ the solid region of the vortex breakdown bubble has essentially disappeared as the breakdown bubble is forced completely outside of the swirler cone. Profiles of axial velocity for the XEVc at $y = 0.38D_{sw}$ are shown in figure 151. This figure clearly shows the difference between the baseline case and the long lance configurations. The three shortest lance configurations are all very similar, but it is seen that the vortex breakdown bubble is forced downstream by the longest lance. At $y = 0.77D_{sw}$ downstream (fig. 152), the difference between the baseline and long lance cases is still clearly seen. The bifurcated jet and vortex breakdown bubble are clearly visible for the configurations with the long lance, and the early transition from a solid to an annular structure of the vortex breakdown bubble is seen with increasing lance length. A similar trend is seen in figure 153 for $y = 1.92D_{sw}$ downstream. The structure of the vortex breakdown at this position is very similar for all lance configurations, and the longest lance has a slightly higher velocity at the centre of the flow.

Figure 154 shows profiles of axial velocity with downstream direction. While the baseline case shows no recirculation in the centre of the flow, the shortest lance shows formation of a vortex breakdown with a downstream stagnation point near $y = 0.9D_{sw}$. Longer lances show

little change in the velocity profile very near the swirler outlet but show that the downstream stagnation point moves slightly upstream. The longest lance causes the recirculation in the centre of the flow to virtually disappear.

Contours of radial velocity (fig. 155) show the spreading of the bifurcated jet as it leaves the swirler for all lance configurations. Spreading is highest for the case of $L_{La} = L_{sw}$. This is because the breakdown is forced downstream of the outlet, and the jet tends to exit the swirler before splitting in two. The position of the breakdown requires the jet to spread very rapidly in order to travel around the breakdown.

Contours of tangential velocity are shown for the XEVc in figure 156. This figure shows a more coherent swirl for the configurations with the long lance, especially downstream of the vortex breakdown. Profiles of tangential velocity (fig. 157) show that at $y = 0.38D_{sw}$, the tangential velocity is highest for the baseline case and its point of maximum velocity is closer to the swirler axis than for the other configurations. Further downstream, at $y = 0.77D_{sw}$, the tangential velocity profiles have similar magnitude for all configurations. Far downstream, however, at $y = 1.92D_{sw}$, the tangential velocity profile is seen to be very strong for the configurations with the long lance, as compared to the baseline condition.

Contours of total turbulence for the XEVc are shown in figure 160. This figure shows that while the baseline swirler generated a large region of intense turbulence immediately downstream of its outlet, the configurations with the lance created high turbulence only in the region of the jet. This is because for configurations with the lance the flow in this region does not exhibit the large velocity fluctuations as the flow tries to recirculate, but

rather has a more organized, coherent structure. Further downstream of the swirler outlet, the configurations with the lance all show a region of high turbulence corresponding to the formation of a turbulent core in the centre of the flow. This core is clearly absent for the baseline burner and is weak for a lance length of $L_{La} = L_{sw}$. Figure 161 shows that the turbulence level in the centre of the flow is reduced by approximately 30% for the configurations with lances. The turbulence intensity was slightly higher for the short lances compared to the longer lances in the centre of the flow, and near the wall all configurations had a similar level.

Figure 162 shows profiles of total turbulence for the XEVc along the centreline of the swirler. This figure shows a significant decrease in the turbulence level once the flow begins to recirculate. The turbulence level remains at a nearly constant level moving downstream and is unaffected by different lance positions.

Figure 163 shows that the magnitude of the axial turbulence is significantly reduced only for the case of the longest lance, but the area of highest axial turbulence is significantly smaller for all configurations with a lance. It is seen that highest turbulence for the configurations with lances is in the region of the bifurcated jet, as a result of the high shear generated between the jet and the inner recirculation zone. Axial turbulence for a lance length of $L_{La} = L_{sw}$ is lower because the jet has a very high spreading rate and a smaller axial velocity component compared to the other swirlers, and also because the tip of the lance at the swirler outlet damps fluctuations of axial velocity in the centre of the flow. Profiles of axial turbulence (fig. 164) for the XEVc showed that turbulence was highest for

the baseline swirler in the centre of the flow. All configurations with lances showed similar turbulence levels across the entire flow, although the axial turbulence was slightly lower for the configuration with a lance length of $L_{La} = L_{sw}$.

Contours of radial turbulence (fig. 165) show a significant reduction for the configurations with lances compared to the baseline. Radial turbulence was highest for all configurations except the baseline and for a lance length of $L_{La} = L_{sw}$ in the centre of the flow as a result of the turbulent core oscillating laterally. For a lance length of $L_{La} = L_{sw}$, radial turbulence was comparatively weak in the turbulent core, but was higher in the region corresponding to the bifurcated jet. Figure 166 shows that the radial turbulence component is highest in the centre of the flow for the baseline swirler. The other configurations show a reduction of nearly 50% in the radial turbulence level in this region of the flow, but similar levels very near the wall. All configurations with lances show a peak in the radial turbulence in the centre of the flow as a result of the turbulent core, and show a similar level of anisotropy of the radial turbulence. The greatest anisotropy was seen in the centre of the flow and ranged from 1.2 for a lance length of $L_{La} = L_{sw}$, to 1.5 for the baseline swirler. The anisotropy level was close to a value of 1.0 in the region of the jet for all swirler configurations.

Contours of tangential turbulence are shown in figure 168 for the XEVc. These plots show that introducing the lance caused the tangential turbulence to localize in the bifurcated jet. Figure 169 shows that the tangential turbulence is highest in the centre of the flow for the baseline swirler, but is highest in the region of the jet for the configurations with lances. Figure 170 shows that the tangential turbulence component is approximately 2.5

times greater than the axial component for all lance configurations. It is seen that the tangential component is slightly more anisotropic for all configurations with lances than for the baseline case.

6.3.3 The XEVd with different lance lengths

The velocity vector fields for the XEVd with different lance lengths are shown in figure 171. These figures show very similar flow structure and vorticity levels for all configurations. The recirculating core was observed in the particle images for all configurations, which resulted in some bad vectors in three of the five images in this region. While more realistic vectors were calculated in the other two images, the data in this region is still considered as inaccurate.

Axial velocity contours for the XEVd (fig. 172) show that the greatest change in the vortex breakdown bubble is observed for a lance length of $L_{La} = 0.25L_{sw}$. It appears from this image that the hollow-cone breakdown becomes slightly shorter for this configuration and the recirculating core narrows. The strong recirculating core is seen for all configurations, but the magnitude of its backflow velocity appears to be reduced for the case of $L_{La} = L_{sw}$.

Figure 173 shows that at a distance of $y = 0.38D_{sw}$ downstream of the swirler outlet the velocity of the bifurcated jet is reduced with increasing lance length, and the velocity of the backflow in the centre of the flow is also reduced. At $y = 0.77D_{sw}$ downstream of the outlet (fig. 174) it is seen that the jet has the highest velocity for the baseline case, but is only slightly slower for increasing lance length. At this location, the recirculating core has formed for the baseline case and the two shortest lance lengths. The core is just starting

to form for the case of $L_{La} = 0.75L_{sw}$, but is not yet visible for the case of $L_{La} = L_{sw}$. Further downstream (fig. 175) it is seen that the recirculating core has formed for all five configurations. The core has a similar backflow velocity for the baseline configuration and for the two shortest lances, however its backflow velocity is significantly reduced with increasing lance length.

Figure 176 shows profiles of axial velocity with downstream distance for the XEVd with different lance lengths. Little difference is seen in the velocity profiles for the baseline and the two shortest lances. All three of these configurations show a strong vortex breakdown characterized by the presence of the recirculating core extending downstream to the combustion chamber outlet. Longer lances decrease the strength of the recirculating core, and it disappears for full extension of the lance.

Contours of radial velocity (fig. 177) show little difference from one configuration to the next. All images show unrealistic velocity values in the region corresponding to the recirculating core. As with the baseline case of the XEVd, there is little seeding in this region and measurements here are unreliable. Contours of tangential velocity are shown in figure 178. These images show reduced tangential velocity immediately downstream of the burner exit with increasing lance length, but less difference further downstream. Tangential velocity profiles at $y = 0.38D_{sw}$ downstream of the swirler outlet (fig. 179) show a slightly lower tangential velocity for short and moderate lance lengths, but there is a significant reduction in the tangential velocity for a lance length of $L_{La} = L_{sw}$. A similar trend is seen further downstream at $y = 0.77D_{sw}$ (fig. 180), and it is seen that the location of

maximum tangential velocity moves closer to the axis of the swirler with increasing lance length. Downstream of the vortex breakdown bubble, at $y = 1.92D_{sw}$ from the swirler outlet, the tangential velocity profiles show little difference between the different configurations. (fig. 181).

Figure 182 shows contours of total turbulence for the different configurations. The level and distribution of total turbulence in the combustion chamber shows very little change from one configuration to the next. Turbulence was highest near the bifurcated jet due to the high shear caused by the recirculating flow. While the turbulence values along the axis of the swirler cannot be viewed as accurate, due to the poor seeding in this region, it is expected that this would be a region of very high turbulence. This is due to the high shear between the downstream traveling flow and the recirculating core. Figure 183 shows profiles of total turbulence for the different configurations. Turbulence levels are very similar for all configurations, but are seen to increase slightly with increasing lance length, particularly in the region of the bifurcated jet. Figure 184 shows profiles of total turbulence along the centreline of the XEVd. The turbulence level is reduced along the entire length of the field of view for a lance length of $L_{La} = L_{sw}$, but is unaffected by other lance positions.

Contours of axial turbulence (fig. 185) also show very little difference from one configuration to the next. Axial turbulence is highest in the region of the jet, and quickly dissipates moving downstream. Profiles of axial turbulence (fig. 186) show that there is little difference in the turbulence level from one configuration to the next. Axial turbulence is highest in the centre of the flow, although actual values cannot be considered accurate in this region.

Contours of radial turbulence (fig. 187) show little difference between the configurations. High radial turbulence is observed in the region of the recirculating core as a result of its lateral oscillation. Turbulence values in this region cannot be considered accurate due to poor seeding in the core. Figure 188 shows that the radial turbulence level is very similar for all swirler configurations, and is relatively constant across the flow, except for the region of the recirculating core. Figure 189 shows that the radial turbulence level is very similar to the level of the axial turbulence component and is relatively constant across the entire flow.

Contours of tangential turbulence are shown in figure 190, and show very similar turbulence levels for all configurations. Tangential turbulence is highest in the region of the jet at the swirler exit, and also in the recirculating core. Figure 191 shows profiles of tangential turbulence for the different configurations. Here it is seen that increasing the lance length causes an increase in the turbulence level in the region of the jet. Tangential turbulence is also high in the recirculating core, although the actual values are considered unreliable. Differences in the anisotropy of the tangential turbulence can be seen in figure 192. The baseline case exhibits the least anisotropy as a result of the low tangential turbulence. Increases in lance length cause increases in the tangential turbulence, and, as a result, cause the anisotropy of the tangential component, relative to the axial component, to increase.

It was seen that the extended lance had very little effect on the flow structure of the XEVd. While the lance increased the strength of the vortex breakdown for the XEVa and XEVc, it was seen that the XEVd already had a very strong vortex breakdown, and introduction of the lance was unable to further strengthen it. A lance length of $L_{La} = L_{sw}$

was shown to disturb the flow structure by forcing the vortex breakdown bubble downstream. This weakened the breakdown bubble to the point that the recirculating core began to break up. Further increases in the lance length would likely cause the recirculating core to disappear completely.

6.3.4 The XEVb with different lance lengths

Velocity vector fields for the XEVb with different lance configurations are shown in figure 193. Changing the lance length is seen to create little change in the overall flow structure or in the magnitude of the vorticity in the recirculation zones. During testing, however, it was seen in the particle images that certain lance positions excited shedding of coherent vortices from the swirler outlet. While the particle images for the baseline case closely resembled those of the XEVa (fig. 65), particle images for a lance length of $L_{La} = 0.25L_{sw}$ (fig. 194) show coherent vortices propagating downstream in a helical pattern. These vortices were less coherent for a lance length of $L_{La} = 0.50L_{sw}$, and disappeared completely for longer lance lengths. It is evident from this that introduction of a short lance excited a helical instability mode that was only stable over a narrow range of lance positions.

Figure 195 shows that the vortex breakdown is enlarged and strengthened by the presence of the long lance, although the central recirculating core does not form. Inserting the lance to a position of $L_{La} = 0.25L_{sw}$ causes the vortex breakdown bubble to lengthen and spread further upstream. Inserting the lance further to positions of $L_{La} = 0.5L_{sw}$ and $L_{La} = 0.75L_{sw}$ causes lengthening of the solid region of the breakdown bubble but no changes to

the overall length of the breakdown. A lance length of $L_{La} = L_{sw}$ forced the breakdown bubble completely outside of the swirler cone and nearly eliminated the solid region of the breakdown. Figure 196 shows that at $y = 0.38D_{sw}$ downstream of the outlet, the velocity of the jet is slightly reduced for $L_{La} = L_{sw}$, but shows little difference for other lance positions. The recirculation in the centre of the flow shows little difference for $L_{La} = 0.25L_{sw}$, but is slightly increased for the two intermediate lance lengths and reduced for $L_{La} = L_{sw}$. Figure 197 shows that the jet is slowest for the case of $L_{La} = L_{sw}$, and that the annular region of the vortex breakdown is furthest upstream for this configuration. At $y = 1.92D_{sw}$ downstream of the outlet, all four shortest lance configurations show increased velocity in the centre of the flow compared to the baseline condition. The higher velocity in the centre of the flow is a result of the increased spreading of the vortex breakdown bubble.

Figure 199 shows profiles of axial velocity with downstream direction along the centreline of the combustion chamber. This figure shows that short lance lengths increase the strength of the vortex breakdown, as the maximum value backflow velocity increases in magnitude and moves closer to the swirler outlet. The downstream stagnation point is seen to move upstream as the hollow-cone structure widens and opens. Further increases in lance length decrease the magnitude of the backflow velocity, and the backflow nearly disappears for full extension of the lance.

Contours of radial velocity (fig. 200) show little difference compared to the baseline condition. It can be seen that for $L_{La} = L_{sw}$ the jet has the widest spreading, as it actually exits the swirler before it splits in two. Figure 201 shows little difference in the tangential

velocity fields compared to the baseline condition. It is seen for all configurations that the tangential velocity is highest in the region of the jet near the outlet, but downstream of the vortex breakdown the tangential velocity is highest near the swirler axis. Figure 202 shows that at $y = 0.38D_{sw}$ downstream of the swirler outlet there is little difference in the tangential velocity profiles. Further downstream at $y = 0.77D_{sw}$ (fig. 203), the location of maximum tangential velocity for the baseline burner is further away from the centreline and that the maximum tangential velocity is slightly reduced with increasing lance length. At $y = 1.92D_{sw}$ downstream of the swirler outlet (fig. 204), it is seen that all configurations have the highest tangential velocity profile near the swirler axis, and that this value increases with increasing lance length.

Figure 205 shows contours of total turbulence for the XEVb with different lances. For all configurations it is seen that the maximum turbulence level occurs in the region of the jet, and that high turbulence is observed along the swirler axis as a result of the turbulent core in that region. Profiles of total turbulence (fig. 206) show that the turbulence level is nearly doubled in certain regions of the flow for the longest lance position. Turbulence is highest in the centre of the flow, corresponding to the turbulent core, and near the wall as a result of the wider spreading jet. Figure 207 shows contours of turbulence along the centreline of the XEVb swirler. This figure shows that lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = L_{sw}$ slightly reduce the turbulence level upstream of $y = D_{sw}$, but other configurations show little change relative to the baseline.

Contours of axial turbulence for the XEVb are shown in figure 208. These images show

that axial turbulence is highest for all configurations in the region of the jet. Axial turbulence is slightly reduced for a lance length of $L_{La} = L_{sw}$ due to the fact that the jet exits the swirler and then undergoes very high spreading. This causes the inner shear layer to form at a sharp angle relative to the flow, and a reduction in the axial component of turbulence. Profiles of axial turbulence are shown in figure 209. This figure shows that at this location in the flow, axial turbulence is minimum in the centre of the flow. Higher axial turbulence is observed in the region of the jet for lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.75L_{sw}$, and reduced turbulence is seen across most of the flow for a lance length of $L_{La} = L_{sw}$.

Contours of radial turbulence are shown in figure 210. This figure shows similar radial turbulence levels in the region of the jet for all burner configurations, and high turbulence along the axis of the swirler that is increased for moderate lance lengths. Profiles of radial velocity are shown in figure 211. Here it is seen that moderate and long lance lengths increase the radial turbulence in the centre of the flow by causing the turbulent core to move slightly upstream. Further away from the centreline, less of a difference is seen between the different turbulence profiles. While the radial turbulence component was lower than the axial component across the entire width of the flow for the baseline swirler (fig. 212), the radial component is significantly higher in the centre of the flow for the swirlers with lances. This is a result of the turbulent core moving slightly upstream.

Contours of tangential turbulence are shown in figure 213 for the XEVb with different lance lengths. This turbulence component is highest in the region of the bifurcated jet, and is significantly stronger for a lance length of $L_{La} = L_{sw}$. Profiles of tangential turbulence

(fig. 214) show that tangential turbulence is much higher for a lance length of $L_{La} = L_{sw}$, especially in the centre of the flow and in the region of the jet. Figure 215 shows that while the tangential turbulence is approximately twice as large as the axial turbulence component for most of the configurations, it is between 2.5–3.5 times greater for a lance length of $L_{La} = L_{sw}$.

The long lance was seen to have a significant effect on the flow of each swirler. The XEVa showed no change in the tangential velocity, although lances with lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.5L_{sw}$ were seen to increase the strength of the vortex breakdown to the point that a recirculating core that stretched far downstream formed in the centre of the hollow-cone vortex breakdown bubble. The XEVc showed the most dramatic change of all as the lance increased the tangential velocity of the flow downstream of the jet and caused it to undergo vortex breakdown for all lance positions. The XEVd showed the least change with lance position. Short lance lengths, which were observed to increase the strength of the vortex breakdown of other swirlers, had no effect on the flow. Longer lance lengths, however, caused a weaker vortex breakdown. The XEVb showed strengthening of the vortex breakdown for short lance lengths as the hollow-cone structure opened wider. Increasing lance lengths weakened the breakdown somewhat as they caused it to close slightly and move downstream.

Though the lance caused different effects on the flow field of each swirler, one outstanding trend was seen for all swirlers. Increasing the lance to a length of $L_{La} = 0.25L_{sw}$ caused maximum strengthening of the vortex breakdown bubble, and increasing it beyond this point

gradually weakened the breakdown. Extending the lance to a position of $L_{La} = L_{sw}$ forces the breakdown downstream of the point where it naturally tends to stabilize, and creates a weak breakdown.

In general, while a lance length of $L_{La} = 0.25L_{sw}$ is observed to strengthen the vortex breakdown bubble this configuration is not necessarily optimal. Such a configuration alters the structure of the vortex breakdown, and may create a flow structure that is susceptible to combustion instabilities. It is likely that the optimal configuration is one where the lance is positioned such that its downstream tip is near the point where the upstream tip of the vortex breakdown bubble naturally tends to stabilize. Such a configuration provides a stable anchoring point for the vortex breakdown bubble and will help generate a stable flow field.

6.4 Effect of mixing tube length

The circular mixing section downstream of the swirler outlet is a feature of the AEV burners used by ALSTOM Power Ltd. The purpose of the mixing tube is to allow the fuel and air additional time to mix before entering the combustion zone. A removable transition piece was constructed for each swirler which provides a smooth transition between the concave surfaces of the blades and the inner surface of the mixing tube. The transition piece eliminated the step that would have otherwise resulted at the exit of the swirler, and had a contour described by a fifth order polynomial. The length of the transition pieces was approximately 0.6", and the length of the mixing tube was measured from the downstream tip of the transition piece to the sudden expansion. The configuration described as $L_{mt} = 0.0$ " consists of the

swirler with the transition piece mounted such that the sudden expansion is flush with the downstream tip of the transition piece.

The primary function of the mixing tube was not to alter the flow field, although it was expected to have a significant effect on it. It was expected that by moving the swirler upstream of the sudden expansion the tangential velocity would be reduced and the strength of the vortex breakdown weakened. Furthermore, by reducing the area ratio at the sudden expansion, it was expected that the strength of the inner recirculation zone would be reduced. It was expected that the configuration of $L_{mt} = 0.0''$ would cause wider spreading of the jet entering the combustion chamber as a result of the transition piece diffusing the flow outwards. Further increases in the mixing tube length were expected to straighten out the bifurcated jet and cause the vortex breakdown bubble to propagate upstream into the tube itself. It was observed that the pressure drop and the discharge coefficient for each swirler did not change compared to the baseline case, regardless of the mixing tube length.

6.4.1 The XEVa with different mixing tube lengths

Figure 216 shows the velocity vector fields for the XEVa with different mixing tube lengths. These figures show that the configuration with a mixing tube length of $L_{mt} = 0.0''$ causes the bifurcated jet to have a higher spreading rate at the swirler outlet and penetrate less far into the flow. Contours of vorticity show the elongated vortices created as the breakdown bubble lengthens and stabilizes inside the mixing tube. Longer mixing tubes increase the penetration of the jet and cause the vortex breakdown bubble to stabilize further downstream

compared to the case with the mixing tube length of $L_{mt} = 0.0''$.

Contours of axial velocity are shown in figure 217 for the XEVa. This figure shows that the vortex breakdown bubble moves upstream for $L_{mt} = 0.0''$, such that the solid region of the breakdown is stabilized upstream of the sudden expansion. Increases in mixing tube length were seen to cause the vortex breakdown bubble to move slightly downstream and weaken compared to the case of $L_{mt} = 0.0''$. Figure 218 shows that the case of $L_{mt} = 0.0''$ causes the bifurcated jet to spread most widely compared to the other configurations. Propagation of the breakdown upstream into the mixing tube causes the highest velocity in the centre of the flow for a mixing tube length of $L_{mt} = 0.0''$. The location of the jet is similar for all of the other mixing tube configurations, and increasing the mixing tube length causes the axial velocity in the centre of the flow to increase as the backflow begins to break up in this region. Further downstream at $y = 0.77D_{sw}$ (fig. 219), there is less of a difference in the width and position of the jet for all configurations. The case of $L_{mt} = 0.0''$ causes deceleration of the flow in the bifurcated jet, and for all configurations the velocity in the centre of the flow is seen to increase with mixing tube length. At a distance of $y = 1.92D_{sw}$ downstream (fig. 220), little difference is seen among the configurations away from the centre of the flow. Increasing the length of the mixing tube is seen to increase the velocity of the flow in the centre of the flow. This is a result of the vortex breakdown bubble stabilizing inside the mixing tube.

Figure 221 shows profiles of axial velocity with downstream distance for the XEVa with different mixing tube lengths. This figure shows that the mixing tube with a length of $L_{mt} =$

0.0" causes the downstream stagnation point to move upstream of the sudden expansion. It is expected that a small central backflow region exists inside the mixing tube for this configuration. Longer mixing tubes force the downstream stagnation point downstream of the sudden expansion, but it is seen that the breakdown bubble moves further upstream of the sudden expansion, and the velocity in the centre of the flow increases with increasing tube length.

Figure 222 shows the radial velocity contours for the XEVA. All configurations show similar behaviour to the baseline case, as the flow spreads in the jet and converges in the centre of the flow and in the outer recirculation zone. These figures also show increased spreading of the jet for the case of $L_{mt} = 0.0"$, and decreased spreading of the jet for the cases with longer mixing tubes.

Figure 223 shows contours of tangential velocity for the different mixing tube configurations of the XEVA. These images show that the burner maintains its highly coherent swirl regardless of the mixing tube length, but otherwise the tangential velocity is unaffected. Figure 224 shows that the tangential velocity profiles are not significantly affected by the mixing tube configurations near the swirler outlet. Slightly further downstream at $y = 0.77D_{sw}$ (fig. 225), it is seen that a mixing length of $L_{mt} = 0.0"$ causes slight reduction in the magnitude of the tangential velocity, but this increases with increasing mixing tube length. Figure 226 shows that $y = 1.92D_{sw}$ downstream of the sudden expansion there is little difference in the tangential velocity profiles for any of the configurations.

Contours of total turbulence are shown for the XEVA with different mixing tube lengths

in figure 227. This figure shows that there is a significant effect on the turbulence level with different mixing tube lengths. A mixing tube length of $L_{mt} = 0.0''$ causes the total turbulence level to increase slightly immediately downstream of the swirler outlet, and also generates higher turbulence further downstream. Longer mixing tubes show steadily decreasing turbulence in the region of the jet, and it appears from the images for the longest two mixing tubes that the highest turbulence would, in fact, be inside the mixing tube. Profiles of total turbulence show that turbulence is slightly reduced for the shorter mixing tubes, and is reduced by approximately 50% in the region of the jet for the longest mixing tubes. Profiles of total turbulence along the axis of the swirler (fig. 229) show that the turbulence level is very slightly increased moving downstream of the swirler outlet.

Figure 230 shows contours of axial turbulence for the XEVa with different mixing tube lengths. This figure shows that the mixing tube causes the highest axial turbulence to localize in the region of the jet. It appears from this image that as the mixing tube length is increased, the region of highest axial turbulence is likely inside the mixing tube. Figure 231 shows that the mixing tubes cause slightly higher axial turbulence in the centre of the flow and reduced levels in the bifurcated jet.

Contours of radial turbulence (fig. 232) show that a mixing tube length of $L_{mt} = 0.5''$ causes reduction of the turbulence level along the axis of the burner. This indicates that this configuration does not have a turbulent core in the centre of its flow. Longer mixing tube lengths show reappearance of the turbulent core and reduced radial turbulence in the region of the jet, as a result of its reduced spreading. Profiles of radial turbulence at $y = 0.77D_{sw}$

from the swirler outlet show that the radial turbulence in the centre of the flow is increased for configurations with non-zero mixing tube lengths. The radial turbulence in the jet decreases slightly with increasing mixing tube length, as a result of a straighter jet exiting the mixing tube. The level of radial turbulence for the baseline swirler is approximately 80% of the level of the axial component across the entire flow. A mixing tube length of $L_{mt} = 0.0''$ shows similar levels between the axial and radial turbulence components. Longer mixing tubes shows lower radial turbulence than axial turbulence in the jet, but significantly increased radial turbulence in the centre of the flow as a result of the turbulent core.

Figure 235 shows contours of tangential turbulence for the XEVa with different mixing tubes. A mixing tube length of $L_{mt} = 0.0''$ causes increased tangential turbulence downstream of the bifurcated jet, but similar levels near the swirler outlet. Longer mixing tubes show reduced tangential turbulence at the swirler outlet, and again it appears that the region of highest turbulence is likely inside the mixing tube. The reduced tangential turbulence is most likely caused by homogenization of the flow as it passes through the mixing tube. Immediately downstream of the swirler exit, there would be six high-speed swirler jets issuing from the slots between the swirler blades, which would cause regions of very high shear and therefore high tangential turbulence. Longer mixing tubes allow more time for the flow to become more homogeneous, and it is expected that the highest tangential turbulence would occur inside the mixing tube, very near the swirler outlet. Profiles of tangential turbulence (fig. 236) show similar turbulence levels between the baseline and configurations with mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ in the region of the jet. Lower tangential

turbulence is observed for longer mixing tubes, and all mixing tube configurations show a slight peak in the centre of the flow. Figure 237 shows that the anisotropy of the tangential turbulence relative to the axial turbulence for the longest two mixing tubes is in the range of 2.0 across the entire flow, similar to the baseline case. The greatest anisotropy is seen for a mixing tube length of $L_{mt} = 0.0''$, which shows values between 3.0–3.5 throughout most of the flow. Mixing tube lengths of $L_{mt} = 0.5''$ and $L_{mt} = 1.0''$ shows greatest anisotropy in the centre of the flow and reduced levels around the bifurcated jet.

6.4.2 The XEVc with different mixing tube lengths

Figure 238 shows the velocity vector fields for the XEVc with different mixing tube configurations. It is seen that configurations of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ cause little change to the flow other than increased spreading at the swirler. For a mixing tube length of $L_{mt} = 1.0''$, the jet splits in two and a weak recirculation begins to form in its centre. Increasing the mixing tube length beyond this causes more distinct splitting of the jet, stronger recirculation in its centre, and regions of coherent vorticity to appear.

Figure 239 shows contours of axial velocity for the XEVc. Little difference is seen for a mixing tube length of $L_{mt} = 0.0''$ and a mixing tube length of $L_{mt} = 0.5''$ causes the outer recirculation zone to take on a triangular form as the bifurcated jet begins to form and spread. The faint beginnings of a hollow-cone vortex breakdown can be seen in the centre of the flow for $L_{mt} = 1.0''$, and this becomes stronger with increasing mixing tube length. For the configuration of $L_{mt} = 2.0''$ it is clearly seen that the vortex breakdown bubble has developed

the hollow-cone structure typical of this type of swirler. It is expected that increasing the mixing tube length would further increase the strength of the vortex breakdown to a point. Eventually a limit would be reached where further increases in the mixing tube length would have no effect on the flow. Profiles of axial velocity are shown in figure 240 at a distance of $y = 0.38D_{sw}$ downstream of the swirler outlet. This figure shows that the behaviour of the flow changes little for mixing tube lengths of up to $L_{mt} = 0.5''$. A transitional flow is seen for a mixing tube length of $L_{mt} = 1.0''$ as the flow begins to recirculate in its centre. Longer mixing tubes cause a vortex breakdown bubble to form which accelerates the bifurcated jet. Further downstream at $y = 0.77D_{sw}$, it is seen that mixing tube lengths of $L_{mt} = 0.5''$ and $L_{mt} = 1.0''$ cause a change in the flow structure relative to the baseline case. For these configurations the axial velocity profile is flat across the width of the combustion chamber and the maximum velocity is reduced. Longer mixing tubes are seen to cause formation of a weak vortex breakdown at this location. Further downstream at $y = 1.92D_{sw}$, the axial velocity profiles have the same basic shape, however it is seen that increasing the mixing tube length increases the velocity in the centre of the flow.

Figure 243 shows profiles of axial velocity with downstream direction for the XEVc. This figure shows that introduction of the mixing tube causes the velocity profile to move upstream for short mixing tubes. For a mixing tube length of $L_{mt} = 1.0''$, a stagnation point occurs in the flow at approximately $y = 0.8D_{sw}$ downstream of the outlet. The longest two mixing tubes create a vortex breakdown bubble in the centre of the flow, but its strength is very weak.

Contours of radial velocity are shown in figure 244. These figures show that mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ cause the spreading of the flow to increase at the swirler outlet. Increasing the mixing tube length to $L_{mt} = 1.0''$ causes the flow exiting the swirler to split in two, and further increases in mixing tube length cause the radial flow fields to take on a structure similar to that of the other circular swirlers.

Contours of tangential velocity are shown in figure 245. Here it appears that increasing the length of the mixing tube decreases the tangential velocity immediately downstream of the swirler outlet but increases it downstream of the jet. Figure 246 shows that the tangential velocity is reduced with increasing mixing tube length at a distance of $y = 0.38D_{sw}$ mm downstream of the outlet. Further downstream at $y = 0.77D_{sw}$ (fig. 247), less difference is seen in the profiles as the tangential velocity is reduced for the baseline swirler and configurations with short mixing tubes. Even further downstream at $y = 1.92D_{sw}$ (fig. 248), the tangential velocity profile shows low tangential for the baseline condition and the configurations with mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$. Longer mixing tubes, which cause initiation of vortex breakdown, show much stronger tangential velocity profiles.

Figure 249 shows contours of total turbulence for the XEVc with different mixing tube lengths. Increasing the mixing tube length is seen to decrease the level of turbulence at the outlet of the mixing tube. It appears from these images that increasing the mixing tube length causes the region of high turbulence to move upstream inside of the mixing tube, leaving only weak turbulence at the sudden expansion. Profiles of total turbulence (fig. 250) show that the overall turbulence level in the centre of the flow steadily decreases with

increasing mixing tube length, and is approximately one third the level of the baseline case for a mixing tube length of $L_{mt} = 2.0''$. The baseline case and short to moderate mixing tube lengths show a linear decrease in turbulence moving radially outwards, but the configuration with a mixing tube length of $L_{mt} = 2.0''$ shows a flat profile across the entire width of the flow. All configurations have a similar turbulence level near the wall of the combustion chamber. Figure 251 shows profiles of total turbulence along the centreline of the XEVc. This figure shows steady decay in the turbulence level immediately downstream of the swirler outlet as longer mixing tubes cause the flow to become more coherent and eventually recirculate.

Contours of axial turbulence (fig. 252) show highest turbulence in the region of the jet. For the baseline case and configurations with mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ where no central recirculation is observed, the axial turbulence is highest near the centre of the flow. For longer mixing tubes, the axial turbulence is highest near the edge of the mixing tube, corresponding to the location of the bifurcated jet that exists for these configurations. Longer mixing tube lengths show that the region of highest axial turbulence appears to exist inside the mixing tube. Figure 253 shows highest turbulence for the baseline case. As the flow begins to recirculate the axial turbulence is reduced as the flow becomes more coherent, and for cases where weak central recirculation occurs, axial turbulence is seen to be highest in the region of the bifurcated jet.

Contours of radial turbulence (fig. 254) show no reduction in turbulence for mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$, but rather show that the region of high radial turbulence moves slightly upstream into the mixing tube. Longer mixing tubes show a

sudden and significant reduction in the radial turbulence as the flow ceases its drastic radial oscillation and begins to recirculate. The region of highest radial turbulence appears to move upstream inside the mixing tube for the longest mixing tubes. Figure 255 shows profiles of radial turbulence across the flow field. This figure shows reduction of the turbulence level for mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ as the region of high turbulence moves upstream. A more significant reduction in turbulence is observed for longer mixing tubes as the flow begins to recirculate, and the region of highest turbulence move upstream inside the mixing tube. Figure 256 shows profiles of radial turbulence anisotropy relative to the axial turbulence component. This figure shows that the baseline configuration and the shortest mixing tubes exhibit the greatest degree of anisotropy in the centre of the flow as a result of flapping of the single jet exiting the swirler. Longer mixing tubes show reduced radial turbulence relative to the axial component in the region of the jet, but increased radial turbulence along the centreline.

Figure 257 shows contours of tangential turbulence for the XEVc with different mixing tube lengths. As with the other turbulence components, these figures show that increasing the length of the mixing tube causes the region of highest turbulence to move upstream. For the longest mixing tubes, it appears that the region of high turbulence is completely inside the mixing tube. Figure 258 shows a steady decrease in the level of tangential turbulence in the centre of the flow as it moves upstream inside the mixing tube. Figure 259 shows that the anisotropy of the tangential turbulence relative to the axial component, is highest in the centre of the flow and lowest is the region of the jet. All configurations exhibit

similar anisotropy levels, although it appears that it is greatest for a mixing tube length of $L_{mt} = 0.0''$, and least for a mixing tube length of $L_{mt} = 2.0''$

6.4.3 The XEVd with different mixing tube lengths

Velocity vector fields for the XEVd with different mixing tube configurations are shown in figure 260. This figure shows that a mixing tube length of $L_{mt} = 0.0''$ causes the bifurcated jet to widen and its penetration to decrease. Further increases in the mixing tube length reduce the spreading of the jet relative to the configuration of $L_{mt} = 0.0''$ and increase its penetration. Contours of vorticity show that the inner and outer recirculation zones move radially outwards for a mixing tube length of $L_{mt} = 0.0''$, then move slightly inwards for longer mixing tubes. It also appears that increases in the mixing tube length reduce the strength of the strong recirculating core in the centre of the flow.

Contours of axial velocity are shown in figure 261. This figure shows that extending the mixing tube length to $L_{mt} = 0.0''$ causes the vortex breakdown bubble to propagate upstream inside the transition piece, and weakened the recirculating core. Further increases in the mixing tube length cause the recirculating core to break up, and for mixing tubes longer than $L_{mt} = 1.0''$, the core disappears. Increasing the length of the mixing tube causes the vortex breakdown bubble to propagate upstream inside of the mixing tube. Figure 262 shows the axial velocity profiles for the different swirler configurations at a distance of $y = 0.38D_{sw}$ downstream of the swirler outlet. As with the XEVa, it is seen that a mixing tube length of $L_{mt} = 0.0''$ causes the bifurcated jet to spread most widely. The location of

the jet is similar for all other configurations, and it is seen that increasing the mixing tube length reduces the velocity of the flow in the centre of the flow, as the vortex breakdown moves upstream. Further downstream at $y = 0.77D_{sw}$, it is seen that the strength of the recirculating core in the centre of the flow is reduced with increasing mixing tube length. This trend is seen more clearly at $y = 1.92D_{sw}$ from the outlet. It is also seen that the axial velocity of the downstream traveling flow in the centre of the hollow-cone structure increases with increasing mixing tube length.

Figure 265 shows profiles of axial velocity with downstream distance for the XEVd with different mixing tubes. This plot shows that increasing the mixing tube to lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$ causes the strength of the recirculating core to weaken, although the upstream position of the vortex breakdown bubble does not move. Further increases in the mixing tube length cause the central core to disappear, and pull the breakdown bubble further inside the mixing tube.

Contours of radial velocity are shown in figure 266. These figures show the high spreading of the jet for a mixing tube length of $L_{mt} = 0.0''$, but otherwise show little difference in the radial velocity field for the various configurations.

Contours of tangential velocity are shown in figure 267 for the XEVd. Little difference can be seen in the tangential velocity field between the various burner configurations. All configurations show a strong tangential velocity field with a maximum value near the axis of the swirler. Figure 268 shows the tangential velocity profiles for this swirler at a distance of $y = 0.38D_{sw}$ downstream of the outlet. This figure shows that the tangential velocity

profiles are flatter for configurations with the mixing tube, although the magnitude of the velocities are similar. Further downstream at $y = 0.77D_{sw}$, small differences are seen in the tangential velocity profiles (fig. 269), but the tangential velocity is slightly reduced for mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$. At $y = 1.92D_{sw}$, the velocity profiles are all very similar, but a higher velocity value is seen for the baseline swirler near the axis of the combustion chamber. Profiles of total turbulence along the centreline of the XEVd are shown in figure 273. This figure shows a steady decrease in the turbulence level as longer mixing tubes cause the recirculating core to weaken and eventually disappear.

Figure 271 shows the contours of total turbulence for the XEVd with different mixing tube lengths. This figure shows that turbulence is reduced for the XEVd immediately downstream of the mixing tube outlet. This is because increased the length of the mixing tube causes the region of high turbulence generated at the swirler outlet to stabilize inside the mixing tube. It is also seen that increased mixing tube lengths cause reduced turbulence along the axis of the swirler as the recirculating core breaks up. Profiles of total turbulence show that the turbulence level is slightly increased for mixing tube lengths of $L_{mt} = 0.0''$ and $L_{mt} = 0.5''$, but is reduced for longer mixing tubes.

Contours of axial turbulence are shown in figure 274 for the XEVd with different mixing tube lengths. This figure shows that the highest axial turbulence for each configuration occurs in the region of the jet, but that the overall level is very similar. Axial turbulence is reduced along the axis of the swirler as the high shear created by the recirculating core dissipates. Profiles of axial turbulence (fig. 275) show similar turbulence levels for most

configurations across the entire flow. A mixing tube length of $L_{mt} = 0.5''$ shows increased turbulence in the region of the jet as a result of its higher penetration and longer mixing tubes show reduced turbulence in the centre of the flow due to the disappearance of the recirculating core.

Contours of radial turbulence (fig. 276) show highest levels in the region of the jet, and similar turbulence levels among the different configurations. High radial turbulence is seen along the centreline of the flow for the baseline swirler due to radial oscillation of the recirculating core. High turbulence is seen for all configurations in this region, but the turbulence level decreases with increasing mixing tube length as the core stop recirculating and becomes a region of increasingly weak turbulence. Profiles of radial turbulence are shown in figure 277. This figure shows that radial turbulence is highest in the centre of the flow. Further away from the centreline, the different configurations show similar turbulence levels, although radial turbulence is slightly reduced for the longest mixing tube. Figure 278 shows that the level of the radial turbulence component is similar to that of the axial component in the region of the jet. Along the centreline, these two components still have a similar magnitude for the baseline case and for the configuration with a mixing tube length of $L_{mt} = 0.0''$. This is a result of the high axial turbulence level measured along the centreline for these two swirlers. Configurations with longer mixing tubes exhibited very axial turbulence and high radial turbulence along the centreline, and shows an anisotropy level of 1.2–1.4, depending on the specific configuration.

Contours of tangential turbulence are shown in figure 279. This set of images shows that

increasing the mixing tube length causes the region of high turbulence generated by the swirler to stabilize inside the mixing tube. As a result, configurations with longer mixing tubes show reduced turbulence immediately at the sudden expansion. Longer mixing tubes also show a marked decrease in the tangential turbulence level on the centreline of the flow as the recirculating core disappears. Profiles of total turbulence are shown in figure 280. This figure shows slightly increased turbulence for mixing tube length of $L_{mt} = 0.0''$ and $L_{mt} = 0.1''$ relative to the baseline. This is because the region of high turbulence for the baseline case is localized immediately at the swirler outlet but decays very quickly. The three longest mixing tubes show decreased tangential turbulence relative to the baseline across the entire flow. Figure 281 shows similar relative levels of tangential turbulence to axial turbulence for most configurations. For most cases the anisotropy level is near 2.0 across the entire flow. The swirler with a mixing tube length of $L_{mt} = 0.0''$ shows greatest anisotropy due to its elevated tangential turbulence at the region of the flow. This swirler also shows reduced anisotropy in the centre of the flow due to weakening of the recirculating core.

6.4.4 The XEVb with different mixing tube lengths

Velocity vector fields are shown in figure 282 for the XEVb with different mixing tube lengths. This set of images shows that for a mixing tube length of $L_{mt} = 0.0''$ the jet has a very high spreading at the swirler outlet. Longer mixing tubes cause less spreading of the jet and deeper penetration downstream. Contours of vorticity show elongation of the recirculation zones as the hollow-cone shape of the vortex breakdown bubble spreads more widely.

Figure 283 shows contours of axial velocity for the XEVb. These figures show that a mixing tube length of $L_{mt} = 0.0''$ causes the hollow-cone vortex breakdown bubble to form with a large annular section and stabilize inside the mixing tube. Increases in the mixing tube length cause the hollow-cone structure to close slightly, and the lower backflow velocity immediately downstream of the mixing tube outlet indicates that the configurations with mixing tubes have a weaker breakdown. Figure 284 shows the axial velocity profiles for the XEVb $y = 0.38D_{sw}$ downstream of the swirler outlet. This figure shows that, as before, the mixing tube with a length of $L_{mt} = 0.0''$ causes widest spreading of the jet. Longer mixing tubes also cause spreading of the jet relative to the baseline, and show similar axial velocity of the bifurcated jet. Increasing the mixing tube length beyond $L_{mt} = 0.5''$ causes slowing of the flow in the centre of the jet. Further downstream at $y = 0.77D_{sw}$ (fig. 285), it is seen that the velocity of the jet for a mixing tube length of $L_{mt} = 0.0''$ is much slower compared to the other cases, and the annular region of the vortex breakdown bubble exists in this region. The configurations with longer mixing tubes show an increased velocity of the bifurcated jet relative to the baseline case, and a reduced velocity in the centre of the flow as the result of a weaker vortex breakdown. Further downstream at a distance of $y = 1.92D_{sw}$ (fig. 286), little difference is seen in any of the velocity profiles, except for the case of $L_{mt} = 0.0''$ where the axial velocity in the centre of the flow is seen to be higher.

Figure 287 shows profiles of axial velocity with downstream distance for the XEVb. This plot shows that the strongest vortex breakdown bubble is generated by the swirler in the baseline condition. A mixing tube length of $L_{mt} = 0.0''$ causes the breakdown bubble to

move upstream of the sudden expansion. Longer mixing tubes force the breakdown bubble slightly further downstream compared to the case of $L_{mt} = 0.0''$. Very long mixing tubes weaken the vortex breakdown bubble to the point that negative velocities barely exist in the centre of the flow for configurations with mixing tube lengths of $L_{mt} = 1.5''$ and $L_{mt} = 2.0''$.

Figure 288 shows contours of radial velocity for the XEVb. Higher spreading of the jet is seen for the case with the mixing tube length of $L_{mt} = 0.0''$. Weaker spreading and higher penetration of the jet is seen for the other mixing tube configurations.

Figure 289 shows contours of tangential velocity for the XEVb. These plots show slightly reduced tangential velocity for the configurations with mixing tubes in the region of the jet immediately downstream of the swirler outlet. Further downstream, little difference is seen between the different configurations. Tangential velocity profiles are shown in figure 290 at a distance of $y = 0.38D_{sw}$ downstream of the swirler outlet. This figure shows similar velocity profiles for all configurations with mixing tubes, and a slightly higher tangential velocity for the baseline case. Further downstream at $y = 0.77D_{sw}$ (fig. 291) it is seen that the maximum tangential velocity of the baseline swirler is further away from the centreline than for the other configurations, but that the velocity magnitudes are similar. At $y = 1.92D_{sw}$ downstream of the outlet, less difference is seen in the tangential velocity profiles, except that the tangential velocity is slightly higher for the mixing tube with a length of $L_{mt} = 0.0''$.

Figure 293 shows contours of turbulence intensity for the XEVb. This image shows that highest turbulence levels are observed in the region of the jet for all configurations. A mixing tube length of $L_{mt} = 0.0''$ causes the region of high turbulence to spread further outward

at the sudden expansion. The region of high turbulence at the swirler's outlet appears to stabilize further upstream of the sudden expansion for longer mixing tubes. Profiles of total turbulence (fig. 294) show highest turbulence levels for the baseline swirler in the region of the jet. Increasing the mixing tube length reduces the turbulence level near the sudden expansion, and creates a very flat turbulence profile across the entire flow. Figure 295 shows profiles of total turbulence for the XEVb along the centreline of the swirler. This figure shows a steady decrease in the turbulence level immediately downstream of the swirler outlet as the region of highest turbulence is pulled upstream inside the mixing tube.

Contours of axial turbulence are shown in figure 296. This figure shows that the highest axial turbulence is in the region of the jet. The axial turbulence level is significantly reduced for mixing tubes longer than $L_{mt} = 1.0''$. Figure 297 shows that the baseline case has a much higher turbulence level than any of the other configurations. While the maximum turbulence level for the configuration with a mixing tube length of $L_{mt} = 0.0''$ is similar to that of the baseline, the turbulence is localized to the region immediately downstream of the swirler outlet for this configuration. As a result, at $y = 0.38D_{sw}$ downstream of the swirler outlet, all of the configurations with mixing tubes have an axial turbulence level that is approximately two thirds of that of the baseline.

Contours of radial turbulence (fig. 298) show drastically reduced radial turbulence at the sudden expansion for all configurations with a mixing tube. Highest radial turbulence is seen in the region of the jet, and high radial turbulence is also observed in the centre of the flow in the region of the recirculating core. It appears from this set of images that

increasing the mixing tube length causes the region of high radial turbulence to form inside the mixing tube. Profiles of radial turbulence (fig. 299) show that the baseline configuration has a much higher turbulence level in the region of the jet. The other configurations show significantly reduced turbulence. All configurations with a mixing tube, except for a mixing tube length of $L_{mt} = 0.0''$, show relatively constant turbulence levels across the flow. For a mixing tube length of $L_{mt} = 0.0''$ radial turbulence is slightly increased in the centre of the flow due to the turbulent core in this region. Contours of radial anisotropy (fig. 300) show that radial turbulence is slightly reduced compared to the axial component for the baseline swirler. All mixing tube configurations except for $L_{mt} = 0.5''$ show increased relative levels of radial turbulence in the centre of the flow as a result of fluctuations from the turbulent core. Further away from the centreline, the radial turbulence level was lower than the axial component.

Figure 301 shows contours of tangential turbulence. This figure shows highest turbulence in the region of the jet, and that tangential turbulence is highest for the baseline configuration. Extending the mixing tube length shows reduced turbulence downstream of the sudden expansion as the region of high turbulence forms inside the mixing tube. Profiles of tangential turbulence are shown in figure 302. These show that the baseline configuration has the highest turbulence level, and that the longest mixing tube exhibit very low tangential turbulence across the entire flow field. Figure 303 show that the magnitude of the tangential turbulence for the baseline case was 1.7–2.0 times higher than the axial component across the entire flow. Longer mixing tube lengths, which have very low axial turbulence components

in this region showed slightly greater anisotropy across the flow. The configuration with a mixing tube length of $L_{mt} = 0.0''$ showed the highest degree of anisotropy due to its very low axial turbulence level in this region and its higher tangential turbulence.

While the primary purpose of the mixing tube was not to alter the flow structure, it was seen that it had a significant effect on the flow field. It was seen that for all swirlers except the XEVc, the mixing tube with a length of $L_{mt} = 0.0''$ caused increased spreading and reduced penetration of the bifurcated jet. This was expected as a result of the diffuser effect of the transition piece. Longer mixing tubes were seen to straighten the jet and increase its penetration for these three swirlers. Longer mixing tubes were also seen to cause the vortex breakdown to propagate upstream inside of the tube. The XEVc showed the greatest change with different mixing tube lengths. While short lengths do not actually cause the flow to break down, there is a significant change in the flow as the jet begins to spread more widely and split in two. Longer mixing tubes increase the spreading of the jet and cause a vortex breakdown bubble to form. Even the longest mixing tube length of $L_{mt} = 2.0''$ causes only a weak breakdown to form, although it is anticipated that longer mixing tubes would strengthen the breakdown to a point.

It is anticipated that configurations with a mixing tube length of $L_{mt} = 0.0''$ would perform poorly in combustion tests. While the burner would likely provide adequate stabilization of the combustion process, the fact that the vortex breakdown bubble stabilizes inside the mixing tube suggests that the flame would probably stabilize partly inside the tube as well. In high pressure combustion operation, this would be very hard on the burner and

possibly cause severe damage in a very short time. Longer mixing tubes would likely perform better as the vortex breakdown bubble does not tend to propagate so far upstream into the mixing tube, and damage to the burner would be less likely to occur. Tests showed that introducing a mixing section between the swirler outlet and the sudden expansion caused the region of high turbulence to stabilize inside the mixing tube, which would provide very good mixing of fuel and air. Longer mixing tubes would allow additional time for mixing of fuel air, which is advantageous in premix operation as hot spots due to poor mixing are eliminated. On the other hand, better mixing of pilot fuel with combustion air would also occur, and this would impede ignition during startup.

6.5 The elliptic swirler

The XEVe-6 was designed with a geometry similar to that of the XEVa. The total slot area was the same for both swirlers, and the cone angle of the XEVe-6 along the major axis was the same as that for the XEVa. The purpose of testing the XEVe-6 was to determine the effect of an elliptic outlet on the flow structure. While the elliptic burner model tested at ALSTOM Power Ltd. showed a very different flow structure compared to the baseline burner model, it was not clear whether the elliptic shape of the burner outlet or its reduced area was responsible for these changes. The XEVe-6 was designed with the same outlet area as the four circular swirlers, and extensive tests were performed to evaluate its effect on the flow structure.

6.5.1 Structure of the baseline flow

The XEVe-6 was first tested in the baseline condition to observe differences in its flow structure at various azimuthal angles. A pressure drop of 6.4% was measured across this swirler, corresponding to a discharge coefficient of 0.35. The swirl number was estimated for this swirler by computing its value along the major and minor axes. The swirl number has its highest value of $S_N \simeq 1.08$ along the major axis where the blades had the highest curvature, and a lower value of $S_N \simeq 0.47$ along the minor axis where the curvature was least. The gave an average value of $S_N \simeq 0.78$ which was slightly greater than that of the XEVa.

Figure 304 shows the velocity vector fields for the elliptic burner at various azimuthal

orientations. It is obvious from this set of images that the flow from the elliptic swirler is very asymmetric. Contours of vorticity are flooded in this figure in order to highlight the secondary vortices formed by this swirler that are not observed for the circular swirler. In a plane aligned with the major axis (0°) it is seen that the bifurcated jet exits the burner at a very low angle. That is, the jet has a high spreading rate and low penetration into the flow. As a result of this, two flattened vortices are formed in the outer recirculation zone. As the laser sheet is rotated against the direction of swirl (positive angle), it is seen that the spreading rate of the jet decreases and its penetration increases. In a plane aligned with the minor axis, the jet exits the burner with almost no spreading, and two large circular vortices are formed in the outer recirculation zone. As the laser sheet is rotated beyond the minor axis, the spreading rate of the jet increases once again, and the vortices in the outer recirculation zone begin to flatten. There is virtually no difference between the vector plots measured at 0° and 180° .

Looking at the vector field acquired at 90° , it is seen that a circular pair of vortices have formed in the outer recirculation zone. Moving back through angles of 60° and 30° , it is seen that these vortices move slightly downstream, and at 0° they are even further downstream with a set of flattened vortices forming upstream of them. Comparing 180° to 150° , it is seen that these vortices have continued to move downstream, rather than moving back toward the burner outlet. When the laser sheet is rotated back to 90° , the original set of vortices are near the downstream end of the field of view, and a new set of circular vortices have formed at the sudden expansion. From a single image, the symmetric nature of the vector

field might indicate that the swirler is shedding axisymmetric ring vortices. Comparison of the images from one angle to the next, however, indicates that this cannot be the case. Instead, it is apparent that flow structure from the elliptic burner actually has the structure of a double helix.

Instantaneous three dimensional velocity vector plots are shown in figure 305 for the elliptic swirler along the major axis. The bifurcated jet at the swirler exit and the recirculation in the centre of the flow can be seen in these images. While the flow is turbulent over the entire flow field, the secondary vortices can also be seen in each of the single images.

Contours of axial velocity are shown for different azimuthal angles in figure 306. This figure clearly shows the low penetration of the bifurcated jet along the major axis of the swirler and the high penetration along the minor axis. It is seen that this swirler generates a comparatively small egg-shaped vortex breakdown bubble that extends approximately one swirler diameter downstream of the outlet and has an axisymmetric structure. Further downstream, the flow in the centre of the combustion chamber propagates towards the combustion chamber exit with a high axial velocity. Figure 307 shows instantaneous axial velocity contours for the elliptic swirler along the major axis. The jet at the swirler exit and the central recirculation zone in the centre of the flow can be seen in each image.

Profiles of axial velocity at $y = 0.38D_{sw}$ downstream of the swirler outlet are shown in figure 308. Here it is seen that the bifurcated jet has a higher velocity near minor axis of the swirler. As the laser sheet is rotated past this plane, the jet slows and begins to widen then abruptly narrows as the laser sheet is brought back to the major axis. It is

seen that the vortex breakdown bubble is essentially axisymmetric. Further downstream at $y = 0.77D_{sw}$ mm (fig. 309), it is seen that the jet has its highest velocity along the minor axis and has shown the greatest amount of spreading around 120° to 150° . The jet is slowest along the minor axis, and the central recirculation is approximately axisymmetric. Further downstream at $y = 1.28D_{sw}$ (fig. 310), the vortex breakdown bubble has disappeared and the axial velocity profile has become more axisymmetric. Even further downstream at $y = 1.92D_{sw}$ (fig. 311), the flow has become even more axisymmetric.

Contours of radial velocity (fig. 312) for the elliptic swirler are very different from those seen for the circular swirler. It is clear from these images that the jet has its highest spreading along the major axis and at 150° and 180° . Near the minor axis, where the jet penetrates very far into the flow, spreading is very low. It is seen in all of the individual images that alternating regions of converging and diverging flow are encountered when moving downstream on either side of the swirler axis. The fact that regions of diverging flow occur along the major axis as regions of converging flow along the minor axis indicates that the flow from the elliptic swirler is undergoing an axis-switching process. Instantaneous contours of radial velocity are shown in figure 313. The regions of alternating converging and diverging flow can be seen at the same location in each of the individual images.

Figure 314 shows contours of tangential velocity for the elliptic burner. In the region immediately downstream of the swirler outlet, it is seen that there is a region of high velocity corresponding to the bifurcated jet. The highest tangential velocity in this region is observed in a plane aligned with the major axis, which is expected since this is the region of the swirler

with the highest curvature. Near the minor axis of the swirler, where blade curvature is low, the tangential velocity is low at the swirler outlet. Downstream of the vortex breakdown bubble, the tangential velocity appears to be uniform from one image to the next. Figure 315 shows instantaneous contours of tangential velocity for the elliptic swirler along the major axis. The coherent swirl to the flow is clearly seen in each of these images.

Figure 316 shows profiles of tangential velocity for the elliptic swirler at $y = 0.38D_{sw}$ downstream of the outlet. It is seen in this figure that the tangential velocity is highest near the major axis and lowest near the minor axis. The same trend is seen further downstream at $y = 0.77D_{sw}$ in figure 317, although the tangential velocity profiles are flatter at all azimuthal locations. Further downstream (figs. 318 and 319) the velocity profiles are much flatter, and the highest tangential velocity is now seen near the minor axis.

Contours of total turbulence intensity are shown in figure 320. These images show that turbulence is highest immediately downstream of the swirler outlet and is weaker downstream of the breakdown bubble. Significant differences are seen in the turbulence level at the different swirler orientations due to changes in the flow field. In general, the turbulence level appears to follow the bifurcated jet, spreading widely along the major axis and penetrating further downstream along the minor axis. Figure 321 shows profiles of total turbulence for the elliptic swirler $y = 0.77D_{sw}$ downstream of the swirler outlet. Turbulence is seen to be highest for locations where jet penetration is highest, and is lowest where the jet tends to immediately spread into the sudden expansion.

Figure 322 shows contour plots of axial turbulence. It is seen that the region of highest

axial turbulence closely follows the bifurcated jet, and that turbulence is slightly reduced near the major axis where jet penetration is lowest. Profiles of axial turbulence verify this trend (fig. 323). This figure shows that turbulence is comparatively low in the centre of the flow, but is increased in the region of the jet for locations near the minor axis, but remains low in locations near the major axis.

Contours of radial turbulence (fig. 324) show a high level in the centre of the flow, as a result of the turbulent core along the axis of the swirler. Radial turbulence near the outlet has a similar magnitude at all locations, but the region of highest turbulence is much wider for configurations with high jet spreading. Figure 325 shows a similar level of radial turbulence for all configurations. Turbulence is highest in the centre of the flow and is reduced moving radially outwards. Figure 326 shows that the anisotropy of the radial turbulence relative to the axial turbulence changes noticeable at different locations. Along the major axis, where the jet spread rapidly but does not penetrate far into the flow, the radial turbulence is approximately 1.2–1.4 times greater than the axial turbulence component. Near the minor axis where the jet penetrates far into the flow but does not spread very much, the radial turbulence level is only 60% that of the axial turbulence in the region of the jet. Along the centreline of the burner the radial turbulence is 1.5 times greater than the axial component as a result of oscillation of the turbulent core.

Figure 327 shows contours of tangential turbulence for the different configurations. These plots shows high tangential turbulence immediately downstream of the swirler outlet for configurations with very high spreading (0° , 120° , 150° and 180°) and much lower turbulence

for configurations where the jet does not spread. Figure 328 is at a location downstream of the location of maximum turbulence, but shows locations near the major axis have highest tangential turbulence and locations near the minor axis have reduced turbulence. Figure 329 shows least anisotropy of the tangential turbulence relative to the axial turbulence in the centre of the flow. Moving radially outwards, it is seen that the anisotropy increases near the major axis where tangential turbulence is very high, but slightly reduces near the minor axis where tangential turbulence is much lower.

6.5.2 Comparison of the elliptic and circular swirlers

Figure 93 shows the velocity vector fields for the XEVe-6 along the major axis (top right image) and the minor axis (bottom right image) along with the vector fields for the circular swirlers. This image shows that the flow field from the elliptic swirler is very different from any of those of the circular swirlers. With the elliptic swirler, the bifurcated jet recirculates in the centre of the flow in two very short elongated vortices which end far upstream from the tip of the bifurcated jet. It is also seen that the elliptic burner causes formation of several additional sets of vortices further downstream that do not appear in the flow of any of the other burners. Figure 94 shows that the direction of swirl of the XEVe-6 is opposite that of the other swirlers, and that the magnitude of the tangential velocity is similar to that of the XEVa. The tangential velocity of the elliptic swirler is relatively uniform across the flow, and does not show the linear decay exhibited by the XEVa.

Contours of axial velocity are shown in figure 95. The high spreading of the bifurcated

jet along the major axis is seen to disrupt the recirculation zone at the sudden expansion, although along the minor axis this region has a structure similar to that of the XEVa. The vortex breakdown bubble formed in the centre of the flow does not have the hollow-cone shape seen in the flow of the circular swirlers, but instead forms as a small egg-shaped bubble that ends near the outlet of the swirler cone. At $y = 0.38D_{sw}$ downstream of the swirler exit, the axial velocity profile along the minor axis is seen to resemble that of the XEVa (fig. 96), although the hollow-cone behaviour is not seen in the centre of the flow. The axial velocity of the bifurcated jet is seen to be very low along the major axis, and minimal recirculation is seen in the outer recirculation zone. At $y = 0.77D_{sw}$ downstream (fig. 97), the maximum velocity of the central recirculation zone is similar to that of the XEVa, although it is located in the centre of the flow. The structure of the jet along the minor axis is similar to that of the XEVa, however it is wider and the inner shear layer is closer to the centre of the flow. The flow along the major axis exhibits only weak recirculation at the sudden expansion, and the jet is very wide and slow moving. Further downstream at $y = 1.28D_{sw}$ (fig. 98), the flow no longer resembles that of the circular swirlers since the vortex breakdown bubble does not have the hollow-cone structure. At $y = 1.92D_{sw}$, the axial velocity is almost completely uniform between the major and minor axes. Here it is seen to have its highest velocity in the centre of the flow and no backflow.

Figure 100 shows that the axial velocity of the elliptic swirler along its centreline is very similar to that of the XEVb. This figure shows that the upstream stagnation point of the egg-shaped vortex breakdown bubble stabilizes near to the outlet of the swirler, and that its

downstream tip is at approximately $y = 0.9D_{sw}$. Downstream of the breakdown bubble, the flow velocity shows a steady increase.

Contours of radial velocity are shown in figure 101. This image shows that the radial velocity field for the elliptic swirler is very different from that of the circular swirlers. While the circular swirlers show spreading of the flow only in the bifurcated jet and convergence in the recirculation zones, the elliptic swirler shows alternate regions of diverging and converging flow moving in the downstream direction.

Contours of tangential velocity (fig. 102) for the elliptic swirler are little different from those for the circular swirlers, except that the swirl direction is opposite. Tangential velocity profiles at $y = 0.38D_{sw}$ (fig. 103) downstream of the swirler exit show that the swirl is stronger along the major axis and has a velocity magnitude slightly greater than the XEVa. Further downstream (figs. 104–106) it is seen that the tangential velocity profile becomes very flat across the radius of the combustion chamber, and that the highest tangential velocity is aligned with the minor axis.

Contours of total turbulence are shown in figure 107. This figure shows highest turbulence for the elliptic swirler along the major axis and reduced turbulence along the minor axis. Like the circular swirlers, highest turbulence is seen in the region of the bifurcated jet, as a result of the high shear created by the recirculating flow. Figure 108 shows that the turbulence level along the minor axis is very similar to that of the XEVa. Along the major axis, turbulence is highest near the centre of the flow but decreases near the combustion chamber wall.

Profiles of total turbulence along the axis of the swirler are shown in figure 109. This figure shows that the turbulence level for the elliptic swirler is virtually identical to that of the XEVa and the XEVb.

Figure 110 shows that the axial turbulence is highest for the elliptic burner along its minor axis in the region of the jet. Along the major axis, turbulence is low as a result of the low penetration of the jet. Profiles of axial turbulence (fig. 111) show that the axial turbulence level of the elliptic burner is highest along its minor axis, and reaches a level similar to that of the XEVa. Lower spreading of the jet along this axis, however, causes the region of high turbulence to remain close to the swirler axis. Axial turbulence is very low along the minor axis of the elliptic swirler.

Figure 112 shows contours of radial turbulence for the different swirler configurations. Here it is seen that the elliptic has turbulence levels that are similar to those of the circular swirlers. Figure 113 shows that radial turbulence levels in the centre of the flow are similar for the elliptic swirler and the XEVa, however turbulence levels drop off for the elliptic swirler moving radially outwards. Figure 114 shows that the elliptic swirler has highest radial turbulence anisotropy compared to the axial component in the centre of the flow. Along the minor axis the radial turbulence is approximately 75% that of the axial component due to the high penetration and low spreading of the jet. Along the major axis the opposite trend is observed, and the radial component is as much as 50% greater than the axial component.

Contours of tangential turbulence (fig. 115) show much higher levels along the major axis than along the minor axis immediately at the swirler outlet. At $y = 0.77D_{sw}$ downstream

of the swirler outlet, the tangential turbulence level is slightly increased along the major axis, and has a value slightly higher than that of the XEVa. Tangential turbulence is very anisotropic along the major axis, reaching levels 3.4 times greater than the axial component in the region of the jet.

6.5.3 Effect of long lance position on the elliptic swirler

After the elliptic swirler was tested in the baseline condition, it was tested with the long lance. It was expected that the lance would have an effect on the flow that was similar to that for the circular swirlers, but that the lance would provide a minimal disturbance to the asymmetry of the flow, since it primarily affected the flow in the centre of the swirler.

Figures 330 and 331 show three-dimensional velocity vector fields for the elliptic swirler with different lance lengths in planes aligned with the major and minor axes respectively. Only minor changes are seen in each set of vector fields with different lance positions, and the flow is still very asymmetric between the two planes.

Figures 332 and 333 show contours of axial velocity along the two axes of the elliptic swirler. Figure 332 shows only minor changes in the velocity field along the major axis with lance position, however figure 333 shows that there is a tendency of the vortex breakdown bubble to make a transition from its egg shape to the hollow-cone type of structure. Velocity profiles at $y = 0.38D_{sw}$ downstream of the swirler outlet (figs. 334 and 335) show that extending the lance displaces the vortex breakdown bubble slightly downstream, slowing the backflow region at this point in the flow. Little difference is seen in the velocity profile in

the region of the bifurcated jet along either axis. Further downstream at $y = 0.77D_{sw}$ (figs. 336 and 337), a more significant difference can be seen in the axial velocity profiles. The lance displaces the vortex breakdown bubble downstream for longer lance lengths, and along the major axis moderate lance lengths are seen to increase the velocity of the bifurcated jet. Along the minor axis, it is seen that increasing the lance length to a length of $L_{La} = 0.5L_{sw}$ decreases the velocity of the jet, but increasing the length beyond this point causes an increase in the jet velocity. Further downstream at $y = 1.92D_{sw}$ (figs. 338 and 339), little difference is seen in the axial velocity profiles for the different configurations along either axis.

Figure 340 shows profiles of axial velocity with downstream direction along the centreline of the elliptic swirler with different lance lengths. This figure shows that the lance has a minimal effect on the velocity profile along the centreline. Longer lances show slight weakening of the breakdown bubble as the magnitude of the backflow velocity decreases and the breakdown bubble shortens slightly. Downstream of the breakdown bubble, longer lances show increased positive axial velocity. It is also seen in this figure that the elliptic swirler generates a vortex breakdown bubble with a stronger recirculation along the centreline than the XEVa.

Contours of radial velocity are shown in figures 341 and 342 for the swirler along the major and minor axes respectively. Comparing the images in figure 341, it is seen that the alternating patterns of converging and diverging flow in the combustion chamber persist for all configurations, however the velocity magnitude is slightly reduced for a lance length of

$L_{La} = 1.0L_{sw}$. This same trend is observed in figure 342 along the minor axis. The lance has very little effect on the radial velocity, and the asymmetry of the flow is maintained.

Figures 343 and 344 show contours of tangential velocity for the elliptic swirler along the major and minor axes respectively. Slight reduction in the tangential velocity is seen immediately downstream of the swirler outlet in the centre of the flow for all lance positions along both planes. Slight reduction in the tangential velocity is seen in the velocity profiles aligned with the major axis at $y = 0.38D_{sw}$ downstream of the swirler outlet for lance lengths of $L_{La} = 0.25L_{sw}$ and $L_{La} = 0.5L_{sw}$ (fig. 345). Little difference is seen at this location for tangential velocity profiles in the plane of the minor axis (fig. 346). Further downstream at $y = 0.77D_{sw}$ from the swirler outlet (figs. 347 and 348), it is seen that a lance length of $L_{La} = 0.25L_{sw}$ causes slight reduction in the tangential velocity along the minor axis, longer lances cause a slight increase. Further downstream at $y = 1.92D_{sw}$ (figs. 349 and 350) it is seen that shorter lances cause a slight decrease in the tangential velocity and longer lances show little difference from the baseline.

Figures 351 and 352 show contours of total turbulence for the elliptic swirler along the major and minor axes respectively. It is seen from these plots the total turbulence level is immediately increased in both planes as soon as the lance is introduced. While the turbulence level along the major axis remains high far downstream for all lance configurations, the turbulence level is seen to be highest along the minor axis for a lance length of $L_{La} = 0.25L_{sw}$, and then decrease with increasing lance lengths. Figure 353 shows that along the major axis turbulence is lowest for the baseline case and is highest for lance lengths of $L_{La} = 0.25L_{sw}$ and

$L_{La} = 0.50L_{sw}$. Along the minor axis the turbulence level at this location is similar between the baseline swirler and the longest lance configuration (fig. 354). Short and intermediate lance lengths show increased turbulence across the entire flow.

Profiles of total turbulence along the centreline of the elliptic swirler are shown in figure 355. This figure shows that the lance has little effect on the turbulence level immediately downstream of the swirler outlet. Further downstream, a significant increase in the turbulence level is seen for a lance length of $L_{La} = 0.50L_{sw}$

Contours of axial turbulence for the elliptic swirler with different lance lengths are shown in figures 356 and 357. This figures show that the lance has only a minor effect on the axial turbulence component. Profiles of axial turbulence along the major axis confirm this trend (fig. 358). Along the minor axis (fig. 359), lance lengths of $L_{La} = 0.5L_{sw}$ and $L_{La} = L_{sw}$ are seen to cause reduction in the axial turbulence component in the region of the jet, however little difference is seen for the other configuration or in the centre of the flow.

Contours of radial turbulence are shown in figures 360 and 361. These plots show that the lance has little effect on the level of radial turbulence along either axis. Figures 362 and 363 also show little difference between the different configurations. Figure 364 shows similar levels of radial anisotropy for all swirler configurations across the entire major axis of the swirler. It is seen that the level of the radial turbulence is slightly higher than that of the axial turbulence as a result of the high spreading of the jet along this axis. Along the minor axis, the level of the radial turbulence is slightly lower than the axial turbulence in the region of the jet for most swirlers. This is a result of the high penetration of the jet

exiting the swirler along this axis. In the centre of the flow, radial turbulence is highest due to oscillation of the turbulent core.

Contours of tangential turbulence (figs. 366 and 367) show a significantly larger region of high turbulence extending downstream of the swirler outlet for configurations with lances. Figure 368 shows that tangential turbulence was lowest along the major axis for the baseline swirler, and the two shortest lances showed the greatest increase, particularly in the centre of the flow. Along the minor axis (fig. 369) it is seen that the baseline and the configuration with a lance length of $L_{La} = L_{sw}$ have similar tangential turbulence levels. Short and moderate lance lengths have the highest turbulence along this axis. Figures 370 and 371 shows that the tangential anisotropy is greatest for short to moderate lance lengths. A lance length of $L_{La} = 0.25L_{sw}$ generated a tangential turbulence level that was approximately 3.5 times greater than the axial turbulence level, while the baseline gave an anisotropy in the range of 2.0.

It was found that the long lance had only a minor effect on the mean velocity field of the elliptic swirler. The asymmetric flow exhibited by the elliptic swirler is a result of the shape of the swirler outlet, and the long lance was unable to disturb this flow. It was seen however that the long lance had a significant effect on the turbulence level of this burner. While the axial and radial turbulence components remained largely unchanged, there was a significant increase in the level of the tangential turbulence. This would provide very good mixing in the region of the flame front, and increased combustion efficiency.

6.5.4 Effect of mixing tube length of the elliptic swirler

A transition piece was constructed for the elliptic swirler that provided a smooth transition from the elliptic outlet of the swirler to the 2" diameter of the circular mixing tube. Along the minor axis, this transition piece was longer than those for the circular swirlers, and configuring the elliptic burner with a mixing tube length of $L_{mt} = 0.0$ " resulted in the transition piece protruding beyond the sudden expansion. For this reason, the elliptic swirler was not tested in this configuration.

As before, the purpose of using the mixing tube with this swirler was to allow additional time for the mixing of the fuel and air before entering the combustion zone. It was expected that the mixing tube would reduce the strength of the recirculation at the sudden expansion and cause the vortex breakdown bubble to move upstream into the mixing tube. It was also expected that longer mixing tube lengths would have the detrimental effect of destroying the asymmetry of the flow.

Figures 372 and 373 show that the mixing tubes have a strong effect on the flow field. Figure 372 shows that along the major axis introduction of a mixing tube downstream of the swirler causes less spreading of the bifurcated jet and much stronger penetration downstream. The vortex breakdown bubble begins to strongly take on a hollow-cone structure. Contours of vorticity show that the secondary vortices disappear with the introduction of the mixing tube and elongated vortices form along the edge of the hollow-cone breakdown. Along the minor axis, the bifurcated jet is seen to exit the swirler with a high axial component and very little spreading for $L_{mt} = 0.5$ " (fig. 373). Longer mixing tubes increase the spreading of the

jet and decrease the downstream penetration of the jet. Increasing the length of the mixing tube increases the length of the hollow-cone vortex breakdown and increase the size of the annular section. Contours of vorticity show that the secondary vortices downstream of the breakdown disappear and the recirculation zones near the outlet become more elongated.

Figures 374 and 375 show axial velocity contours for the different mixing tube configurations. Contours along the major axis (fig. 374) show that introduction of the mixing tube causes the vortex breakdown bubble to immediately increase in length and take on the hollow-cone structure. Increases in the length of the mixing cause little change in the structure of the hollow-cone breakdown, however the vortex breakdown bubble is drawn further into the mixing tube for longer tube lengths. Along the minor axis (fig. 375), the breakdown bubble is seen to gradually increase in length and its hollow cone structure opens with increasing mixing tube length. This figure also shows that the vortex breakdown is drawn inside the mixing tube for longer mixing tubes. Comparing figures 374 and 375, it is seen that increasing the mixing tube length causes the flow to become more symmetric, although it is still very asymmetric for all configurations. Figure 376 shows the axial velocity profiles along the major axis $y = 0.38D_{sw}$ downstream of the swirler outlet. Introducing the mixing tube causes the bifurcated jet and the vortex breakdown bubble to widen. It is seen that increasing the length of the mixing tube causes the velocity of the backflow to decrease as the hollow-cone breakdown bubble moves upstream into the mixing tube. As the vortex breakdown bubble moves upstream, it increases the blockage of the burner outlet and causes the bifurcated jet to accelerate at the swirler outlet. Figure 377 shows that a similar trend

occurs along the minor axis. It is seen, however, that along the major axis increasing the mixing tube length increases the velocity of the bifurcated jet, while on the minor axis the velocity of the bifurcated first increases and then decreases. This is because in the baseline case the bifurcated jet has a much higher axial velocity along the minor axis than along the major axis. At first, increasing the mixing tube length causes the velocity of the jet along the minor axis to exhibit the same trend as was seen on the major axis, but then causes deceleration of the flow as the flow becomes more symmetric. Comparing figures 376 and 377 it is seen that the velocity profiles for the case of $L_{mt} = 2.0''$ have a nearly identical shape and similar numerical values. Figure 378 shows the axial velocity profiles at $y = 0.77D_{sw}$ downstream of the swirler outlet. It is seen that the mixing tube causes the bifurcated jet to spread and the hollow-cone breakdown to move upstream. A similar trend is seen on the minor axis (fig. 379), where it is seen that the longest mixing tube decelerates the jet and causes the flow to become more symmetric. Further downstream at $y = 1.92D_{sw}$ (figs. 380 and 381), it is seen that the hollow-cone structure has disappeared and that the downstream traveling flow emanating from the centre of the hollow cone has narrowed. The flow is more symmetric this far downstream, especially for the longer mixing tubes.

Figure 382 shows profiles of axial velocity with downstream distance along the centreline of the elliptic swirler with different mixing tubes. This figure shows that the upstream tip of the vortex breakdown bubble for the configuration with a mixing tube length of $L_{mt} = 0.5''$ stabilizes far upstream of the sudden expansion. Longer mixing tubes push the breakdown bubble upstream from this position, but show significant weakening of the breakdown bubble

as the magnitude of the backflow velocity decreases and the breakdown bubble shortens.

Figure 383 shows that the mixing tube has a very strong effect on the regions of alternating converging and diverging flow along the major axis. For the case of $L_{mt} = 0.5''$, these alternating regions disappear as the radial flow pattern becomes more like that of the circular swirlers. Increasing the mixing tube length serves to make this pattern appear more strongly. Along the minor axis, this effect on the radial flow is not as strong (fig. 384). It is seen that the flow for the case of $L_{mt} = 0.5''$ still closely resembles that of the baseline, and it is not until the mixing tube reaches a length of $L_{mt} = 1.0''$ that the flow resembles that of the circular swirler. Comparing these two sets of images, it is seen that the radial flow pattern is asymmetric for all configurations, but becomes more symmetric for longer mixing tubes.

Figure 385 shows contours of tangential velocity along the major axis. This image shows that while the tangential velocity at the swirler outlet is highest near the axis for the baseline case, its point of maximum velocity moves radially outwards with the jet for the configurations with mixing tubes. Figure 386 shows a similar trend along the minor axis, and also shows that the tangential velocity is reduced with increasing mixing tube length. Figures 387 and 388 show tangential velocity profiles along the major axis at a distance of $y = 0.38D_{sw}$ downstream. Along the major axis, it is seen that the tangential velocity has a similar level for all configurations, but the mixing tube causes the maximum value to move radially outwards. The tangential velocity is seen to be slightly higher along the minor axis for configurations with the mixing tube, and the mixing tube causes the velocity profile to

become flatter near its maximum value, rather than quickly tapering off. Moving further downstream to a distance of $y = 0.38D_{sw}$, it is seen that longer mixing tubes cause slightly reduced tangential velocity and a flatter velocity profile. At $y = 1.92D_{sw}$ downstream of the swirler outlet, it is seen that along the major axis (fig. 391) the velocity profiles are very similar, but the tangential velocity is slightly increased for most mixing tubes. Less of a difference is seen along the minor axis (fig. 392), and all of the configurations have a similar velocity profiles.

Figures 393 and 394 show contours of total turbulence for the elliptic swirler along the major and minor axes respectively. Figure 393 shows that a mixing tube length of $L_{mt} = 0.5''$ reduces the maximum level of turbulence, but extends the region of highest turbulence further downstream relative to the baseline. Further increases in mixing tube length cause reduction in the turbulence level at the sudden expansion as the region of high turbulence forms inside the mixing tube. Along the minor axis, a slightly different trend is seen. A mixing tube length of $L_{mt} = 0.5''$ generates turbulence of a similar magnitude to the baseline case, but the region of high turbulence extends further downstream. Longer mixing tubes cause the region of high turbulence at the sudden expansion to become smaller, but not to the extent that was seen along the major axis. Along both axes, it appears that the region of highest turbulence forms inside the mixing tube for all configurations. Profiles of turbulence along the major axis (fig. refE0MTTb) shows increased turbulence at $y = 0.38D_{sw}$ downstream of the outlet for the case of a mixing tube length of $L_{mt} = 0.5''$. This is because the turbulence for the baseline case is localized very close to the swirler outlet. Longer mixing tube cause

reduction in turbulence in this region. Profiles of turbulence along the minor axis (fig. 396) show increased turbulence in the region of the jet for mixing tube lengths of $L_{mt} = 0.5''$ and $L_{mt} = 1.0''$. This is a result of higher penetration of the jet into the flow. Longer mixing tubes show decreased turbulence in the region of the jet.

Figure 397 shows profiles of total turbulence along the centreline of the elliptic swirler. Long mixing tubes decrease the turbulence level at the sudden expansion as the vortex breakdown bubble is pulled inside the mixing tube, but further downstream short to moderate mixing tube lengths slightly increase the turbulence level.

Contours of axial turbulence are shown in figures 398 and 399 for the elliptic swirler. Along both axes, the axial turbulence is highest in the region of the jet. Along the major axis (fig. 398), the axial turbulence is localized immediately downstream of the swirler outlet for the baseline case and for the shortest mixing tube as the jet does not penetrate far into the flow. Longer mixing tubes increase the penetration and axial turbulence is higher further downstream. Along the minor axis (fig. 399) axial turbulence is highest for a mixing tube length of $L_{mt} = 0.5''$, which gives highest penetration of the jet. Longer mixing tubes decrease the jet penetration and as a result the axial turbulence level decreases. Profiles of axial turbulence along the major axis show that the baseline swirler has highest axial turbulence in the centre of the flow, and that this decreases moving radially outwards. At $y = 0.38D_{sw}$ downstream of the outlet, the shortest mixing tube provide a relatively constant level of axial turbulence across the entire flow, and longer mixing tubes show reduced turbulence in the centre of the flow and higher turbulence closer to the jet. Along the minor

axis (fig. 401), turbulence is seen to be lowest in the centre of the flow and greater in the region of the jet. Configurations with mixing tube lengths of $L_{mt} = 0.5''$ and $L_{mt} = 1.0''$ show increased turbulence in the region of the jet, as it penetrates deeper into the flow than for the baseline case. Longer mixing tubes shows decreased axial turbulence across the entire flow.

Contours of radial turbulence are shown in figures 402 and 403. Both sets of images show high turbulence along the jet as a result of the high shear in that region, as well as along the centreline of the flow due to radial oscillation of the turbulent core. Increasing the length of the mixing tube causes the location of maximum radial turbulence to spread outward from the centre of the flow. Figure 404 shows profiles of radial turbulence along the major axis. This figure shows slightly reduced turbulence in the centre of the flow and a more significant reduction at a radial location of $r = 0.5R$ for configurations with mixing tubes. This is a result of the vortex breakdown bubble moving upstream inside the mixing tube. Moving further outward from the centreline, the configurations with mixing tubes show increased turbulence. This behaviour is the result of the jet penetrating further downstream into the flow. Along the minor axis (fig. 405) a mixing tube length of $L_{mt} = 0.5''$ shows similar turbulence levels in the centre of the flow, but greatly increased levels in the region of the jet, which penetrates further downstream for this configuration. Longer mixing tubes show reduced radial turbulence relative to the baseline, as the region of highest turbulence forms inside the mixing tube. Along the major axis, the radial turbulence level is seen to be 1.1–1.5 times greater than the axial component for the baseline case. For the configurations with

the mixing tubes, the radial and axial turbulence components have similar magnitudes away from the centre of the flow. Oscillation of the turbulent core creates higher radial turbulence in the centre of the flow, and here the turbulence is very anisotropic. Along the minor axis, the jet penetrates further into the flow, and as a result the axial turbulence component is greater than the radial component away from the centre of the flow. The radial turbulence is greatest in the centre of the flow, however, due to radial oscillation of the turbulent core.

Contours of tangential turbulence are shown in figures 408 and 409. Increases in mixing tube length cause an immediate reduction in the tangential turbulence level along the major axis (fig. 408), as the region of highest turbulence forms inside the mixing tube. Along the minor axis a similar trend is seen, except that the reduction in turbulence level is not as great. Profiles of tangential turbulence along the major axis are shown in figure 410. This plot shows similar levels of turbulence across the entire flow field for all configurations, except for $L_{mt} = 0.5''$, which shows increased turbulence. This is because although the turbulence level was comparatively low for this configuration, it extends further downstream than for the baseline configuration. Profiles of tangential turbulence along the minor axis (fig. 411) showed similar levels of turbulence in the centre of the flow for all configurations with the mixing tube, and slightly increased turbulence near the wall for a mixing tube length of $L_{mt} = 0.5''$. Figure 412 shows that in the centre of the flow, the anisotropy of the tangential turbulence component relative to the axial component is greater for the configurations with mixing tubes than for the baseline. Further away from the centreline, the anisotropy was greatest for the baseline swirler. Along the minor axis, configurations with longer mixing

tubes showed greatest anisotropy. Shorter mixing tubes showed trends similar to the baseline configuration.

Introducing the mixing tube downstream of the elliptic outlet was seen to have a very significant effect on the flow field of the elliptic burner. Even short mixing tube lengths were observed to strongly affect the flow field of this swirler and cause it to take on a structure resembling that of the circular swirlers. The double helix structure of the flow was not observed for any configurations with a mixing tube. Comparison of axial velocity fields along the two axes of the swirler showed, however, that in spite of the transition of the flow toward that of a circular swirler, the flow field was still asymmetric. Comparison of contours of radial velocity indicated that the regions of alternate converging and diverging flow disappeared with the introduction of the mixing tube. This indicates that the axis-switching is disrupted and that the performance of the elliptic swirler would be slightly degraded by introduction of the mixing tube.

Table 3: Summary of baseline burner parameters

Swirler	S_N	dP	C_D	Comments
XEVa	0.64	6.4%	0.35	hollow-cone breakdown
XEVe	0.23	2.2%	0.61	no vortex breakdown
XEVd	1.17	9.0%	0.29	recirculating core present
XEVb	0.55	3.3%	0.50	hollow-cone breakdown
XEVe-6	0.78	6.4%	0.35	complex asymmetric flow structure

6.6 Comparison of ALSTOM burner to the XEVa and XEVe-6

While there are significant differences in the geometry of the standard burner tested in the ALSTOM Power Ltd. water channel and the XEVa, there are enough similarities in the

design to expect some similarities in the flow structure.

Figure 414 compares axial velocity profiles between the two swirlers at a distance of $y = 0.17D_{sw}$ from the sudden expansion. This figure shows very close agreement between the two swirlers in the region of the vortex breakdown bubble. The bifurcated jet of the XEVa shows higher spreading than the ALSTOM burner and a reduced maximum velocity. Further downstream at $y = 0.29D_{sw}$ (fig. 415), reasonable agreement is also seen. At this location, the XEVa shows a reduced backflow velocity in the centre of the flow. The jet of the XEVa shows a similar trend in that it is further from the centreline than the jet of the ALSTOM burner and has a reduced velocity. Figure 416 shows a comparison of the velocity profiles at $y = 0.50D_{sw}$ from the sudden expansion. Greater differences are seen at this location as the vortex breakdown bubble of the XEVa begins to take on the hollow cone structure. The jet of the XEVa is still further out radially in the flow, but its velocity has not decayed as rapidly as for the ALSTOM burner.

Figure 417 compares profiles of tangential between the two swirlers $y = 0.17D_{sw}$ downstream of the swirler outlet. A similar velocity magnitude is seen between the two profiles, however the shape of the profiles are different. The ALSTOM experimental burner shows a distinct peak in the tangential velocity while the XEVa exhibits a more constant velocity profile across the width of the combustion chamber. The region of lower tangential velocity in the profile of the XEVa is likely a result of spurious vectors and should be continuous with surrounding data. Further downstream at $y = 0.29D_{sw}$ and $y = 0.50D_{sw}$ (figs. 418 and 418, the same trend is observed and it is also seen that the tangential velocity for the XEVa does

not decay as quickly moving in the downstream direction.

Figure 420 shows profiles of axial turbulence for the ALSTOM burner and the XEVa. This figure shows that the maximum axial turbulence is in the region of the jet for both burners, but that the flow from the XEVa is significantly greater across the entire flow. The same trend is seen moving further downstream (figs. 421 and 422).

Reasonable agreement in the velocity magnitudes and the overall structure of the flow is seen for these two burners. The geometry of the burners and the operating conditions under which they were tested are quite different and account for these differences. First, the XEVa was tested under conditions of atmospheric pressure and temperature at the sudden expansion. Because of the design of ALSTOM's water channel test-rig, however, the ALSTOM burner was tested under a column of water that raised the pressure at its outlet by as much as 15% above atmospheric pressure. Differences in geometry between the two burners also had a significant effect on the vortex breakdown bubble. The breakdown bubble of the XEVa had a hollow-cone shape and stabilized with its upstream end near the outlet of the swirler. The vortex breakdown of the ALSTOM burner had a solid egg shape and was seen to stabilize inside the burner cone, likely as a result of the increased pressure at the burner exit.

Figure 423 shows profiles of axial velocity for the XEVe-6 and the elliptic ALSTOM burner along the major axes. Less agreement between these two swirlers is expected because of the more significant geometric differences between the two. While the XEVa and XEVe-6 swirlers had the same outlet area, the outlet area of the elliptic ALSTOM burner was

reduced by 70% relative to the standard burner. One of the main differences seen in this figure is that the vortex breakdown bubble of the ALSTOM burner is far downstream of the burner outlet. The upstream tip of the breakdown bubble for the XEVe-6 stabilized near the swirler outlet. The jet exiting the ALSTOM swirler is also much stronger as a result of the acceleration of the flow at the swirler outlet. The XEVe-6 showed very high spreading at the swirler outlet along the major axis and low penetration of the jet. Figure 424 shows axial velocity profiles for the two elliptic burners along the minor axis. This figure shows rapid deceleration of the jet for the ALSTOM burner and large spreading. The XEVe-6 showed reduced spreading along the minor axis and increased penetration of the jet, resulting in a jet that does not decay as quickly moving in the downstream direction.

While both the elliptic ALSTOM burner and the XEVe-6 showed asymmetric behaviour indicative of axis switching, there was little agreement between the two swirlers as a result of their very different geometries. The reduced outlet area of the ALSTOM burner caused the vortex breakdown bubble to stabilize completely downstream of the burner outlet, while the breakdown for the XEVe-6 stabilized in a position similar to the XEVa. Other significant differences were the increased pressure at the outlet of the ALSTOM burner and also a difference in aspect ratio of the outlets. The ALSTOM burner had an eccentricity of $e = 0.7$ and the XEVe-6 had an eccentricity of $e = 0.6$.

Figure 65: Typical particle image for the XEVa

Figure 66: Three dimensional velocity vector field for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 67: Instantaneous three dimensional velocity vector fields for the XEVA, $Re=100,000$, $\phi = 0^\circ$

Figure 68: Three dimensional velocity vector field for the XEVA as viewed from the bottom of the combustion chamber, $Re=100,000$, $\phi = 0^\circ$

Figure 69: Contours of axial velocity for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 70: Instantaneous contours of axial velocity for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 71: Evolution of the axial velocity of the XEVa moving downstream, $Re=100,000$, $\phi = 0^\circ$

Figure 72: Contours of radial velocity for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 73: Instantaneous contours of radial velocity for the XEVA, $Re=100,000$, $\phi = 0^\circ$

Figure 74: Contours of tangential velocity for the XEVA, $Re=100,000$, $\phi = 0^\circ$

Figure 75: Instantaneous contours of tangential velocity for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 76: Evolution of the tangential velocity of the XEVa moving downstream, $Re=100,000$, $\phi = 0^\circ$

Figure 77: Contours of total turbulence for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 78: Profiles of total turbulence for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 79: Contours of axial turbulence for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 80: Contours of radial turbulence for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 81: Contours of tangential turbulence for the XEVa, $Re=100,000$, $\phi = 0^\circ$

Figure 82: Profiles of turbulence components for the XEVa, $Re=100,000$, $y = 0.13D_{sw}$, $\phi = 0^\circ$

Figure 83: Profiles of turbulence components for the XEVa, $Re=100,000$, $y = 0.38D_{sw}$, $\phi = 0^\circ$

Figure 84: Profiles of turbulence components for the XEVa, $Re=100,000$, $y = 0.64D_{sw}$, $\phi = 0^\circ$

Figure 85: Profiles of turbulence components for the XEVa, $Re=100,000$, $y = 1.15D_{sw}$, $\phi = 0^\circ$

Figure 86: Three dimensional velocity vector fields for the XEVa burner, baseline condition, coloured by vorticity, $Re=100,000$

Figure 87: Contours of axial velocity for the XEVA burner, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 88: Comparison of axial velocity profiles of the XEVA at various azimuthal locations, $Re=100,000$, $y = 0.38D_{sw}$

Figure 89: Comparison of axial velocity profiles of the XEVA at various azimuthal locations, $Re=100,000$, $y = 1.92D_{sw}$

Figure 90: Contours of radial velocity for the XEVA burner at various azimuthal locations, baseline condition, $Re=100,000$

Figure 91: Contours of tangential velocity for the XEVA burner at various azimuthal locations, baseline condition, $Re=100,000$

Figure 92: Comparison of tangential velocity profiles of the XEVA at various azimuthal locations, $Re=100,000$, $y = 1.92D_{sw}$

Figure 93: Comparison of velocity vector fields for the different swirlers viewed normal to laser sheet, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 94: Comparison of velocity vector fields for the different swirlers viewed from bottom of combustion chamber, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 95: Comparison of axial velocity contours for different swirlers, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 96: Comparison of axial velocity profiles of the different swirlers, $Re=100,000$, $y = 0.38D_{sw}$, $\phi = 0^\circ$

Figure 97: Comparison of axial velocity profiles of the different swirlers, $Re=100,000$, $y = 0.77D_{sw}$, $\phi = 0^\circ$

Figure 98: Comparison of axial velocity profiles of the different swirlers, $Re=100,000$, $y = 1.28D_{sw}$, $\phi = 0^\circ$

Figure 99: Comparison of axial velocity profiles of the different swirlers, $Re=100,000$, $y = 1.92D_{sw}$, $\phi = 0^\circ$

Figure 100: Comparison of axial velocity profiles vs. downstream displacement for the different swirlers, $Re=100,000$

Figure 101: Comparison of radial velocity contours for the different swirlers, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 102: Comparison of tangential velocity contours for the different swirlers, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 103: Comparison of tangential velocity profiles of the different swirlers, $Re=100,000$, $y = 0.38D_{sw}$, $\phi = 0^\circ$

Figure 104: Comparison of tangential velocity profiles of the different swirlers, $Re=100,000$, $y = 0.77D_{sw}$, $\phi = 0^\circ$

Figure 105: Comparison of tangential velocity profiles of the different swirlers, $Re=100,000$, $y = 1.28D_{sw}$, $\phi = 0^\circ$

Figure 106: Comparison of tangential velocity profiles of the different swirlers, $Re=100,000$, $y = 1.92D_{sw}$, $\phi = 0^\circ$

Figure 107: Comparison of total turbulence contours for the different swirlers, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 108: Profiles of total turbulence for the different swirlers, baseline condition, $Re=100,000$, $y = 0.77D_{sw}$, $\phi = 0^\circ$

Figure 109: Profiles of total turbulence vs. downstream displacement for the different swirlers, baseline condition, $Re=100,000$

Figure 110: Comparison of axial turbulence contours for the different swirlers, baseline condition, $Re=100,000$, $\phi = 0^\circ$

Figure 111: Profiles of axial turbulence for the different swirlers, baseline condition, $Re=100,000$, $y = 0.77D_{sw}$, $\phi = 0^\circ$

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7 Results of numerical simulations

A smaller part of this project was to attempt to develop a numerical model that gave results matching the experimentation. While detailed measurements are possible in the region of the flow downstream of the swirler outlet, the flow inside the swirler cone is very difficult to measure. For this reason, numerical simulations are preferred to investigate the flow in this region. Once a good numerical model has been developed, it allows investigation of other swirler models without having to construct a physical model. Computations also allow prediction of mixing capabilities of the different swirler configurations.

Because of the three-dimensional complexity of the flow inside and downstream of the swirler, this is a very difficult model to simulate. The complex nature of the recirculating flow and the number of shear layers created in the flow are very difficult to accurately model.

7.1 Comparison of experimentation to CFD

Simulations were conducted in FLUENT 5.5 and 6.0 as described in section 4. Because of the time line of the project, the simulations were performed before experimental data was available for verification of the model.

Figure 425 shows a comparison of the numerical simulations to the experimental results for the XEVa. Since the velocity data shown in these figures was recorded in cylindrical coordinates, contours of radial and tangential velocity do not show opposite colour on opposite sides of the swirler axis. That is, in contours of radial velocity, red represents regions propagating away from the centreline and blue represents flow propagating towards the swirler

axis. In contours of tangential velocity blue shows flow propagating clockwise about the centreline and red represents flow propagating counterclockwise about the centreline.

Contours of axial velocity show that the CFD predicts the basic structure of the flow, although there are significant differences. Experimentation showed that the vortex breakdown bubble stabilizes with its upstream end at the swirler outlet. Computations, however, predicted that the breakdown would stabilize inside the swirler cone with its upstream tip almost touching the apex of the swirler cone. Computations failed to predict the hollow-cone structure of the vortex breakdown bubble and instead predicted a solid breakdown without an annular region.

Contours of radial velocity also show that the basic flow structure is predicted, but with some differences. CFD predicts a higher spreading of the jet as it leaves the swirler. Contours of tangential velocity show reasonable agreement. Tangential velocity is seen to be highest in the jet, and the tangential velocity downstream of the outlet is seen to be highest along the axis of the swirler.

Figure 426 shows a comparison of axial velocity between experimental data and computations at a distance of $y = 0.38D_{sw}$ downstream of the swirler outlet. This close to the outlet, very good agreement is seen between the two profiles. The magnitude of the velocity is nearly identical across the entire flow field. The location of the jet was predicted to form slightly outward from its actual location, and the velocity gradient along the inner shear layer was predicted to be lower than was actually measured. In the centre of the flow, a similar velocity magnitude was seen between experimentation and computation, but the hollow

cone structure was not predicted. Further downstream at $y = 0.77D_{sw}$ (fig. 427), there was less agreement between experimentation and simulation. Both showed a similar backflow velocity in the centre of the flow, but the hollow-cone structure was not predicted. The jet was predicted to be further away from the centreline than it was found to be in experiments, and its velocity was also lower. Figure 428 shows velocity axial velocity profiles at $y = 1.92D_{sw}$ from the swirler outlet. This figure shows little agreement between the two profiles. The backflow velocity is of similar magnitude between the two cases, however experimentation showed that the backflow existed as a hollow-cone structure, while computation predicted the backflow in the centre of the flowfield. It is also seen from this plot that in spite of the boundary conditions, FLUENT did not enforce the no-slip condition along the combustion chamber wall.

Figure 429 shows a comparison of tangential velocity profiles at $y = 0.38D_{sw}$ from the sudden expansion. Poor agreement is seen in this plot. Experimentation showed the highest velocity in the region of the jet, while simulation predicted it to exist further outward from the centreline. Here again, it is seen that the no-slip condition was not enforced by FLUENT. Further downstream at $y = 0.77D_{sw}$ and $y = 1.92D_{sw}$ (figs. 430 and 431) the agreement between experimentation and simulation is very poor. Experimentation showed highest velocity near the axis of the swirler and a linear decrease moving towards the combustion chamber wall. Simulation showed a nearly constant tangential velocity profile that decreases to zero along the axis of the flow, but did not go to zero at the combustion chamber wall.

Figure 432 shows comparison of experimentation and simulations for the XEVc. For

this swirler, there is little agreement between the two sets of plots. While experimentation showed that the flow from the XEVc did not break down and recirculate in its centre, the simulations predicted formation of a very weak vortex breakdown bubble downstream of the swirler outlet. Comparing radial velocity contours, it is seen that simulations predict very wide spreading of the jet as it passes around the vortex breakdown bubble. Experimentation showed very weak spreading of the jet at the swirler outlet. Contours of tangential velocity show better agreement in predicting a weak but coherent swirl extending downstream of the swirler outlet.

Profiles of axial velocity at $y = 0.38D_{sw}$ from the sudden expansion show poor agreement between experiments and simulations. Figure 433 shows that simulations predicted a vortex breakdown with a weak backflow velocity in the centre of the flow. Experiments showed that this did not happen, but rather that the swirling jet exited the swirler without recirculating. Further downstream at $y = 0.77D_{sw}$ (fig. 434), experimentation showed that the single jet had the same structure as further upstream and had slowed only slightly. Simulations predicted a very weak backflow in the centre of the jet, and very wide spreading and deceleration of the jet. At $y = 1.92D_{sw}$ (fig. 435) experimentation showed that the flow structure was similar to that observed further upstream but with greater slowing of the jet. Simulation predicted greatest axial velocity along the wall of the combustion chamber and a nearly zero velocity in the centre of the flow at the downstream tip of the vortex breakdown bubble. These simulations also showed that the no-slip condition was not enforced along the combustion chamber wall.

Figure 436 shows comparison of tangential velocity profiles at $y = 0.38D_{sw}$ from the sudden expansion. Poor agreement is seen in this figure as experimentation showed a high velocity in the centre of the flow, in the region of the single swirling jet. Simulation predicted a much weaker tangential velocity with a maximum velocity in the region of the bifurcated jet. The velocity profile for simulation showed little decay moving outwards from the centre of the flow, and did not go to zero at the combustion chamber wall. Further downstream at $y = 0.77D_{sw}$ from the outlet (fig. 437), poor agreement was also observed. Experimentation showed a much higher velocity, and simulation predicted a flat velocity profile that did not go to zero at the combustion chamber wall. At $y = 1.92D_{sw}$ from the outlet, poor agreement was seen and the tangential velocity profiles did not decay to zero at the combustion chamber wall.

Figures 439 and 440 show a comparison of experimental results to numerical simulations for the XEVe-6 along the major and minor axes respectively. Axial velocity contours show reasonable agreement along the minor axis, but poor agreement along the major axis. Experiments showed that the jet along the major axis spread immediately upon entering the combustion chamber and did not penetrate far downstream into the flow. Computations predicted penetration of the jet reasonably far into the flow, and then converging into the centre of the flow at approximately $y = 0.5D_{sw}$ downstream of the outlet. Along the major axis the jet was predicted to show little spreading in the region of the sudden expansion and good penetration into the flow. While the predicted behaviour is indicative of the axis-switching process, it shows little resemblance to the actual flow. Radial velocity contours

showed little agreement between experiments and simulations. Simulations predicted spreading in the region of the jet, but the alternate patterns of converging and diverging flow were not predicted. The tangential velocity in the downstream region was predicted to be much weaker than was actually observed.

Figure 441 shows little agreement along the major axis at a distance of $y = 0.38D_{sw}$ from the sudden expansion. The shear inner layer is predicted to exist in the correct location, but the velocity of the jet is overpredicted and the strength of the backflow is underpredicted. Velocity profiles along the minor axis (fig. 442) show little better agreement. The velocity of the jet is similar, but the strength of the backflow is underpredicted. Further downstream at $y = 0.77D_{sw}$ (figs. 443 and 444), there is better agreement in the backflow region. The position of the jet shows agreement along both axes, but its velocity is overpredicted along the major axis. Very poor agreement is seen further downstream at $y = 1.92D_{sw}$ along either axis (figs. 445 and 446). Experimentation showed that the highest velocity was in the centre of the combustion chamber as the flow propagated towards the outlet. Simulations showed zero velocity along the axis at this location and a higher velocity moving outwards. Once again, the no-slip condition was not enforced.

Tangential velocity profiles showed little agreement near the swirler outlet (figs. 447 and 450). Neither the maximum velocity magnitude nor its overall shape were predicted well. Further downstream at $y = 0.77D_{sw}$ and $y = 1.92D_{sw}$ even less agreement was seen.

Simulations performed using the scheme described in chapter 4 were seen to give very poor resemblance to experimentation. There are two factors responsible for this poor agreement.

The first is the treatment of the boundary conditions at the wall. While the wall boundary conditions in FLUENT were set to the no-slip condition, it is clear from all of the velocity profiles that this was not enforced. This had a significant effect on the flow near the wall. It is likely that a finer mesh is necessary in the region of the wall in order to resolve the boundary layer properly.

The other main difference between experimentation and computation that may account for the differences seen is the turbulence model. Experiments showed that the turbulence for these swirlers was very anisotropic. Most simulations showed increased radial turbulence along the axis of the flow and increased axial turbulence further out from the centreline. Most measurements showed that the tangential turbulence level was at least two times higher than the axial component at all locations in the flow. The $k-\epsilon$ turbulence model is an isotropic model which assumes that the turbulence level is the same in all directions. In order to obtain a better result, an anisotropic model, such as the Reynolds stress model, would be required. In order to obtain results that give better agreement with experimentation, the above mentioned difficulties must be resolved.

Figure 425: Comparison of experimental and computational results from the XEVA, $Re=100,000$, major axis

Figure 426: Comparison of axial velocity profiles for experimental and computational results from the XEva, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 427: Comparison of axial velocity profiles for experimental and computational results from the XEva, $Re=100,000$, $y = 0.77D_{sw}$, major axis

Figure 428: Comparison of axial velocity profiles for experimental and computational results from the XEVa, $Re=100,000$, $y = 1.92D_{sw}$, major axis

Figure 429: Comparison of tangential velocity profiles for experimental and computational results from the XEVa, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 430: Comparison of tangential velocity profiles for experimental and computational results from the XEVA, $Re=100,000$, $y = 0.77D_{sw}$, major axis

Figure 431: Comparison of tangential velocity profiles for experimental and computational results from the XEVA, $Re=100,000$, $y = 1.92D_{sw}$, major axis

Figure 432: Comparison of experimental and computational results from the XEVc, $Re=100,000$, major axis

Figure 433: Comparison of axial velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 434: Comparison of axial velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 0.77D_{sw}$, major axis

Figure 435: Comparison of axial velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 1.92D_{sw}$, major axis

Figure 436: Comparison of tangential velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 437: Comparison of tangential velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 0.77D_{sw}$, major axis

Figure 438: Comparison of tangential velocity profiles for experimental and computational results from the XEVc, $Re=100,000$, $y = 1.92D_{sw}$, major axis

Figure 439: Comparison of experimental and computational results from the XEVe-6, $Re=100,000$, major axis

Figure 440: Comparison of experimental and computational results from the XEVe-6, $Re=100,000$, minor axis

Figure 441: Comparison of axial velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 442: Comparison of axial velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.38D_{sw}$, minor axis

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Figure 446: Comparison of axial velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 1.92D_{sw}$, minor axis

Figure 447: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.38D_{sw}$, major axis

Figure 448: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.38D_{sw}$, minor axis

Figure 449: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.77D_{sw}$, major axis

Figure 450: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 0.77D_{sw}$, minor axis

Figure 451: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 1.92D_{sw}$, major axis

Figure 452: Comparison of tangential velocity profiles for experimental and computational results from the XEVe-6, $Re=100,000$, $y = 1.92D_{sw}$, minor axis

8 Conclusions

It was found in this project that even very small changes to the geometry of a swirl stabilized gas turbine burner can have a very large effect on the flowfield. These changes affect the combustion process and can have a significant effect on its stability and efficiency.

In the preliminary study at ALSTOM Power Ltd, two instability modes were identified: a natural helical mode resulting from the swirling of the flow, and a forced axisymmetric mode that was excited by pressure pulsations. The axisymmetric mode was of greater interest, and was characterized by drastic axial oscillation of the vortex breakdown bubble combined with shedding of axisymmetric ring vortices from the swirler outlet. The elliptic burner caused acceleration of the flow due its reduced outlet area, and therefore a higher vortex shedding frequency. This burner was observed to stabilize oscillation of the vortex breakdown bubble due to the higher total pressure inside the burner cone resulting from the acceleration of the flow. The long lance with its downstream tip positioned approximately at the upstream tip of the vortex breakdown bubble was observed to physically impede motion of the vortex breakdown bubble. It was seen in both the current tests and in combustion tests performed with the long lance in a separate project that the strength of the axisymmetric instability was greatly reduced as a result of anchoring the vortex breakdown bubble.[21]

Velocity measurements at ALSTOM Power Ltd. showed that the bifurcated jet exiting the burner widened and slowed as it moved downstream, and that the vortex breakdown bubble stabilized partially inside the burner cone. Activating the forcing mechanism to excite the axisymmetric instability caused only slight changes in the structure of the flow,

but caused a significant increase in the turbulence level in the centre of the flow.

The non-circular outlet of the elliptic burner was seen to have the greatest effect on the flow structure, as the vortex breakdown bubble stabilized downstream of the burner outlet. Widening of the jet in the downstream direction was observed along both axes, but it was found that the spreading of the jet was greatest along the minor axis. This is an indication of axis switching. It is expected that the combined effects of the reduced oscillation of the vortex breakdown bubble and the apparent axis switching of the flow would provide a significant improvement in the stability of a combustion process. The complex three-dimensional evolution of vortices undergoing axis-switching would result in failure of the Rayleigh criterion to be met as the strength of the period heat release is reduced.[13, 14]

The swirlers tested in the Aerospace Laboratory at the University of Cincinnati were designed to reflect the main design features of the experimental burner tested at ALSTOM Power Ltd. The basic flow structure for the baseline burner was characterized by a diverging bifurcated jet exiting the swirler and recirculating on the outside of the flow at the sudden expansion. The entire flow had a strong clockwise swirl centred about the axis of the swirler and underwent vortex breakdown creating a large recirculation zone in the centre of the flow. The vortex breakdown bubble was observed to stabilize with its upstream end near the swirler outlet. It had a hollow-cone structure for most circular configurations with a stagnation point in its centre, and a downstream moving jet emanating from this point. Measurements conducted at various azimuthal locations showed that the flow from each circular swirler was essentially axisymmetric. The flow from the XEVa displayed a similar

structure to the full size burner model tested at ALTOM Power Ltd. Differences between the two flows are explained by the fact that the full size burner was tested with different boundary conditions at its outlet, namely an increased pressure due to the column of water above its outlet. The full scale burner tested in the water channel was also a different design from the scale model burners, and had a flow structure that was not axisymmetric.

Increasing the slot area while leaving all other swirler parameters unchanged was observed to reduce the swirl of the flow. In the current tests, the tangential velocity was reduced to such a degree that the flow was unable to breakdown, and the flow exited the burner as a single slow moving jet. Tests conducted on the XEVc show quite clearly that it would perform poorly in combustion tests. While a recirculation zone was created at the sudden expansion, none was created in the centre of the flow and this configuration would be incapable of stably anchoring the flame front in the combustion chamber. The optimal slot size would be greater than that of the XEVa but less than that of the XEVc. This would provide a strong vortex breakdown necessary to stabilize the combustion process but would reduce the pressure loss incurred by the swirler.

Widening the swirler cone angle with all other parameters unchanged was observed to increase the swirl number and strengthen the vortex breakdown. While the breakdown bubble maintained its basic hollow-cone shape, a strong recirculating core formed that entrained air into the breakdown bubble from outside of the combustion chamber. Tests indicated that the XEVd would also perform poorly in combustion tests. This swirler generated a vortex breakdown bubble that was too strong, and would have a tendency to draw combustion

products from far downstream back into the combustion zone.

Increasing both the slot area and the cone angle introduced two conflicting effects to the flow. The increased slot area reduced the swirl and weakened the breakdown while the widened cone angle increased swirl and strengthened the breakdown. The net effect was a slight reduction in the strength of the breakdown. The vortex breakdown bubble maintained its basic hollow-cone shape, although it was smaller and its annular area showed less spreading. Of all four circular swirlers tested in the baseline configuration, it is expected that the XEVb would perform best in actual combustion tests. It generated a sufficiently strong vortex breakdown in the centre of the flow, necessary for stable combustion and incurred only a moderate pressure loss.

The long lance had a significant effect on the flow of the circular swirlers. In general, short to moderate lance lengths were seen to increase the strength of the vortex breakdown. For the XEVa, short lances induced formation of the central recirculating core, and for the XEVc, they caused the flow to undergo vortex breakdown. Longer lances were seen to force the vortex breakdown bubble downstream and cause it to form in an unstable configuration. In combustion tests, the length of the lance would have a significant effect on the stability of the combustion process. Short lances could degrade the combustion process by causing the flow to break down too strongly, and long lances could induce oscillation of an unstable vortex breakdown bubble. It is expected that there would be an optimal lance position that would provide very stable combustion.

Introducing a mixing tube downstream of the swirler exit was also seen to have a signif-

icant effect. In general, a mixing tube length of $L_{mt} = 0''$ showed greatest spreading of the bifurcated jet as a result of the diffuser effect of the transition piece. Longer mixing tubes caused straightening of the jet and movement of the vortex breakdown bubble upstream of the sudden expansion. Turbulence data showed that the region of highest turbulence was inside of the mixing tube which would provide very good mixing of fuel and air. It was also seen that mixing tubes caused the vortex breakdown bubble to move upstream of the sudden expansion and stabilize inside the tube. This is undesirable, since the flame would most likely stabilize inside the mixing tube as well and shorten the life of the burner, especially in high pressure combustion. It is expected that using a smaller swirler with a smaller diameter mixing tube in the same combustion chamber and at the same mass flow rate would force the breakdown bubble downstream of the sudden expansion and result in better combustion.

The elliptic swirler had the greatest effect on the flow. Its flowfield was very asymmetric in the baseline condition. Along the major axis, the bifurcated jet had a very high swirl number and spreading but low axial penetration. Along the minor axis, the opposite was seen as the jet penetrated far into the flow but had low swirl and little spreading. Comparison of velocity contours at different azimuthal locations indicated that the flow was undergoing axis-switching. The vortex breakdown bubble of the elliptic burner did not have the hollow-cone shape characteristic of the circular swirlers, but rather had a short egg-shaped structure. The flow of the elliptic burner showed other significant differences from those of the circular swirlers as secondary vortices were observed downstream of the vortex breakdown bubble, and alternating regions of converging and diverging flow were observed moving

in the downstream direction. The flow field elliptic burner showed little resemblance to the flow field of the elliptic burner tested at ALSTOM Power Ltd. This was a result of not only the different boundary conditions that the swirlers were tested under, but was also a result of the very different design of the two swirlers. It is expected that the XEVe-6 would perform very well in combustion tests. The vortex breakdown bubble is sufficiently strong to stabilize combustion in the centre of the flow, and the apparent axis switching would prevent fulfillment of the Rayleigh criterion.[13, 14]

The long lance had only a minimal effect on the structure of the flowfield for the elliptic swirler. The asymmetric structure of the flow field was a result of the shape of the outlet of the swirler, and a small obstruction in the centre of the flow was unable to significantly alter this flow. It is expected that the combination of the elliptic burner and the correct lance length would provide very stable combustion. Since the lance is unable to disrupt the flow field significantly, the Rayleigh criterion would not be met and the lance would also provide physical stabilization of the vortex breakdown bubble.

The mixing tube had a significant effect on the flowfield of the elliptic swirler. The vortex breakdown transitioned to a hollow-cone structure with the introduction of a mixing tube and the entire flow started to become increasingly symmetric with increasing tube length. The alternating patterns of converging and diverging flow disappeared with the introduction of a mixing tube and it appeared that the flow no longer underwent axis switching. It is expected that the introduction of the mixing tube would destabilize the combustion process of the elliptic swirler and that an elliptic mixing tube would provide better performance.

The numerical model used on the swirlers gave poor agreement with experimentation. The flow fields of the circular swirlers were seen to be very complex with completely three-dimensional flow, the formation of an inner and an outer recirculation zone, and the formation of many different shear layers. As a result, the flow fields of these swirlers were extremely difficult to simulate. The flow field of the elliptic swirler was even more complex than those of the circular swirlers, making accurate prediction even more difficult. One of the main problems with the numerical simulations is that the k - ϵ turbulence model assumes that the turbulence level is the same in all directions in the flow. Measurements showed that the turbulence for all swirler configurations was actually very anisotropic. The other problem with these simulations was that the no-slip condition was not enforced along the combustion chamber walls.

Future tests in this project should focus on the XEVa, XEVb and XEVe-6 swirlers, since measurements indicate that they would give the best performance in combustion tests. While averaged PIV measurements showed the time-averaged structure of the flow very well, phase-locked PIV measurements would be useful to visualize the vortex shedding process and to identify instability modes. It is also recommended that PIV measurements be made on the jet cross section for the elliptic swirler in order to further explore the complex structure of the flow. A further step in this project would be to inject a trace gas through the internal passages of the swirler and to measure its concentration downstream of the sudden expansion to evaluate the mixing capabilities of the different configurations. Finally, it is recommended that combustion tests be considered for the XEVa, XEVb and XEVe-6 swirlers.

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A Drawings of test equipment

University of Cincinnati	Frequency Spacer Assembly	Date: 09/12/00		Scale 1:2
		Drawer: G. Li		Part No.: 007.0

Section B-B

Enlargement 3:1

Section C-C

Enlargement 3:1

University
of
Cincinnati

Rotating
Mounting Plate

Date: 07/23/01

Scale: 1:3

Drawn by: G. Anning

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University of Cincinnati	Tube section #1	Date: 07/23/01	Scale: 1:1
		Drawn by: G. Anning

University of Cincinnati	Tube section #2	Date: 07/23/01	Scale: 1:1
		Drawn by: G. Anning

Material: Aluminum

University of Cincinnati Tube section #3

Date: 07/23/01

Scale: 1:1

Drawn by: G. Anning

University of Cincinnati	Tube section #4	Date: 07/23/01	Scale: 1:1
		Drawn by: G. Anning

University of Cincinnati	Thin spacer	Date: 07/23/01	Scale: 1:2
		Drawn by: G. Anning

Notes:

△ Shall have a sliding fit with the part shown in the enclosed drawing "Rotating Mounting Plate"

University of Cincinnati	Mounting Ring	Date: 08/22/01	Scale: 1:1
		Drawn by: G. Anning	4 pieces

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