EXPERIMENTAL CHARACTERIZATION OF VORTEX STRUCTURE IN
SINUSOIDAL WAVY CHANNELS AND A CASE STUDY FOR FUEL CELL
APPLICATIONS

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ABSTRACT

The High temperature fuel cells (solid oxide & reformed hydrogen fuel cells) present an opportunity for significantly improvements in the energy conversion at many scales. But to compete with current energy sources, cost and durability (lifetime) are important factors. One of the major challenges before it commercialize is the thermal management, an efficient thermal management will significantly improve the life time and reduces the cost of the fuel cell system. Use of sinusoidal wavy channel as an interconnect or bipolar plates which provides the channels for gas streams, will help in improving the thermal management of fuel cells.

In the present work, an experimental study is performed on sinusoidal wavy channels along with a case study for fuel cell applications. Fluid mixing is perhaps an extremely way to enhance the heat and mass transfer in channel and duct flows. A wavy flow channel is one such device that provides core flow mixing by inducing span-wise and stream-wise vortex generation, depending upon the geometry, and promotes the heat and mass transfer enhancement. These flow patterns and swirl or vortex structure are quite complex and not well understood.

Fluid recirculation and its structure in low Reynolds number flows in sinusoidal wavy-plate channel are characterized by flow visualization and laser doppler velocimetry (LDV). The flow channel geometry is effectively two-dimensional (width>>plate spacing) and is described by its waviness aspect ratio $\gamma = (2x$ amplitude $/ pitch)$ and inter-plate spacing ratio $\varepsilon = (spacing / 2x$ amplitude). With increasing flow rates, wall-curvature-induced effects manifest in fluid separation downstream of the wavy-surface peak, its reattachment upstream of the subsequent peak, and the consequent encapsulation
of lateral recirculating cells in the channel-wall concavities. These trough region vortices tend to grow spatially and envelop much of the core flow region as the flow rate and/or plate spacing $\varepsilon$ increases.
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I also thank Dr. Stephen Samms and Jerry Hallmark at Motorola labs for giving me the opportunity to work on Reformed hydrogen fuel cell system (RHFC). Samms, thanks for mentoring me the details of RHFC system. It was pleasure.

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NOMENCLATURE

$A$    amplitude of wall waviness, [mm]

$d_h$  hydraulic diameter ($= 2S$), [mm]

$f$    Fanning friction factor

$H$    Fin height, [mm]

$L$    pitch of fin waviness, [mm]

$Re$   hydraulic-diameter based Reynolds number ($= u_m d_h/\nu = 2Re_S$)

$S$    fin spacing, [mm]

$u, v$ axial and lateral velocity components, [m/s]

$x, y$ Cartesian coordinates

Greek symbols

$\alpha$    flow cross-section aspect ratio ($= S/H$)

$\epsilon$ channel spacing ratio ($= S/2A$)

$\gamma$   channel corrugation ratio ($= 2A/L$)

Subscripts

$i$    at inlet conditions

$m$    mean or average value

$o$    at outlet conditions
Chapter 1

GENERAL INTRODUCTION AND SCOPE OF WORK

1.1 Introduction

Continued rapid expansion of the world’s population and the desire to maintain existing standards of living in developed and developing countries has put and will continue to put tremendous pressures on existing resources and the environment. Energy, both its conversion and use, is essential to this entire process. Thus, an urgent need for evermore efficient, economically viable and environmentally sound energy conversion systems exists and continues to grow. Within this context, fuel cell systems are expected to play a major role. From a Second law of thermodynamics standpoint, their potential for effectively contributing to the urgent need outlined above is great. This is true for fuel cells as stand-alone systems and even more so as systems working in concert with more conventional energy conversion processes. What are remarkable are the relatively low emissions and comparatively high electrical efficiencies. As present, fuel cell technology is entering the stage of commercialization, which is an appropriate moment to try and assess its economic potential in the field of automobiles, power generation, space exploration, marine engines etc. At this stage, four types of fuel cell namely, the polymer electrolyte fuel cell (PEFC), the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC) have been mainly developed.

Among the various fuel cell types, the solid oxide fuel cell (SOFC) carries the highest potential with respect to fuel versatility, longevity, and life cycle costs. Besides tubular, planar-bipolar SOFC types are in a development phase. With a bipolar SOFC higher energy densities per volume and weight, and thus, lower capital costs may be attained. To this aim, however, considerable technical barriers have still to be overcome
namely sealing and electrical interconnection of bipolar SOFC stacks are much more
difficult for the bipolar than for the tubular type. The “ideal SOFC” would combine the
technical simplicity and reliability of tubular SOFCs with the low-cost potential of planar
bipolar SOFCs.

![SOFC Cross stack configuration](image1)

**Fig.1.1 a. SOFC Cross stack configuration**

**Fig.1.1 b. Anode supported SOFC**

A planar SOFC geometry consists of a cermet electrolyte sandwiched between the
porous layers of the anode and cathode, fuel and oxidant/coolant flow ducts, and
interconnector, and a typical schematic is given in Fig. 1.1a. Anode supported SOFC is
one of the different types of SOFC as shown in Fig 1.1b. Furthermore, by considering a
thick anode layer as a supporting structure, a relatively thinner electrolyte layer can be
used. The consequent reduction in ohmic losses also allows the lowering of operating
temperature to 700 – 850°C, which reduces the cost of SOFC stacks and balance of plant.

Most of the current R&D work on SOFCs is centered round the monolithic or
planar stack concepts because such designs are expected to yield high outputs and
efficiencies. One of the most significant improvements is the design of the interconnect
or bipolar plates which, while providing the channels for the gas streams, allow the
passage of high current densities in short parallel paths along the stack and across thin cell plates. As the SOFC is operating at high temperature (500-1200°C), a uniform temperature distribution and cooling of SOFC stack is important. Thermal management of SOFC’s is primarily effected through forced convection of excessive air (oxidant – coolant) flows in the interconnect channels. At present rectangular or square cross-section shape interconnect channels are used in SOFC stack, but the thermal cooling is not uniform which leads to sealing issues. To solve this problem, one of the ways is to use sinusoidal wavy shape channel as interconnect as shown in Fig 1.2 Sinusoidal wavy fins have been used in compact heat exchanger to enhance the heat and mass transfer. A

![Diagram of SOFC stack with interconnect](image)

Fig. 1.2 Sinusoidal wavy shaped Interconnect channels in SOFC

detailed description of compact heat exchangers with wavy fins is described below. But till this point a detailed study of LDV measurements along with flow visualization to examine the spatial variation of the velocity in different planes of the flow through variety of wavy channels has not been done, which is necessary for optimizing the configuration of wavy channels. In the present work an experimental study is performed
to characterize the vortex structure in a sinusoidal wavy channel, along with a case study for fuel cell applications.

1.2 Introduction to Compact Heat Exchanger

In forced-convection heat transfer between a gas and a liquid, the heat transfer coefficient of the gas is significantly low as compared to that of the liquid. One of the ways to increase the heat transfer coefficient and increased effective heat transfer area is to use of specially configured surfaces (such as fins). For heat transfer between gases, the total surface area of heat exchanger may be 10 times larger than that of liquid-to-liquid heat exchangers in which the total heat transfer rate is comparable. In this case especially, the use of extended surfaces can substantially reduce the size of heat exchanger. These considerations have led to the development of heat exchangers with large surface area density that accommodates enhanced heat transfer rates. Such heat exchangers are referred to as “compact heat exchangers.” In general, the ratio of total heat transfer surface area over total volume for a compact heat exchanger is greater than 700m²/m³.

Compact heat exchangers can be classified as two main types: plate types or primary surface heat exchangers (such as plate heat exchanger) Fig 1.3, and plate-fin type or secondary surface heat exchanger (such as plate-fin heat exchanger) Fig 1.4. The hydraulic diameters for most compact heat exchangers are very small and often located in the range of 1 mm to 10 mm. In industrial applications, the flows are often characterized by laminar or low Reynolds number flow. Some advantages are observed in compact heat exchangers compared to the traditional shell-and-tube heat exchanger, such as high thermo-hydraulic performance, small size and compact volume (high ratio of surface area to volume). These advantages make compact heat exchangers very attractive in various industrial applications. Some examples of such enhanced surface compact cores include
offset-strip fins, louvered fins, perorated fins, and corrugated or wavy fins as seen fig 1.5.

Because of the smaller hydraulic diameter fluid flows through such inter-fin passages.
are often laminar or low Reynolds number flows in nature. To be effective, the enhancement technique must be applicable to the low-Reynolds-number regime, and is based on the following the two basic concepts:

1. Special channel shapes, such as the wavy channels in current study, which provide mixing due to secondary flows due periodic boundary layer modulation, separation or disruption.
2. Repeated disruption and growth of boundary layers with bluff-body downstream wake generation. This concept is employed in the offset-strip fin, louvered fin, and perforated fin.

Of these, wavy fins are particularly attractive for their simplicity of manufacture, potential for enhanced thermal-hydraulic performance, and ease of usage in both plate-fin and tube-fin type exchangers. The wavy-fin surfaces are also high-performance surfaces comparable to louvered and strip fin surfaces, in which the fin surface waviness causes the flow direction to change periodically. Consequently, the boundary layer separates and reattaches periodically around the trough regions to promote enhanced heat transfer; increased pressure drop penalty is also accompanied. At high flow rates, swirl flows made up of counter-rotating vortices are observed in the main flow direction.

1.3 Literature review of Flow visualization in Wavy channels

Extended or finned surfaces are widely used in compact heat exchangers to enhance heat transfer and reduce their size [Kays, Manglik and Webb]. Geometrically modified fins are often incorporated which not only increase the surface area density of the exchanger but also improve the convection heat transfer coefficient. Some examples include offset-strip fins, louvered fins, perorated fins, and corrugated or wavy fins [Kays, Manglik, Webb, and Shah]. Of these, wavy fins are particularly attractive for their simplicity of manufacture, potential for enhanced thermal-hydraulic performance, and ease of usage in both plate-fin and tube-fin type exchangers.

The earliest repository of experimental data, though rather limited in geometry range and flow conditions, the classical Kays and London sourcebook, which only lists f and j data for a flow wavy-fin cores. Some of the earliest attempts at characterizing the flow behavior and associated heat/mass transfer enhancement mechanisms were
restricted to turbulent flows. Most notably, Sparrow and co-workers have considered plate channels with sharp triangular corrugations. Using naphthalene sublimation technique they found significant mass/heat transfer enhancement. Much of the laminar or low Reynolds number flow (Re < 2000) work has been theoretical. Computational and simulations of flow and heat transfer in channels with sinusoidal as well as sharp and rounded-edged triangular waviness have been carried out. The wall waviness is found to induce steady recirculation or lateral vortices in the concavities of the corrugated-plate channel, and their strength and severity with severity of wall waviness.

Focke and Knibbe observed a striking ox-horn vortex pattern in wavy channel for Re<200 by using o-cresolphthalein as PH indicator in flow visualization experiment. Flow separation first takes place at Re~200 and the separated region increase in size with Re number until the reattachment point almost coincides with the top of the down stream crest. Fig.1.6 shows the sketched provided by Focke and Knibbe, as it shows only the sketch drawn based on the observations. Rush et al. experimentally investigated local heat transfer and flow behavior for laminar and transitional flows in sinusoidal wavy passages. Flow visualization methods were used to characterize the flow field and detect the onset of macroscopic mixing. The entire channel exhibited unsteady, macroscopic
mixing at Re = 1600 and the onset of this mixing is linked directly to the significant increases in local heat transfer.

For sinusoidal wavy channels with a great deal of experimental research has been done by Nishimura and coworkers. Using flow visualization techniques they observed flow separation and recirculation zones in the wave troughs at low Reynolds numbers as shown in Fig 1.7. As the Reynolds number increased above a critical value (less than 1000) these recirculation zones interacted with the core fluid through shear layer instability near wall fluid was exchanged with core fluid and macroscopic mixing occurred. Using a channel with nine wavelengths they concluded that the flow becomes three dimensional at Re~100 with span wise and stream wise vortices.

Most of the work in literature is done on the onset of instability rather than local structure of vortices in corrugated channel and also till this date, a detailed study of LDV
measurements to examine the spatial variation of the velocity in different planes of the flow through variety of wavy channels along with the flow visualization has not been done, which makes the present study unique.

1.4 Introduction of Fuel Cells

William Grove (1839) conducted the first known demonstration of the fuel cell. It operated with separate platinum electrodes in oxygen and hydrogen submerged in a dilute sulfuric acid electrolyte solution, essentially reversing a water electrolysis reaction. High temperature solid oxide fuel cells (SOFC) began with Nernst’s 1899 discovery of the still-used yttria-stabilized zirconia solid-state ionic conductor (Nernst, [1899]), although little additional practical development occurred until the 1960’s. General Electric developed low temperature polymer electrolyte membrane (PEM) fuel cells in the year 1960 for NASA’s Gemini space program. Both PEM and solid oxide fuel cell systems made slow progress until recently. Fueled by technology advances allowing greatly enhanced performance, continuing environmental concern, and a need to develop future power systems that are independent of petroleum fuel stock, interest in all types of fuel cell systems for stationary, automotive, and portable power applications is now very high. In all of these applications, there is a need for reduced system cost, high reliability, and acceptable performance. While the performance of many systems has made the greatest strides, there is still much work to be done.

The future of power generation will almost certainly include fuel cell systems. The basic advantages common to all fuel cell systems are as follows:

1) Potential for a high operating efficiency (up to 50-70%), that is not a strong function of system size.
2) Zero or near-zero greenhouse emissions, with level of pollution reduction depending on the particular fuel cell system and fuel option.

3) No moving parts, except pumps or compressors, thus providing stealthy, vibration-free, and highly reliable operation.

4) A highly scaleable design.

5) Multiple choices of potential fuel feedstocks, from renewable ethanol to biomass hydrogen production.

6) A nearly instantaneous recharge capability compared to batteries.

1.5 Basic Fuel Cell Operation

Fig 1.8 shows a generalized schematic of a fuel cell. Electrochemical reactions for the anode and cathode are shown for a hydrogen-fed polymer electrolyte membrane fuel cell (H₂ PEMFC), a direct methanol fuel cell (DMFC). Liquid or gas-phase fuel and oxidizer streams enter through flow channels, Separated by electrolyte/electrode assembly. Reactants are transported by diffusion and/or convection to the catalyzed electrode surfaces, where electrochemical reactions take place. In PEM fuel cells (these include H₂ and DMFC), transport to the electrode takes place through an electrically conductive carbon paper or carbon cloth backing layer, which covers the electrolyte on both sides. These backing layers (typical porosity 0.3-0.8) serve the dual purpose of transporting reactants and products to and from the electrode and electrons to and from the bipolar plates to the reaction site. An electrochemical oxidation reaction at the anode produces electrons that flow through the bipolar plate/cell interconnect to the external circuit, while the ions pass through the electrolyte to the opposing electrode. The
electrons return from the external circuit to participate in the electrochemical reduction reaction at the cathode.

With growing need of power in different industrial application various fuel cells technologies were evolved in last four-five decades. Fig 1.9 shows the different types of fuel cells. One of the major difference in fuel cells is the electrolyte used, for example the Proton exchange membrane fuel cells (PEMFC) uses solid polymer electrolyte membrane (Nafion®), while the solid oxide fuel cell (SOFC) uses Ceramic oxide electrolyte. The other difference is the operation temperature of fuel cells, PEMFC operates at 60-120 °C, and SOFC operates around 600-1000 °C etc. The source of anode fuel is also one of the major differences in fuel cell technologies, Reformed hydrogen fuel cells uses the Methanol as the fuel and by converting it into reformed hydrogen (75% H₂, 24% CO₂, 1% CO) using steam reforming technique it is feed to anode side of the fuel cells. On the other hand in PEMFC pure hydrogen gas is feed to anode side of the fuel cells. A detailed discussions is presented in chapter 5 on reformed hydrogen fuel cells.
Fig. 1.9 Different types of Fuel Cells system
Depending on the power requirements fuel cells are broadly classified into micro (P<100Watts) and macro fuel cells (P>100 watts). Table 1.1 summarizes the various fuel cell technologies with their pros & Cons. The fuel cell is a unique and fascinating system. For optimal performance and design, accurate system modeling for prediction of performance as a function of the myriad of possible operating conditions and transients is needed, but such modeling requires an understanding of all relevant phenomena. Although the fundamentals of operation are hidden in basic electrochemistry, advances in all areas are made in such a rapid fashion that it is nearly impossible for one researcher to be fully cognizant of all aspects of the state of the art. In order to make strides in the three primary needs of high performance, low cost, and high reliability, and one must possess a basic understanding of the principles of electrochemistry, materials and manufacturing, and heat and mass transfer. Because of this highly interdisciplinary nature of fuel cell systems, many successful research programs are built around a team approach involving investigators from complementary disciplines.

1.6 Scope of Study

The scope of study is included an experimental study of characterizing the vortex structure in sinusoidal wavy channel along with a case study for fuel cell applications. Fluid mixing is perhaps an extremely way to enhance the heat and mass transfer in channel and duct flows. A wavy flow channel is one such device that provides core flow mixing by inducing span-wise and stream-wise vortex generation, depending upon the geometry, and promotes the heat and mass transfer enhancement. These flow patterns and swirl or vortex structure are quite complex and not well understood. In the present study, a parametric understanding of the flow pattern, vortex structure, and their variation with
the Re, channel geometry, using flow visualization and LDV measurements has been done.

The specific scope of this work can be summarized as below.

1. Flow visualization experiments for the velocity field and its variation with Reynolds number in different wavy-plate channels ($0.25 \leq \text{channel corrugation ratio } (\gamma) \leq 0.5$, and $1.1 \leq \text{channel spacing ratio } (\varepsilon) \leq 1.6$) were performed.

2. To carry out a velocity measurement experiment using Laser Doppler Velocimetry (LDV) technique with variation of channel spacing ration $\varepsilon$ ($0.5 \leq \varepsilon \leq 1$) and Reynolds number.

3. A Detailed study of Solid Oxide Fuel Cells (SOFC). To identify the different components of SOFC systems and a comparative study with Proton Exchange Membrane fuel cells (PEMFC), to identify the difference between these two fuel cell technologies. Also to study the different design concepts of SOFC like planar, monolithic and tubular to understand the technical issues involved with SOFC technologies. Since the Fuel cell hardware is presently in pre-commercial development resulting in the unavailability of performance maps for system design and simulation purposes, the fuel cell modeling will help in optimizing its performance. A thorough literature review of SOFC modeling from 1967-2003 was performed.

4. A case study is presented on Reformed hydrogen fuel cells system. A detailed study is done on PBI membrane along with other RHFC system components. Experiments were performed on 25 W fuel cell stacks with different fuel stoichiometry on anode and cathode to check its compatibility with the design of RHFC system components.
Table 1.1 Summary of different fuel cell technologies

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Electrolyte</th>
<th>Anode Gas</th>
<th>Temperature</th>
<th>Efficiency</th>
<th>Pros &amp; Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Exchange Membrane (PEM)</td>
<td>solid polymer membrane (Nafion)</td>
<td>hydrogen</td>
<td>75 C</td>
<td>35–60%</td>
<td>High performance</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Easily contaminated with CO (&lt;100 ppm required)</td>
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<td></td>
<td></td>
<td></td>
<td>Hi internal humidity need for conductivity</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Low temp makes cooling difficult</td>
</tr>
<tr>
<td>Elevated Temperature PEM</td>
<td>solid polymer membrane (PBI/H3PO4)</td>
<td>hydrogen, reformate</td>
<td>150-200 C</td>
<td>30-55%</td>
<td>Good performance</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>CO tolerant &lt;2%</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Low humidity feed okay</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Relatively unproven technology</td>
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<tr>
<td>Alkaline (AFC)</td>
<td>potassium hydroxide</td>
<td>hydrogen</td>
<td>below 80 C</td>
<td>50–70%</td>
<td>Extremely long life &amp; high performance</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Cannot be fed air to cathode (CO₂ sensitive)</td>
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<td></td>
<td>Liquid electrolyte</td>
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<tr>
<td>Direct Methanol (DMFC)</td>
<td>solid polymer membrane</td>
<td>methanol solution in water</td>
<td>50-75 C</td>
<td>35–40%</td>
<td>Relatively safe, liquid fuel</td>
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<td>Low performance</td>
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<td></td>
<td></td>
<td>High catalyst cost</td>
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<tr>
<td>Phosphoric Acid (PAFC)</td>
<td>H₃PO₄ in sintered glass matrix</td>
<td>hydrogen, reformate</td>
<td>210 C</td>
<td>35–50%</td>
<td>Good performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CO tolerant &lt;2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low humidity feed okay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Liquid electrolyte</td>
</tr>
<tr>
<td>Molten Carbonate (MCFC)</td>
<td>Alkali-Carbonates</td>
<td>hydrogen, methane</td>
<td>650 C</td>
<td>40–55%</td>
<td>Direct oxidation of methane possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High temperatures limit use to higher power</td>
</tr>
<tr>
<td>Solid Oxide (SOFC)</td>
<td>Ceramic Oxide</td>
<td>hydrogen, methane</td>
<td>800–1000 C</td>
<td>45–60%</td>
<td>High performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Direct oxidation of methane (&amp; others) possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High temperatures limit use to higher power</td>
</tr>
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</table>
Chapter 2
Flow visualization experiment for sinusoidal wavy channels

2.1 Introduction

Computational fluid dynamics (CFD) are used to simulate the fluid flows as well as gaseous flows in the research field. CFD tools like finite element/volume methods are often used to handle complex flow structures, for instance, local solvers of the Navier-Stokes equations, which work on various kinds of grids. Usually data sets are computed that provide a huge amount of sampled vector information spread over a two- or three-dimensional domain. Without visualization it is usually impossible to reasonably investigate such data sets. At this point flow visualization comes into play. It provides numerous techniques to view various properties of such huge data sets, e.g., turbulences, vortical structures, separation lines, etc. For quite a long time, experimental setups are used to get an impression of its properties and structures, to get ideas about improvements to their work, and/or to evaluate their models. Three basic types of experimental techniques can be distinguished:

1. Adding foreign material:

Dye or magnesium powder is injected into liquid flow to visualize flow dynamics. In gaseous flows smoke or oil droplets are injected. A problem with injecting material is that the injection process and the injected material may influence the flow. Using electrolytic techniques for generating hydrogen bubbles within the flow decreases these problems to a certain extent. Also photochemical methods are used, for instance, generating dye within the flow using a laser beam. Applying tufts to the walls of a flow
simulation, or coating certain border surfaces of interest with some viscous material like oil, visualizes flow behavior near objects within the flow, for example, flow close to aircraft wings in a wind tunnel.

2. Optical techniques –

Less disturbance of the flow can be achieved using optical methods. Optical properties like light refraction change at places within the flow where there are big local differences in flow density. Working with a light beam, images are generated with shadows and caustics. Another visual property which changes in regions of high density gradients, is the phase of light rays. Interferometry is an example of a technique which exploits such phase shifts.

3. Adding heat/energy –

Heat can be applied to flows to artificially increase the density variation - optical techniques are then used for visualization. Shooting electrons into the flow volume is used to excite gas molecules. After being excited the molecules emit their extra energy as light particles, which visualize flow patterns.

2.2 Experimental Setup

The experimental setup is located in the University of Cincinnati Mechanical Engineering Thermal fluid and thermal processing laboratory. The test section had a cross sectional area of 100 cm x 15 cm and the Reynolds number can be raised up to 1000. The test section is made of Plexiglass, allowing for the lighting and viewing for flow visualization and LDV measurements. Fig 2.1 shows the setup for the wavy channel experiment.
Fig 2.1 Wavy channel experiment setup

In the Test section a honeycomb is placed in the entrance to conditioned the fluid, which help to provide uniform velocity profile in the entrance region of the test section. The honeycomb is made by attaching the plastic coffee stirrer up to the required dimensions.

There is a bypass valve in the test section, it was used to control the flow through the test section. To measure the flow through the test section liquid Rotameter made from Omega (series FLT-115) was used. A detailed flow calibration was performed to determine the Reynolds for a particular volumetric flow through test section. The calculations can be found in the appendix A.

A typical wavy plate-fin core, formed by placing wavy fins side-by-side and bonding
Fig. 2.2 Wavy-plate fins: a) typical sinusoidal corrugated plate fins, and (b) geometrical description of the flow channel.
them to a set of flat plates, is illustrated in Fig. 3a. The geometrical features of the two-dimensional (H>>S) inter-fin flow channel shown in Fig. 3b are described by the fin height \( H \), fin spacing \( S \), amplitude of waviness \( A \), and wavelength or pitch of waviness \( L \). The dimensionless representations of these variables are given by the fin-spacing ratio (\( \varepsilon = S/2A \)), flow cross-section aspect ratio (\( \alpha = S/H \)), and corrugation or waviness aspect ratio (\( \gamma = 2A/L \)). For a given fin height and waviness, \( \varepsilon \) and \( \alpha \) also represent the fin density (\( \varepsilon \) and \( \alpha \) decrease with increasing fin density but fixed \( A \) and \( H \)).

Table 2.1 Geometric parameter space used in flow visualization experiments

<table>
<thead>
<tr>
<th>( H ) min</th>
<th>Plate separation to width ratio</th>
<th>Aspect ratio</th>
<th>Spacing ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.067</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
<td>0.1</td>
<td>0.25</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>0.133</td>
<td>0.50</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.50</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.3 Results and discussions

2.3.1 Dye visualization

Dye visualization is one of the many ways to visualize water flow in a closed channel. In the current study this was one of the first trials to capture the flow pictures. A red color dye is used to visualize the flow by injecting it using an injector. The injector as shown in fig., was made by cutting notches in a gauge 20 surgical needle. The notches
Dye injector

Re=110

Re=250

Re=300

Fig 2.3 Flow pictures of Dye visualization experiments
were cut in evenly spaced location on the needle to have uniform distribution of dye in the flow field. A dye solution was made by mixing adequate amount of red dye with water. The dye solution was stored in a bottle, which has the tubing going to the injector. The atmospheric pressure difference is used to make the flow of dye solution from the bottle to the injector. One of the major advantages of dye visualization is that the experiment can be preformed in normal lighting conditions in the room as compared to the other visualization techniques where a dark room along with projected light source is necessary to capture the flow pictures. geometries with $\varepsilon = 1.0$, and $\gamma = 0.25$. As seen from flow pictures at low Reynolds number $Re=100$ the flow is laminar and the viscous forces dominates the inertial forces, hence there is no recirculation in the wavy channel. As the flow rate is increased the streamline flow is disturbed and disturbance can be seen at the trough of the wavy channel. As seen from the flow pictures ($Re>250$) diffusion of dye is taking place, which makes the whole flow field red. To delay the diffusion of dye in water at higher flow rates milk is added, but still same problem persists. The reason behind the dimensions of the channel which decrease the diffusion time at high flow rates. This experiments was success even with limitation at higher flow rates, it was able to validate the test section construction and concept of flow visualization in wavy channel.

2.3.2 Aluminum Particles

In the experimental visualization, flow pattern photographs are obtained by injecting very fine aluminum dust (63 $\mu$m) in the flow field, illuminating it with a high-luminosity light sheet and capturing the image on a digital camera with a shutter speed of
1/8th second. The experimentally visualized flow fields amply validate the computational stream function simulation. To capture the pictures of the flow field using aluminum particles proper lighting and camera are important. The details of these two critical are discussed below:

**Lighting:** The two most common sources of lightning used in flow visualization are the convectional light source and the laser. Conventional light sources includes spot-lights, tungsten-halogen lamps, mercury lamps and strobscopic, and they are used to visualize the external features of the flow. In contrast the lasers are frequently used to visualize the internal structure of the flow.

In external illumination, the locations of the sources of light in relation to the subject can strongly affect the quality of the photographic images. There are two types of the external illumination depending on the location of the light source with respect to flow field. First is the right-angle arrangement in which the light source is at the top of the flow field, generally it is used in studies involving smoke and water tunnels with dark test sections. Second is the front-illumination, in which the light source is placed in front of the flow field. To visualize the internal features of a flow, light sheets are used. In the past, a narrow sheet of light could be obtained by allowing flood lighting to pass through two narrow slits arranged some distance apart. However there is limitation with the thickness of the sheet (1to 2mm). With the advent of lasers a thin sheet can easily be formed using cylindrical lens or glass rod. The spreading angle depends on the diameter of the lens used, smaller the diameter of the lens, larger the spreading angle. Another method of generating laser sheet is to use an oscillating mirror mounted on an optical
scanner. This technique produces a more uniform light intensity because glass rod usually contains imperfections. However, to achieve a uniform sheet with the oscillating mirrors, the frequency of the oscillations must be equal to at least the inverse of the camera shutter speed. To study the different internal sections of the flow, it can be done by aligning the plane of the light sheet perpendicular to the line of view. For most studies, a 4 to 5 W laser provides a sufficient light intensity.

**Camera:** There are different types of camera available to capture the flow images, of which popular are still cameras, cine cameras, video cameras. The Single Lens Reflex (SLR) camera is the most popular still camera design because it eliminates the parallax error normally associated with direct vision finder cameras. In the current study Digital camera by Soni Mavica X500 series was used to capture the images with a shutter speed of 1/8th second. There are ten wavy sections in the test part. However, the photographs were taken just close to the middle one.

Experimental results for the flow, velocity and their variation with flow Reynolds number in different wavy-plate channels (\(0.25 \leq \gamma \leq 0.5\), and \(1 \leq \varepsilon \leq 1.5\)) are presented. The influence of the flow geometry on the local velocity and the nature of wavy-surface induced lateral vortex structure are delineated.

The onset, development, and growth of steady lateral vortices or re-circulation in the troughs of wavy plate channels with changing flow rates are depicted in Fig.2.4. Flow pictures for flows with \(\text{Re} = 125, 248, 350, \text{and } 490\) in two different wavy-fin geometries with \(\varepsilon = 1.0\) and \(\gamma = 0.25, 0.5\) are presented and the strong influences of Re and severity of wall waviness \(\gamma\) are clearly evident. With increasing flow rates, wall-curvature-
induced effects manifest in fluid separation downstream of the wavy-surface peak, its reattachment upstream of the subsequent peak, and the consequent development and encompassing of re-circulating cells in the wall-valley regions. This lateral vortex is triggered at a much lower flow rate in channels with more severe wall waviness (Re \sim 248 with \gamma = 0.5, as compared to Re > 350 with \gamma = 0.25; \varepsilon = 1.0 in both cases), and the extent of the lateral swirl flow area coverage increases with Re and \gamma. At very lower flow rates (Re \sim 125), however, viscous forces dominate to produce undisturbed streamline flows and swirl is not developed, irrespective of the wall-corrugation severity \gamma.

That the inter-plate-fin spacing, represented by the dimensionless \varepsilon (= S/2A), significantly influences the development of flow recirculation in the wavy-wall valleys is seen from the flow pictures in Fig.2.5. The flow pictures fields for Re = 135, 490, and 700 in channels with \gamma = 0.25, and 1 \leq \varepsilon \leq 1.5 are presented. With increasing Re and/or plate spacing \varepsilon, the lateral vortex in the trough tends to grow and envelop much of the core flow region, thereby promoting flow mixing and increased momentum transport. As the plate separation decreases (\varepsilon \rightarrow 0.5), viscous effects suppress swirl and undisturbed streamline flows prevail that follow the channel-wall contours. This flow behavior, however, depends on both \varepsilon and Re for any given \gamma. At higher flow rates Re=490, 700 the swirl has increased in its size in the case of \varepsilon =0.5 as compared to \varepsilon = 0.25. and also the location of swirl has changed which represents the growth of the separated region. Fig 2.6 show the flow pictures of effect of fin spacing in case of \gamma =0.5 with \varepsilon = 0.5, 0.25 at Re =135, 490, 700.
There is, however, an upper limit to the effect of \( \varepsilon \) in promoting swirl enhancement. With increasing \( \varepsilon \) the influence of wall waviness on the bulk flow and heat transfer diminishes significantly. For the same wall waviness \( \alpha \), the reattachment points move axially to the right with increasing \( \varepsilon \) thereby indicating growth of the separated region as shown in by Zhang [2004] in his numerical study on wavy channels. But after a.

![Graph showing reattachment points for different \( \varepsilon \) and \( \gamma \) at \( \text{Re} = 600 \) for core-flow development.]

Fig. 2.4 Position of reattachment point for different \( \varepsilon \) and \( \gamma \) at \( \text{Re} = 600 \) for core-flow developing Zhang [2004]
larger ($\varepsilon = 0.5 \rightarrow 1.5$), which result in higher wall shear stress in the swirl regime. In the no-swirl regime of low Reynolds number ($\text{Re} < 125$), the decreasing impact of the interactions between viscous and wall-curvature induced forces in the confined wavy-flow passages with increasing $\varepsilon$ for all $\gamma$. As would be expected the greatest effect is seen in channels with more severely corrugated ($\gamma \rightarrow 0.5$) plates.

2.3.3 Comparison of Experimental results with Numerical results

Experimental and computational characterization of swirl flow and heat transfer in a nominally two-dimensional (plate separation-to-width = 0.067), sinusoidal wavy channel with an aspect ratio ($2 \times$ amplitude/wavelength) of 0.25 and the spacing ratio (plate spacing / $2 \times$ amplitude) of 1.0 is presented. The computational work Jhang [2004] is carried out using finite-volume techniques with a non-orthogonal, non-staggered grid. The experimentally visualized flow fields amply validate the computational stream function simulations. At low $\text{Re} (< 200)$ the flow is essentially streamline and contoured to the wall waviness. With increasing $\text{Re} (> 200)$, lateral re-circulation, induced by the wall curvature, sets in the trough regions of the wavy channel. The swirl strength and spatial flow coverage increases with $\text{Re}$ to produce temperature fields that have sharper gradients at the wall, with considerable thinning of the boundary layer, and enhanced heat transfer. The photographs taken in current study are shown in figures, along with the numerical results at the same flow rates in wavy flow channels with same geometry parameters. In the upstream part of the test section, the flow is observed in steady state, while in the downstream part, the flow is becoming little bit unsteady, which show the
Fig. 2.5 Flow pictures showing the effect of corrugation ratio ($\gamma$ = 0.25 to 0.5) at $Re=125, 248, 350, 490$

$\varepsilon = 1, \gamma = 0.25$ $\varepsilon = 1, \gamma = 0.5$

Fig. 2.5 Flow pictures showing the effect of corrugation ratio ($\gamma$ = 0.25 to 0.5) at $Re=125, 248, 350, 490$
Fig.2.6 Effect of $\varepsilon$ on the streamline distribution on lateral swirl generation in wavy-plate channels with $\gamma = 0.25$, and Re = 135, 490 and 700.
Fig. 2.7 Effect of $\varepsilon$ on the streamline distribution on lateral swirl generation in wavy-plate channels with $\gamma = 0.5$, and Re = 135, 490 and 700

a) $\gamma = 0.5$, Re=135
b) $\gamma = 0.5$, Re=490
c) $\gamma = 0.5$, Re=700
Fig. 2.8 Axial flow in a wavy plate channel at different Reynolds number influence of the entrance length. The photographs in Fig. 2.8 show stream line flow patterns, which correspond to the Reynolds number $Re = 125$ in this specific flow channel. The numerical results in these figures also show the stream line flow behaviors, and they agree very well with the experimental results. In the lower flow rate regime, viscous force is dominated in the flow; the friction factors are relatively low. Also, the Fig. 2.8 shows that the effect of wall curvature on the flow behavior can be neglected in the lower flow rate regime. The photographs in Fig. 2.8 show different flow patterns at flow rate $Re = 248$ to 490, which is characterized by swirl flow or vortex flow. It can be
observed that, the trapped vortex is first created in the top trough region, diminished and recreated in the bottom trough region along the axial direction in the wavy flow channel. Once again, the numerical results agree well with the experimental results, and this agreement can be used to verify the numerical codes and numerical results. Due to the strong mixing of the core flow and swirl flow, the pressure drop and heat transfer rate have increased. The effect of wall curvature on the pressure drop and heat transfer behaviors is beginning to show up. The onset of the stream-wise vortex begins at about $Re = 350$, and this can be shown from the Fig 2.8. In swirl flow regime, the flow patterns are almost the same, and the only difference is the swirl size or the coverage, which only depend on the flow rate $Re$ in current experiment study. In low $Re$ swirl flow regime, the size of swirl or vortex is small, but it increases with the flow rate until a critical $Re$, in which the vortex covers almost all the trough region of the wavy channel. Once again, this swirl flow behavior can be clearly seen in both the experimental photographs and numerical simulation results.
Chapter 3  
Laser Doppler Anemometry

3.1 Introduction

The Laser Doppler Velocimetry (LDV) is an optical method to measure local flow parameters of transparent gaseous or liquid flows. In comparison to traditional flow measurement techniques, e.g. the hot-wire anemometer or Prandtl probe, the LDV provides following advantages:

- The LDV method is non invasive. The flow being investigated is not disturbed by a probe. So flow measurements are possible in situations not suitable for conventional techniques, e.g. in internal combustion engines.
- The determination of flow speeds is based on simple geometric correlations. A drift is not possible. So calibration measurements are not necessary.
- The direction of flow speed components being measured is determined by the optical arrangement.
- The LDV technique makes a very high spatial and temporal resolution possible.
- Special optical setups provide the possibility to record two or three velocity component simultaneously.

3.1.1 Principles of LDV

The LDV techniques makes use the fact that the light scattered by a particle moving relatively to the light source show a frequency shift in comparison with the light emitted from the light source (Doppler effect). This frequency shift depends on the directions of the incident and scattered light and on the velocity vector of the particle:

\[
\nu_{Str} = \nu \frac{c - u^* l}{c - u^* k}
\]
- \( \nu_s \): frequency of the scattered light
- \( \nu_i \): frequency of the incident light
- \( c \): speed of the light
- \( l \): unit vector in direction of the incident light
- \( k \): unit vector in scattering direction.
- \( u \): speed vector of scattering particle

---

**Fig. 3.1 Principal of LDA differential beam technique**

Provided the directions of the incident light, the scattered light and the particles movement are given, the frequency shift is proportional to the particle speed. For flow measurements by LDV particles are added to the flow. They have to small enough to track the flow accurately. The light of a laser is scattered by these particles.
The frequency shift is determined and flow speed can be calculated. Typically the frequency shift is too small to be measured directly. Therefore the effect of the beating is used for the determination of the frequency shift. A beating is the oscillation of the intensity observed when two waves of frequencies \( f_1 \) and \( f_2 \) lying closely together heterodyne. The frequency of the beating is \( \Delta f = f_2 - f_1 \). For LDV measurements \( \Delta f \) lies in the range between several KHz up to 100 MHz. These oscillations of the light intensity can easily be converted to electric signals by means of a photo detector.

### 3.1.2 Basic types of LDV Optical Setups

To obtain a signal of the Doppler-shift that may be evaluated by means of heterodyning two beams with different frequencies, a monochromatic coherent light source, i.e. a laser is reduced. Very often Helium-Neon or Argon-ion lasers are used.

Three basics types of Optic setups can be distinguished:

1. **Dual scatter system**: A single laser beam is focused into the measuring volume. The scattered light is collected in distinct directions and heterodyned on a photo detector by means of a system of mirrors and beam splitters.

2. **Dual beam reference mode**: The laser beam is divided into two beams of different intensity. The scatter light if the stronger beam is heterodyned with the so called reference beam on the surface of a photo detector.

3. **Dual beam differential or Fringe mode**: A laser beam is divided into two beams of equal intensity that are focused into the measuring volume intersecting with a defined angle. In this case the light scattered in the measuring volume consist of two parts with different frequencies respectively. A photo detector focused on the measuring volume registers this frequency difference as an oscillation of the light intensity. This frequency registered however is not dependent on the direction of observation. It is proportional to
the speed component perpendicular to the optical axis in the plane defined by the two incident beams. An easier explanation for the formation of the optical signal is shown with the idea that an apparent plane fringe pattern is generated in the intersection volume by two incident beams heterodyning. The scattered light of a particle passing through this fringe zone shows intensity oscillations corresponding to its speed perpendicular to the fringe planes.

3.1.3 Optical arrangements for the differential Doppler technique

In the fringe mode the optical arrangement basically consists of a laser head, the transmitter optics that generates the fringe pattern in the measuring volume and receiver optics with a photomultiplier to record the scattered light. A basic LDV system requires the following elements: Laser, beam splitter, mirror, front lens, and front lens of photomultiplier optics, mask, and photomultiplier. For most LDV applications He-Ne lasers (wavelength 632.8nm, power 0.5-25 mW) or Ar-ion lasers (wavelength 488nm and 514.5 nm, power up to 10 W) are used. They are operated in the TEM00-mode emitting a circular beam with a Gaussian intensity profile over the beam cross section. Such a Gaussian beam is characterized by a beam waist, the position of which is determined by the optics of the laser head causing a distinct divergence.

The laser head and the transmitter optics determine the important parameters of the dimensions of the measuring volume and the fringe spacing and this calibration constant for calculating the flow speed from the Doppler-frequency measured. Due to Gaussian intensity profile of both beams intersecting in the measuring volume the latter one has the shape of an ellipsoid.

The dimensions of the measuring volume can be calculated as follows: (see fig. 3.3)
\[
\delta_x = \frac{\delta_f}{\cos \frac{\theta}{2}}; \quad \delta_y = \delta_x; \quad \delta_z = \frac{\delta_f}{\sin \frac{\theta}{2}}
\]

- \(\delta_x, \delta_y, \delta_z\): dimension of the measuring volume in x-, y-, z- direction
- \(\delta_f\): beam diameter in the measuring volume
- \(\theta\): intersection angle of incident beams

In case of planar wave fronts of the incident beams the resulting fringe pattern in the measuring volume consists of planar light and dark zones in equal spacing. The fringes are oriented parallel to the optical axis and perpendicular to the plane defined by the two incident beams. The fringe \(\delta_f\) can be calculated from the wavelength \(\lambda\) and the intersection angle \(\theta\) of the incident beams

\[
\delta_f = \frac{\lambda}{2 \sin \frac{\theta}{2}}
\]

Consequently the Doppler frequency \(f_D\) measured and the speed component perpendicular to the fringes \(u_x\) are connected by the following equation:

\[
f_D = \frac{2u_x}{\lambda} \sin \frac{\theta}{2}
\]

The receiver optics as shown in fig 3.4 basically comprises a system of lenses that focuses the measuring volume through a pinhole to the photomultiplier. The pinhole serves a spatial filter. Normally a inference filter is added into the optical path to eliminate stray light from other sources than the measuring volume.
Fig. 3.2 Transmitting system

Fig. 3.3. Probe volume
3.1.4 Signal Processing Techniques

The photo detector transforms the oscillations of the intensity of the scattered light into an electric signal, the latter containing the Doppler frequency but various spurious components as well. The depth of modulation depends on the particle size in comparison to the fringe spacing. An increase of the particle size causes a loss of modulation depth. Before being processed for Doppler frequency detection the electrical signals are filtered by a low and high pass filter to remove high frequency noise and the low frequency pedestal from the signal. Depending on the properties of the flow being investigated and the particle concentration in the flow, the signal to noise ratio of the signals various techniques can be applied for frequency detection. They are various signal processing techniques used in LDV system:

- **Counter systems:** In this system the time for a certain number of oscillations is measured. The frequency of an input signal is determined by measuring the time that passes for a certain number of zero crossings. The beginning of a measuring cycle is set by presetting a minimum height of the signal to prevent spurious
components of smaller amplitude form being processed by the counter. Counter systems are most suitable for flows with a low particle concentration which deliver separate Doppler burst.

- **Tracker systems:** In a frequency tracker system a voltage is generated as output signal that is proportional to the frequency of the input signal by employing a voltage controlled oscillator. In contrast to counter system a tracker requires a continuous input signal for proper operation and thus a particle concentration in the flow that ensures the presence of at least one particle in the measuring volume at any time.

- **Harmonic analysis:** Applying harmonic analysis to the signals the Doppler frequency can be determined even from the signals with very high noise levels. Systems of this type employ hardware implanted Fast Fourier Transform (FFT) for signal processing thus transferring the input time signal directly to a frequency signal.

### 3.1.5 Properties of Scattering Particles

The technique of laser Doppler velocity measurement in fluids depends on the presence of suitable particles to produce enough scattered light for analysis. Some suitable particles are usually present naturally in fluids being studied and these may be sufficient for LDA measurements. The two basics requirements of scattering particles are that they (i) follow the flow sufficiently closely (ii) scatter sufficient light to give an acceptable signal to noise ratio from the detector under the conditions of the experiment. Factors influencing the choice of seeding are the fluid problems being studied, the velocity fluctuating expected, the technique used (reference beam or differential Doppler) , the angle of scattering, and the spacing of the fringes. There may also be special factors
such as the presence of high temperature, reactivity of the fluid, or the fouling of the windows. Although increasing the particle size generally increases the scattered light received by the detector, this does not necessarily improve the LDA signal. An important factor to be considered in the differential Doppler technique is the degrading of signal quality when the diameter of the particle become large compared with the fringe spacing.

In laser Doppler experiments with water flows using forward scattered light, seeding is often found to be unnecessary. This is particularly true in recirculating systems where there is no filtering of the water. Suspended contaminating particles are of a size range suitable for LDA and generally give satisfactorily signals although they are not usually present in sufficient numbers for maximum efficiency. But with Back scattered LDV the seeding of the water become necessary.

Consistently good results in water flows can be achieved by the use of polystyrene spheres which can be obtained in well controlled size ranges in latex suspension. The size may be chosen to suit the experiment: large particles being chosen for differential Doppler experiments with large fringes spacing, small ones for back scatter reference beam measurements. Commonly used materials are titanium oxide, silicon carbide, and alumina. The high refractive index of these materials gives a useful increase in scattering efficiency, particularly for small particles in liquid suspension. A suspension of particles in a small quantity of the liquid is usually prepared for adding to the flow system.

3.2 Laser Doppler Velocimetry (LDV) Experimental set up

A Laser Doppler Velocimetry system was used to measure velocities in the experiment. Fig shows the single component 10 mw HeNe LDV system the traversing system used in the experiment. The main components were: an integrated optics unit
(Dantec flowlite), a Flow Velocity Analyze (FVA) Signal Processor (Dantec 58N20), an HP 486DX2 50 MHZ computer, a Unislide traversing mechanism (Velmex), a stepper motor (M062-LS09) and a Unislide traversing controller (Velmex VP9000). The Flowlite integrated laser-optics unit comprises a laser and a probe connected by a fiber optic cable. The optics unit is connected to the Flow Velocity Analyzer and Floware software, which runs on a personal computer under DOS. The laser is equipped with a built in frequency shifter for reversing flows. The probe can have two different front lenses with focal lengths of 160 and 310 mm respectively, but most of the time focal lens of 310 focal length was used. The measurement size is about 0.18 mm in diameter and 3.02 mm in length for the focal length of 310 mm.
3.3 Results and discussions

Before starting the velocity measurements in wavy test section, measurements were performed in parallel plate channel just before the wavy test section. It was done to make sure the flow is fully developed before entering the test section. 

![Graph showing velocity profile](image)

**Fig. 3.6 Velocity profile in parallel plate at Re=1000**

To obtain the velocity values in flow field seeding particles of Silver coated hollow glass spheres with particle size of 13 microns and density of 1.6 g/cc (from Dantec Dynamics) were introduced. Fig 3.6 shows the velocity profile in the parallel plate channel with fin spacing of 1 cm. As expected for fully developed flow in the parallel plate channel the velocity profile is parabolic in shape. This experiment conforms that the flow is fully developed just before entering the test section. The LDV measurements were performed on wavy section after studying the flow pictures. As seen in Fig the velocity measurement line for LDV measurement. The fin height was divided in small steps to improve the accuracy of the measurement. ratio \( \varepsilon = S/2A \) = 1, waviness
ratio \((\gamma = 2A/L) = 0.25\) at \(\text{Re}= 135, 350, 600, 800\). Velocity is normalized by the averaged velocity and the \(y\) distance by wave amplitude.

Fig. 3.7 Flow picture at \(\text{Re}=350\) for test section \(\varepsilon=1, \gamma = 0.25\)

Fig 3.7 shows the results of velocity measurements in test section with the fin-spacing \((2a)\). With increasing flow rates, wall-curvature-induced effects manifest in fluid separation downstream of the wavy-surface peak, its reattachment upstream of the subsequent peak, and the consequent development and encompassing of re-circulating cells in the wall-valley regions. At low Reynolds number \(\text{Re}=135\) viscous effects dominates and undisturbed streamline flows prevail that follow the channel-wall contours. The flow is still periodically full developed as the flow profile is parabolic but it is shifted from the center because of the waviness of the test section. As the Reynolds is increase the wall induced effects dominates the viscous effects, as a results we see the recirculation in the trough of the wavy channel.

One of the unique features of the LDV study is the measurement of the recirculation velocity. The flow near to the recirculation region the velocity of fluid is negative as seen.
Fig. 3.8 Velocity profiles at Re=135, 350, 600, 800 in a test section with $\varepsilon=1$, $\gamma=0.25$
Fig. 3.9 Comparison of velocity profiles at Re=135, 350, 600

the velocity profile at higher Re> 350. The recirculation (negative) velocity increases with increase in the mass flow rates. At higher Reynolds number (Re=800) unsteady flow was observed. Fig. delineates the comparison of velocity profiles at different Reynolds number. As seen from the graph the magnitude of the streamline velocity at higher Reynolds number is greater than lower Reynolds number as also the negative recirculation velocity.

Fig 3.10 shows the velocity profiles at different Re=135, 248, 390, 600 with test section having $\varepsilon = 1.5$, $\gamma = 0.25$. As seen from the graphs with increasing $\varepsilon$ from 1 to 1.5, the recirculation velocity increases and also recirculation also started at lower Reynolds
Fig. 3.10 Velocity profiles at $Re=135, 248, 390, 600$ in a test section with $\varepsilon=1.5$, $\gamma=0.25$
number (Re=248) as compared to higher Reynolds number (Re=390) with $\varepsilon =1$. To calculate the random errors for uncertainty analysis of LDV measurement, a comparative study was performed between velocity magnitude obtained from LDV measurements and numerical values calculated from finite volume method done by Zhang [2004]. Fig delineates the comparison between two different velocity magnitudes for wavy channel $\varepsilon =1, \gamma =0.25$ at Re=350.

![Graph showing comparison of experimental and numerical velocities magnitude for wavy channel $\varepsilon =1, \gamma =0.25$ at Re=350.]

Fig 3.11 Comparison of experimental and numerical velocities magnitude for wavy channel $\varepsilon =1, \gamma =0.25$ at Re=350.

A random error of 3 % was found on velocity measurements. Details on uncertainty analysis of LDV measurement can be found in Appendix B.
CHAPTER 4
SOLID OXIDE FUEL CELLS- A REVIEW

4.1 Introduction to SOFC

The solid oxide fuel cells (SOFC) have grown in recognition as a viable high temperature fuel cell technology. In general, a SOFC system is well suited for applications where a high operating temperature and a longer startup transient are not a limitation, or high amounts of CO impurities are present. The main advantages of the SOFC system include:

1) Tolerance to CO, because it is oxidized as a fuel, eliminating one of the main drawbacks of the PEM fuel cell.
2) High operating temperature greatly reduces activation polarization and eliminates the need for expensive catalysts.
3) Potential for internal reformation of hydrocarbons.
4) Potential for high hybrid system efficiencies (~70%) utilizing a bottoming cycle or cogeneration, as described by Singhal [2000].
5) High-quality waste heat generated is ideal for a cogeneration system.

4.1.1 Basic Principal of Operation of SOFC

The operating principle of a SOFC with an oxide ion conductor is schematically shown in Fig.4.1. When an external load is applied to the cell, oxygen is reduced at the porous air electrode to produce oxide ions. These ions migrate through the solid electrolyte to the fuel electrode, and they react with the fuel, H₂ or CO, to produce H₂O or CO₂. Alternatively, a proton conducting solid electrolyte can be used, where H₂ is oxidized to produce protons that subsequently react with oxygen to form water. In some cases, CH₄ can be oxidized directly on the anode to form CO₂ and H₂O.
Carbon monoxide (CO) and hydrocarbons such as methane (CH₄) can be used as fuels in SOFCs. It is feasible that the water gas shift involving CO (\( CO + H₂O \rightarrow H₂ + CO₂ \)) and the steam reforming of CH₄ (\( CH₄ + H₂O \rightarrow 3H₂ + CO \)) occur at the high temperature environment of SOFCs to produce H₂ that is easily oxidized at the anode. The direct oxidation of CO in fuel cells is well established. It appears that reforming of CH₄ to hydrogen predominates in the present SOFCs.

4.1.3 SOFC cell components:

Table 4.1 provides brief description of the material currently used in the various cell components of the more developed SOFC, and those were considered earlier. Because of the high operating temperatures of the present SOFCs (approx 800-1000 °C),
the materials used in the cell components are limited by chemical stability in oxidizing and reducing environments etc.

Table 4.1 Evolution of cell component Technology for SOFCs

<table>
<thead>
<tr>
<th>Component</th>
<th>1965</th>
<th>1975</th>
<th>Current Status</th>
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</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Porous Pt</td>
<td>Ni/ZrO$_2$ cermet</td>
<td>• Ni/ZrO$_2$ Cermet</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Deposit Slurry, EVD fixed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• ~150 µm thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• 20-40 % porosity</td>
</tr>
<tr>
<td>Cathode</td>
<td>Porous Pt</td>
<td>Stabilized ZrO$_2$</td>
<td>• Doped lanthanum magnanite</td>
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<tr>
<td></td>
<td></td>
<td>Impregnated with</td>
<td>• Extrusion, Sintering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>praseodymium oxide</td>
<td>• ~2mm thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and covered with</td>
<td>• 30-40 % porosity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SnO doped In$_2$O$_3$</td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Yttria stabilized ZrO$_2$</td>
<td>Yttria stabilized ZrO$_2$</td>
<td>• Yttria stabilized ZrO$_2$ (8 mol% Y$_2$O$_3$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• EVD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• ~30-40 µm thickness</td>
</tr>
<tr>
<td>Cell Interconnect</td>
<td>Pt</td>
<td>Mn doped cobalt chromite</td>
<td>• Doped lanthanum chromite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Plasma spray</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• ~100 µm thickness</td>
</tr>
</tbody>
</table>

Present SOFC design make use of thin film concepts where films of electrode, electrolyte, and interconnect material are deposited one on another and sintered, forming a cell structure. An “Electrochemical vapor deposition (EVD)” technique has been
developed to produce thin layers of refractory oxides suitable for the electrolyte, anode and interconnection.

The anode consists of Metallic Ni and Y₂O stabilized ZrO₂ skeleton. The latter serves to inhibit sintering of the metal particles and to provide a thermal expansion coefficient comparable to those of the other cell materials. The anode structure is fabricated with a porosity of 20 to 40 % to facilitate mass transport of reactant and product gases. Doped lanthanum maganite is most commonly used for the cathode material. Similar to anode, the cathode is a porous structure that must permit rapid mass transport of reactant and product gases. The cell interconnection material however impervious to fuel and oxidant gases and must posses good electronic conductivity The solid oxide electrolyte must be free of porosity that permits gas to permeate from one side of the electrolyte layer to other and it should be thin to reduce ohmic losses. Zirconia-based electrolyte are suitable for SOFCs because they exhibit pure anionic conductivity over range of O₂ partial pressures.

4.1.4 Comparison of SOFC and PEMFC technology

There are several major differences between the SOFC and PEM fuel cell systems, table shows the comparison between PEM and SOFC technologies. First, the operating temperature of the SOFC is 600-1000 °C, compared to only 90°C for PEM fuel cells. This high temperature is required to ensure adequate ionic conductivity (of O₂⁻) in the solid phase ceramic electrolyte. In addition, high temperatures reduce activation polarization so much that cell losses are typically dominated by internal cell ohmic resistance through the electrolyte, electrodes, and cell interconnects. SOFC open circuit cell voltages of around 1 V are typical, and operating current densities can vary greatly depending on design. While the theoretical maximum efficiency of the SOFC is less than
Table 4.2 Comparison of PEMFC and SOFC Technology

<table>
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<tr>
<th>Issues</th>
<th>PEMFC</th>
<th>SOFC</th>
</tr>
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<tbody>
<tr>
<td>Operating Temp</td>
<td>Cell: 80-100°C</td>
<td>700-1000°C</td>
</tr>
<tr>
<td></td>
<td>Reformer 165-1000°C</td>
<td></td>
</tr>
<tr>
<td>Load Following</td>
<td>Dependent on reformer</td>
<td>Dependent on reformer</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Perfluorosulfonic acid membrane (Nafion®)</td>
<td>Yttria stabilized zirconia (YSZ)</td>
</tr>
<tr>
<td>Ion transferred</td>
<td>$\text{H}^+$</td>
<td>$\text{O}^{2-}$</td>
</tr>
<tr>
<td>Anode catalyst</td>
<td>Carbon supported Pt or Pt/Ru</td>
<td>Nickel/YSZ</td>
</tr>
<tr>
<td>Cathode catalyst</td>
<td>Carbon supported Pt</td>
<td>Sr-dpoed LA$\text{MnO}_3$</td>
</tr>
<tr>
<td>CH$_4$ Reforming</td>
<td>External</td>
<td>External or Internal</td>
</tr>
<tr>
<td>CO Management</td>
<td>Poison at &gt; 10ppm</td>
<td>Fuel/Water gas shift</td>
</tr>
<tr>
<td>Sulfur Management</td>
<td>&lt;5 ppm required</td>
<td>More tolerant (10-1000ppm)</td>
</tr>
<tr>
<td>Heat Quality</td>
<td>Low Grade (70-90°C)</td>
<td>High Quality (300-1000°C)</td>
</tr>
<tr>
<td>Cogeneration Capabilities</td>
<td>Moderate Water Heating (50-60 °C)</td>
<td>Aids Reforming, Steam Gen, Water heating, &amp; Space htg</td>
</tr>
<tr>
<td>System Electric Efficiency (LHV)</td>
<td>36-40%</td>
<td>45%</td>
</tr>
<tr>
<td>Water Management</td>
<td>Membrane sensitive to dehydration. Humidification of reactants required</td>
<td>No issues</td>
</tr>
</tbody>
</table>
the H₂ PEMFC because of increased temperature, decreased activation polarization is extremely low and operating efficiencies as high as 60% have already been attained for a 220 kW cogeneration system described by Service [2000]. Another major difference between PEM and solid oxide fuel cells are the materials. In the SOFC system, a ceramic such as yttria (Y₂O₃) stabilized zirconia (ZrO₂) is used as the electrolyte. In contrast to PEM fuel cells, O₂ ions are passed from the cathode to anode instead of H⁺ ions from anode to cathode. Other cell components such as interconnects and bipolar plates are typically doped ceramic, cermet, or metallic compounds.

4.1.5 Technical Issues of the SOFC

Although problems of CO poisoning and precious metal loading are eliminated with the SOFC, unique limitations exist. The high operating temperature of the SOFC requires a long startup duration, since commonly used electrolyte conductivity is very low until around 800°C is reached (Larminie and Dicks [2000]). This is a serious limitation for SOFC use as a main propulsion system in automotive applications. Doshi et al. [1999] have shown feasibility of low temperature SOFC operation at 500°C using doped ceria (CeO₂) ceramic electrolytes. Lower temperature operation would allow use of cheaper metallic compounds for cell interconnects, reduced start-up time, increased reliability and reduced manufacturing costs. One of the major challenges in SOFC system design is the component materials, such as the cell interconnect and electrodes. Materials are needed that 1) satisfy the basic electrical and permeation requirements, and 2) have matched thermal expansion properties of other components, to avoid internal stress concentrations and damage during both manufacture and operation.

Despite the technical challenges, the SOFC system is a good potential match for many applications, including auxiliary power for automotive applications, and stationary
cogeneration plants. As a result of the potential, continued development of various types of SOFC technology is expected.

4.2. SOFC Design Concepts

To date, there are essentially four different basic designs for the SOFC system: the planar, seal-less tubular, monolithic, and segmented cell-in-series design as shown in fig 4.2. The planar configuration looks geometrically similar to the PEMFC systems described previously. The electrolyte (~ 25 -250 m thick) is formed by methods such as tape casting into a sheet, onto which electrodes (25-100 m) are coated. Other methods are being actively researched to produce thin electrolyte layers by techniques such as chemical vapor deposition, sputtering, vapor jet deposition, and tape casting. The flow channel structure is used as support for the electrolyte, and a stacking arrangement, similar to that described for PEM fuel cells is used. Although this design is simple to manufacture and model, one of the major problems with it is difficulty sealing the flow fields at the edges of the fuel cell. Compressive, glass, cermet, and glass-ceramic seals have been used. Sealing is still a key issue in planar SOFC design, because it is difficult to maintain system integrity over the large thermal variation and reducing/oxidizing environment.

The second design, and probably the most advanced, is the seal-less tubular concept pioneered by Westinghouse (now Siemens-Westinghouse) in 1980. A schematic of the general design concept is shown in Fig 4.2. Air is injected axially down the center of the fuel cell, which provides preheating of the air to operation temperatures before exposure to the cathode. The oxidizer is provided at adequate flow rates to ensure negligible concentration polarization at the cathode exit, to maintain desired cell temperature, and to provide adequate oxidizer for effluent combustion with unused fuel.
In many SOFC designs, a combustor is utilized to burn fuel and oxidizer effluent, providing a source of heat for cogeneration during normal operation, and enabling a more rapid start-up transient time. In addition, the combustor effectively eliminates unwanted hydrogen or CO, which is especially high during start-up when fuel cell performance is low. Anode-side hydrogen or CO fuel can be provided externally as in other fuel cells, or internally, by anode-side reformation using recycled water vapor product from the anode reaction and the water-gas-shift reaction. The major advantage of this design is that the difficult high-temperature seals needed for other SOFC designs are eliminated. Tubular designs have been tested in 100 kW atmospheric pressure and 250 kW pressurized...
demonstration systems with little performance degradation with time (less than 0.1% per 1000 hour) and efficiencies of 46 and 57% (LHV), respectively (Singhal [2000]). One drawback of this type of tubular design is the more complex and limited range of cell fabrication methods (Singhal [2000]). Another drawback is high internal ohmic losses relative to the planar design, due to the in-plane path that electrons must travel along the electrodes to and from the cell interconnect. This design can also experience significant losses due to limited oxygen transport through the porous (~35% porosity) structural support tube used to provide rigidity to the assembly.

The monolithic and segmented cell-in-series designs are less developed, although demonstration units have been constructed and operated. A schematic of the monolithic cell design is shown in Fig. 4.2. In the early 1980s, the corrugated monolithic design was developed, based on the advantage of high power density compared to other designs. Both co-flow and cross-flow designs have been built and tested in small demonstration units. The high power density of the monolithic design is a result of the high active area exposed per volume and the short ionic paths through the electrolyte, electrodes and interconnects. The primary disadvantage of the monolithic SOFC design, preventing its continued development, is the complex manufacturing process required to build the corrugated system. The segmented-cell-in-series design has been successfully built and demonstrated in two configurations: the bell-and-spigot and the banded configuration. The bell-and-spigot configuration uses stacked segments with increased electrolyte thickness for support. Ohmic losses are high because electron motion is along the plane of the electrodes in both designs, requiring short individual segment lengths (~1-2 cm). The banded configuration avoids some of the high ohmic losses of the bell-and-spigot configuration with a thinner electrolyte, but suffers increased mass transport losses.
associated with the porous support structure used. The main advantage of the segmented cell design is a higher operating efficiency than larger-area single electrode configurations. That is, each cell in series with small active area can produce a higher output in series than the equivalent total active area in a planar design, because individual cells with favorable conditions can achieve a higher voltage when segmented, that is not possible with a non-segmented design, where concentration polarization or local cold spots reduce the entire active area voltage.

The primary disadvantages of the segmented cell designs include the necessity for many high-temperature gas tight seals, relatively high internal ohmic losses, and requirement for manufacture of many segments for adequate power output. As a result of these disadvantages, the majority of SOFC research is now focused on the seal-less and planar design concepts.

4.3 Literature Review of SOFC Modeling

Fuel cell hardware is presently in pre-commercial development resulting in the unavailability of performance maps for system design and simulation purposes. Therefore, predication of fuel cell performance is highly dependent on models. The literature on SOFC modeling can be put in to different categories depending on the studies performed on SOFC.

The finite differences models listed in Table 4.3 are grouped based upon the absence or incorporation of internal reforming as identified under the Cell description section. The columns under General features have S for steady-state and D for dynamic. The Number of Dimensions of the finite differences models range from 1 to 3; Number of Chemical Species range from 3 to 7; and the Number of Unknowns range from 2 to 15.
Under the Regions columns are Air channel, Fuel channel, Interconnect, Anode, Electrolyte, Cathode, and Lumped solid. Only the finite differences models by Fiard and Herbi [1992] explicitly model each of the six fuel cell regions in a single model. Maloney considers all of the regions, but in two separate models. The first is a detailed anode/electrolyte/cathode model used to calculate current-voltage relationships based on conductivity, thickness, temperature, pressure, gas composition, exchange currents, and diffusions paths. The second model is lumped solid with a fuel channel and air channel which calculates temperature and current distributions. All the other finite difference models in the table homogenize the interconnect, electrodes, and electrolyte into a single lumped region.

The consideration of Mass convection, Mass diffusion, Energy conduction, Energy convection, Energy radiation, and Momentum in the models is listed under the Equations column. The only finite difference model that explicitly considers mass diffusion is that by Fiard and Herbin, [1992] who emphasize the electrochemical aspects of a SOFC. Their model does not include the internal reforming or any of the associated chemical reactions. The only models that consider momentum are those by Sira and Ostenstad [1993] and Ahmed, Mchheetes and Kumar [1991]. The momentum equation is only needed to calculate the channel pressure. However, the appropriate assumption in most cases is that the channel pressure is atmospheric and pressure drop is negligible.

The chemical reactions are listed in Table are $H_2$ oxidation, CO oxidation, $CH_4$ oxidation, methane-steam reforming, carbon monoxide Shift, and the Boudouard reaction for the formation of carbon and carbon dioxide from carbon monoxide. The d’s and e’s under the chemistry column indicate dynamic or equilibrium formulations, respectively.
The Electrochemistry that is considered includes Electron balance, Nernst equation, Faraday’s Law, Krichoff’s Law Tafel (activation), Concentration, Joule Heat, and the Butler-Volmer equation. Only the model by Bleise et al. [1993] whose emphasis is electrochemistry, includes the Butler-Volmer equation which represents the general relation between the current at a particular electrode and activation over potential of the process taking place at that electrode. The output of the models includes Temperature, Pressure, Current, Voltage, Power, Mass flow, Gas composition, Fuel utilization and efficiency. All of the models calculate temperature, and most calculate electric current and gas composition. Only the model by Ahmed, Mcpheters, and Kumar [1991] calculates all of those parameters, but only for a hydrogen-oxidation, lumped-solid SOFC.

The special purpose models generally are used to investigate a specific aspect of a fuel cell rather than its overall performance. Magio [1991] investigates the limiting current of SOFC anodes based upon diffusion and kinetics controlled mechanisms. They conclude that the diffusive effects of gas of gaseous reactants form the fluids phase to the external surface of the catalyst grain are negligible, whereas pore radius, surface area and amount of catalyst impact the limiting current density. These phenomena are typically represented in SOFC models at the bulk level through empirical over potential problems, but at the expense of the mechanistic details. Solheim [1993] investigates in-plane diffusion limited current density under the ribs of an interconnected plate. He concluded the current density drops rapidly under the ribs as a function of penetration distance and reactant concentrations. Thus, a reasonable modeling approximation is not to include the area under the interconnect rib as part of the active surface area of the electrodes. Hsiao [1992] investigates methane-steam reforming in porous anodes based upon thickness,
porosity, pore radius, fuel consumption and current density. Newman and Tobias [1962] investigates current distribution in porous electrodes based upon activation polarization and mass transport of the reacting species. They discuss the validity of macroscopic models to describe microscopic phenomena and conclude that the results are reasonable as long as the length characteristics of the microstructure, such as the diameter of a pore or of a matrix particle, are small compared to a characteristic length of electrode such as is thickness. Alderucci [1992] compare SOFC performance based upon steam reforming, partial oxidation, and exhaust gas reforming. They conclude that electrical efficiencies based solely thermodynamics consideration are highest for exhaust gas reforming ad steam reforming and lower for partial oxidation. Solheim, Tunold, and Odegard [1993] look at the influence of temperature, oxygen partial pressure, and initial water content on SOFC performance. They conclude that energy efficiency is highly sensitive to inlet conditions and may be most easily optimized by connecting several cells in series, each running at its optimum combination of initial conditions. Bossel [1992] provides a technique to evaluate potential fuel cell performance using dimensionless analysis of PEN functions based upon the characteristics length of PEN triple layer and ohmic symmetry of the electrodes. He analyzed ten SOFC configurations and concluded that monolithic designs had the highest performance potential for maximum efficiency, power density and current density. He concluded that planar designs were second in all three categories and that tubular designs were third in all categories.

Harvigsten, Elangovan, and Khandhkar [1992] report using a modified version of TOPAZ to calculate temperatures, voltages and current densities in SOFC single cell. Several linear equation solution methods were implemented by them in TOPAZ to reduce the memory requirement and the increase the solution speed. They also made other
modifications to enable calculation of ohmic heating, radiative heat transfer, and convection. Gas flow rates and compositions for hydrogen, water, oxygen and nitrogen were provided as input.

Arato and Cosata [1991] circumvented this problem by limiting their model to two dimensions and making other simplifying assumptions. They lumped the interconnect, anode, electrolyte and cathode as a single composite structure, they assumed the temperature was uniform through the thickness of this solid structure and used a simplified Tafel model based on a uniform voltage throughout the cell. The model was used to calculate steady state temperature and current density profiles and also dynamic response to load changes. However, all of the simplifications greatly limited the overall usefulness of the model.

Early mathematical modeling tubular SOFCs was performed by Dunbar [ ] and Wepfer et al. [1984]. Debendetti and Vayenas [1983] were the first to model flat planar SOFCs. These authors developed a 2-D modeling approach still in use today, which approximates the cell stack as set of unit cells operating as continuously stirred tank reactors (CSTRs). The CSTR approximation assumes that the solid and gaseous phase temperature and compositions are uniform in the unit cell. This approach enables the representations of a unit cell in terms of only three mesh points ( one for air and fuel gas phase, and one for the solid phase) in the calculation of the temperature distribution. However, conduction heat transfer is not accounted for, the cell is considered to be adiabatic, and the model is limited to hydrogen only fuel gases. Conduction heat transfer will alter the temperature distribution in the solid cell, esp. for the thicker anode cell supported SOFC designs. The adiabatic assumption is appropriate for a cell placed deep
inside a stack and not exposed to surroundings, but the cell ends would still be subject to heat loss.

Ahmed, et al. [1991] developed a 2-D model of a monolithic cell following a similar approach as the unit cell approximation described previously. The model again assumes the cell is placed deep within a stack and makes steady state heat and mass balances on the unit cells. The limitations of the models are 1) convection is the only mode of heat transfer accounted for (neglecting conduction and radiation), 2) pure hydrogen is used as fuel, 3) only ohmic cell polarization is considered.

Table 4.4 gives a more detailed view of the commercial fuel cell software available. The Emmeskay fuel cell model is a zero dimensional fuel cell stack software package. The model is based on Math works graphical simulation code Simulink. It can run fixed and variable time steps and can run in real time mode. It can run fixed and variable time steps and can run in a real time mode. The fuel cell stack in this model is modeled as a “black box”, using a MATLAB S-function to link to a compiled proprietary source code. It features details such as water transport across the membrane, water condensation and evaporation, and transfer of the heat generated due to reaction. Two empirically based steady-state fuel cell system models are integrated into NREL’s publicly released vehicle analysis software ADVISOR 2002. GCTool was one of the first fuel cell software packages publicly available. Developed and maintained by ANL, it is sequential model programmed in C-based language. It contains models of different types of fuel cells and system components such as reformers, condensers, pumps and nozzles. The fuel cell package in Easy of Ricardo is similar to GCTool. Both GCTool and Easy5 are block-based fuel cell system simulation software packages. Fluent has released its fuel cell
package in year 2004. It is still going to use the core Finite Volume Fluent code and used the subroutine or UDF for Electrochemical, Electro potential equations.
Table 4.3 SOFC modeling literature from 1967-2003

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<td>Maggio 1991</td>
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<td>SP S 1 3</td>
<td>x</td>
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<td>x</td>
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<td>Hsiao 1992</td>
<td>P in</td>
<td>SP S 1 5 8</td>
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<td>e</td>
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Table 4.4 Overview of some commercial fuel cell software

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Chapter 5

Case study: Reformed Hydrogen Fuel Cells system (RHFC)

5.1 Introduction to RHFC system

As a result of the booming development of electronic applications, demands on portable power suppliers are increasing rapidly. As a portable power source, polymer electrolyte membrane (PEM) fuel cells can produce electricity continuously with the supply of fuels (such as hydrogen and methanol). This advantage enables consumers to use their portable electronics constantly without a charging procedure as necessary with secondary batteries. Hydrogen fuel cells have relatively high power density and lower precious metal (e.g. Pt) loading. As a fuel, pure hydrogen gas is not practical because of storage issues. Hydrogen generation from hydrocarbon fuels is more suitable for supplying fuel.

Currently the most widely used polymer electrolytes of low temperature PEMFCs (<100°C) are based on Perflourosulfonic acid polymer membranes (e.g. Nafion®). It is well known that the conductivity of Nafion® membrane is proportional to the amount of water absorbed in the membrane. Humidification of the fuel streams is required, yet excessive water can result in blocking reactant transport to the reaction zone. Thus, water management using auxiliary facilities is required, increasing the complexity of fuel cell system and reducing efficiency. Another disadvantage with low temperature PEMFCs(<100°C) is the low tolerance towards carbon monoxide. An additional reactor or separator is necessary to clean the reformation gases sufficiently to avoid CO poisoning of the catalyst.
Interest in elevated temperature PEMFCs (140-200°C) is receiving increased attention because above 140°C anode catalyst poisoning by CO is less significant, allowing operation with CO concentrations more than 100 times those allowable in low temperature fuel cells. Therefore, the reformed products from liquid fuels can be fed directly to the fuel cell. Fig 5.1 shows the figurative comparison of different PEM fuel cell technologies. With Conventional PEMFC (operating temp. 25-80°C) the major problem is storage of pure hydrogen, although its performance is excellent. Fuel storage
can be solved using methanol or hydrocarbon used as primary fuel and converted into hydrogen using fuel processor, which then feed to fuel cells. In this technology the PEMFC operates at normal temperature of (25–80°C), but the problem with technology is the bulky and complex fuel processing process. This problem can be eliminated by operating the fuel reformer and combustor at same temp around (230°C) and fuel cell stack at 160 °C. At this Elevated temperature the fuel cell system is tolerant to CO.

5.2 System Components

The Energy Technologies team at Motorola Labs has been actively developing fuel cell based systems for portable electronics since 1999. Recently, efforts have concentrated on demonstrating a net 25W_e reformed methanol power system that possesses high energy density and is compact, lightweight, and efficient. A schematic of this system is shown in Figure 5.2. The key system components are the onboard miniature methanol steam reformer (200-230°C) integrated with an elevated temperature fuel cell stack (150-200°C).

Methanol was chosen as the fuel for this system because it has a relatively high energy density (4780 W_e/hr/l or 6090 W_e/hr/kg at 100% theoretical electrochemical efficiency) while being able to be steam-reformed at temperatures as low as 200°C. Interest in elevated temperature (>120°C) proton exchange membrane fuel cells (PEMFCs) has been growing steadily since the demonstration in the mid 1990s that polybenzimidazole (PBI) doped with strong oxo-acids are capable of good proton conductivity, low gas permeability, and do not require humidification, among other benefits (1). These benefits, along with the relatively high power densities possible using them, provide a solution to the issues associated with low-temperature PEMFCs, such as
high precious metal loadings and low power density (DMFC), and the difficulty of generating and storing very pure H₂ (low temperature PEMFC). Operation at temperatures above 150°C significantly increases the carbon monoxide tolerance of the electro catalysts, allowing operation with H₂ fuel containing up to ~100-300x the CO limits for low temperature direct hydrogen cells (2). The benefit of high CO tolerance is that the production of the H₂ feed by reformation of a liquid hydrocarbon, such as methanol, can be done in a single, relatively small reactor and with no Pd membrane separator, significantly reducing the penalty paid for on-board fuel processing. Additional benefits include: enhanced kinetics for both electrode reactions, and simplified water management, as only gas-phase water is present.

While other materials are actively under investigation as candidates for elevated temperature PEMFC applications, PBI-based MEAs are currently the only commercially available materials for elevated temperature PEMFCs. The majority of research reported on PBI based fuel cells has been done in single cells. In this work, a series of ~25W prototype fuel cell stacks employing Celtec® P-Series 1000 MEAs were built at Motorola Labs, for integration with methanol-steam reformation based miniature fuel processor. The performance of these stacks was evaluated at projected system operating parameters such as the current load (~200mA/cm²), system pressure (ambient), and gas stoichiometry (anode stoichiometry 1.1). In order to achieve better insight and understanding of the limitations of the system, simulated reformate gas of composition 75%H₂:24%CO₂:1%CO was fed to the stack for investigation of the effect of 1% CO on performance. This gas composition was chosen to mimic the gas stream produced by our prototype fuel processor.
5.2.1 PBI Fuel Cell Stack:

The RHFC stack consists of a repeating arrangement of a ribbed bipolar plate, the anode electrolyte matrix, and cathode as shown in fig 5.3. The ribbed bipolar plate serves to separate the individual cells and electrically connect them in series. The material of plate is graphite composite, which was tested in our labs and found to be stable and robust under the fuel cell operation conditions.

The resistance of cell hardware is important because lower resistance results in higher net output power under the same operation conditions. It is well-known that the conductivity of graphite is related to its structure. Conductivity is also a function of temperature. The resistance of our graphite composite was determined as follows. Tests were carried out at 160°C (averaged fuel cell operation temperature) with temperature fluctuations within 5°C in both in-plate and through-plate directions. Figures 5.4 a) and b) shows the voltage/current behavior of the graphite composite in two directions. According to Ohm’s law, the in-plane resistance can be found from the slope of the
curve. Thus, conductivity of this material in the two different directions can be estimated by:

$$\sigma = \frac{1}{\rho} = \frac{l}{RS}$$  \hspace{1cm} (1)

Fig. 5.3 Electrical resistance of graphite complex
The calculated values are listed in Table 1. These values are several orders lower than that of metals (such as silver, copper, alumina etc). Although the conductivity is higher for in-plate direction than through-plate direction, the whole resistance for the in-plate direction is much higher than for the through-plate direction because the cross-section area is much less. It is not suitable for bi-polar plates to pass current through in the in-plate direction in accordance with above analysis. During the operation of a fuel cell, most of current passes through the plate surface contacting the MEA. Therefore, the cross-section area is roughly equal to the projected area of MEA. For stack design, the ratio of MEA area and the total length of the bi-polar plates need to be considered in order to avoid high voltage drop.

5.2.2. Description of PBI Membrane:

PBI membrane is a basic polymer. Acid and water are absorbed by hydrogen bonding with the nitrogen atoms in the benzimidazole rings as shown in Fig.5.5. The maximum amount of bonded acid is about 2 per repeat unit of PBI. In addition to the bonded acid, PBI membrane can imbibe more phosphoric acid as free acid. Both bonded acid and free acid can be washed out by water and methanol in accordance with the study.

<table>
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<tr>
<th>Thickness (cm)</th>
<th>Cross-section area (cm²)</th>
<th>Resistance (Ω)</th>
<th>Conductivity (s/cm)</th>
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<tr>
<td>Through-plate</td>
<td>4.26</td>
<td>32.57</td>
<td>0.027</td>
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of Li et al [2000]. It seems that PBI serves as solvent to solve phosphoric acid (solid solution). As contacting with other strong polar solvents like water, phosphoric acid solvated in the membrane can be solved by water due to stronger solvated effect.

Fig 5.4 Poly [2,2’ (m-phenylene) – 5,5’ bibenzimidazole] (PBI)

It is known that the conductivity of PBI membrane doped by phosphoric acid (PBI/\(xH_3PO_4\)) is the function of doping acid level, temperature and relative humidity. Based on the study of Li et al [2000], the conductivity of PBI/\(xH_3PO_4\) increases with the increasing of acid doping level. For lower level doping (such as around 2 per repeat unit of PBI), proton transport mainly happens between basic sites on the polymer. As increasing doping level, the state of free phosphoric acid in the membrane could be similar to pure phosphoric acid (the IR spectra of PBI/4.2\(H_3PO_4\) is similar to pure phosphoric acid as studied by Glipa et al [1999]). Thus proton could transport between basic sites and between phosphoric acid (the same as proton transport in concentrated phosphoric acid), which contribute to the increasing conductivity. It is agreed that water is critical for the conductivity of PBI/\(xH_3PO_4\) although the required amount of water for sufficient conductivity is much lower than that of Nafion membrane. Ma [2004] et al
suggested that higher conductivity results from a three-dimensional network by hydrogen bond between water and phosphoric acid. It is skeptical that only small amount of water can benefit the network so efficient. Without water, phosphoric acid could be self-dissociated by the following reaction:

\[
2H_3PO_4 \leftrightarrow H_4PO_4^- + H_2PO_4^- \quad \text{fast} \tag{1}
\]

\[
2H_3PO_4 \leftrightarrow H_3P_2O_7^- + H_3O^+ \quad \text{slow} \tag{2}
\]

Water would help the dissociation process as the following:

\[
H_4PO_4^+ + 2H_2O \leftrightarrow H_2PO_4^- + 2H_3O^+ \tag{3}
\]

The \( H_3PO_4 \) could also react with water as:

\[
H_3PO_4 + H_2O \leftrightarrow H_2PO_4^- + H_3O^+ \tag{4}
\]

From above equations, it can be seen that “free proton” could exit especially with the addition of water. The adequate “free proton” within the membrane might be critical to the conductivity. Compared with other ionic species, proton may be easy to transports. As we all known, PBI membrane is a base membrane and it would change to acid membrane with doping acid. Under acidic environment, “free proton” could exit stably. That means that acidic environment could be necessary to gain suitable conductivity. That might explain the conductivity enhancement as increasing acid doping level and account for the increasing conductivity with absorbing water. As mentioned before, phosphoric acid network also improve the conductivity. Although the conductivity mechanism is still not clear, water exiting within membrane enhances the conductivity dramatically.

Another interesting phenomenon is the redistribution of acid within MEA. During the pre-conditioning (activation) period, acid fog was seen from cathode exiting gas. The
fog results from phosphoric acid carrying out by gas, which adsorbs water in the surroundings. Both anode and cathode exhausted gases were condensed, and the solution was tested by PH paper. Strong acid was shown by the test. After all fuel cell testing, the stack was disassembled. It can be seen water droplet gradually generates on the surface of MEA. It seems that phosphoric acid within membrane redistributes during activation. This can result from temperature increase, water generation or current loading, and all factors could contribute the redistribution. It goes into catalyst layer, which can benefit the electrochemical reaction. It is well known that electrochemical reaction within fuel cell occurs at the interface of three phases (catalysts/electrolyte/reactant gases). Acid in the catalyst layer would increase real reaction area (the enhancement of three-dimensional reaction zone). Cell potential under the same current rises due to the decrease of the real current density. The relation between current and true current density can be expressed as the following:

\[ i = \frac{i_s}{a_0l} \]  \[5\]

where \( a_0 \) and \( l \) represents the specific surface area and thickness of catalyst layer respectively. Here \( i_s \) is the superficial current density, i.e.

\[ i_s = \frac{I}{A} \]  \[6\]

\( I \) is the total current passing through the cell and \( A \) is the projected surface area of electrode. Therefore, gas diffusion layer (GDL) is very important because excess acid could block gas transport resulting mass transport loss. Hydrophobic GDL is required to maintain efficient gas transport.
Carbon monoxide tolerance is one of advantages of PBI/$xH_3PO_4$ based fuel cells. As discussed before, methanol is preferred to be employed as the feeding fuel instead of pure hydrogen. As shown in Fig 5.6 the layout of fuel processor, the primary fuel methanol undergoes reforming reactions to produce the required fuel. The reactions based on steam reforming of methanol are known as follows:

\[
\begin{align*}
CH_3OH + H_2O & \rightleftharpoons CO_2 + 3H_2 \quad [7] \\
CH_3OH & \rightleftharpoons CO + 2H_2 \quad [8] \\
CO + H_2O & \rightleftharpoons CO_2 + H_2 \quad [9]
\end{align*}
\]

Equation [7] is the main reforming reaction. Equation [8] and equation [9] represent the methanol decomposition reaction and the water-gas shift reaction. From above equations, it can be found that CO as a byproduct is presented in the reformatted gases, which consist mainly of hydrogen, carbon dioxide and small amount of carbon monoxide, water and un-reacted methanol vapor. In ideal case (only the main reforming reaction occurs), the mixture gas consists of 75% hydrogen and 25% carbon dioxide.

### 5.3 Results & Discussions

During start-up, the stack was heated to 140°C with gas flow. No current load was put on the stack below this temperature to avoid possible liquid water generation which could wash out phosphoric acid (electrolyte) inside PBI membrane and damage the MEA. The stack performance during the break-in. A constant current load of 1.8A was put on the stack for the first 20 hours. After about 2 hours at 2.2A load, the current load was lowered to 2A. Voltage changes with time for these three discharge conditions show the same tendency: voltage increases continuously even though current is held constant.
It appears that the voltage and current behavior during break-in of the PBI stack does not follow the trend of typical PEMFCs V-I curve. There are several factors that could contribute to the steady increase of voltage. As current was drawn from the fuel cell stack, heat $q_{total}$ was generated due to the reversible heat generation $q_r$ and irreversible heat generation $q_{irr}$. These values can be determined by:

\[ q_{total} = q_r + q_{irr} \]  
\[ q_r = \Delta H - \Delta G \]  
\[ q_{irr} = nF(E_{eq} - V) \]

Here $\Delta H$ and $\Delta G$ represents enthalpy change and Gibbs free energy change of the reaction respectively. Gibbs free energy change is related to equilibrium potential as:

\[ \Delta G = -nFE_{eq} \]  

Note that equation (13) shows the maximum electric work that can be delivered by the system. Another potential, thermal potential, can be then similarly defined as:

\[ \Delta H = -nFE_{th} \]

By the above definition, it is convenient to calculate the total heat generation and heat generation rate according to different current loading.

\[ q_{total} = q_r + q_{irr} = nF(E_{th} - E_{eq}) + nF(E_{eq} - V) = nF(E_{th} - V) \]

\[ \dot{q}_{total} = \dot{q}_r + \dot{q}_{irr} = (E_{th} - E_{eq})I + (E_{eq} - V)I = (E_{th} - V)I \]

Total system and electrochemical reaction efficiency can then be determined by:

\[ \eta_{total} = \frac{W_{electric}}{nFE_{th}} = \frac{V}{E_{th}} \times 100\% \]

\[ \eta_{electrochem} = \frac{W_{electric}}{nFE_{eq}} = \frac{V}{E_{eq}} \times 100\% \]
From above discussions, it can be seen that the system would be heated up as long as current passes. Both cathode and anode electrochemical reaction rates benefit from the increasing temperature, according to Arrhenius equation that is commonly employed to describe temperature effect on the reaction rate, which results in the lower overpotential due to the activation polarization (e.g. lower voltage drop and higher cell voltage) at the same current density. Note that the conductivity of electrolyte increases with the enhancement of operation temperature as well, which can also be expressed by Arrhenius equation:

\[
\sigma = \sigma_0 \exp\left(-\frac{E}{RT}\right)
\]  

(19)

where \( E \) represent the activation energy of conductivity.

After 3 hours at constant current load, the temperature of the stack achieved steady state. However, it was found that voltage was enhanced even though stack temperature was stable. Other factors must cause this enhancement. Prior to applying current load, the stack was heated as dry hydrogen and air were fed, conditions that dry out the PBI membrane. After applying a current load, the following reactions occur at the anode and the cathode respectively.

\[
H_2 \rightarrow 2H^+ + 2e
\]  

(20)

\[
\frac{1}{2}O_2 + 2H^+ + 2e \rightarrow 2H_2O
\]  

(21)

Although water is only generated at the cathode side according to Eq. (21), it can be transported to the anode side by diffusion, facilitated by the pressure difference between the cathode and anode (generally gas pressure on cathode side is higher than anode side). One dimensional water transport from cathode to anode can be described as:
\[
\dot{N} = D_{\text{eff}}^{H_2O} \frac{\Delta c^{H_2O}}{l_{\text{mem}}} + c^{H_2O} K \frac{\Delta P}{l_{\text{mem}}} - \frac{\lambda}{nF} I
\]

where \(D_{\text{eff}}^{H_2O}, K\) and \(\lambda\) are water effective diffusion coefficient, water permeability and water electro-osmosis drag coefficient. Current flows from anode to cathode, which means that water flux caused by the electro-osmosis effect is away from the anode side. Water flux caused by the concentration gradient and pressure drop between cathode and anode (usually cathode pressure is higher than anode pressure) is directed to the anode side. The system was running near surrounding pressure for both anode and cathode side. Therefore, water transport was mainly driven by the water concentration gradient. Anode side exhaust gas directed through a “cold trap” (i.e., a glass trap cooled by a water/ice mixture), where water vapor condensed and liquid water was collected. Note that it would take time for the membrane to reach equilibrium hydration from a fully dry state, and water concentration within the membrane could be affected by operation temperature.

**Stack Performance:**

**Version 1 Design:** The first stack built and tested at Motorola Labs was a straightforward design for the purposes of benchmarking fabrication and performance issues, and was described previously (8). Briefly, we identified materials that were stable to the hot phosphoric acid fuel cell environment, constructed a 25W stack, and demonstrated over 300 hours operation producing in excess of 26W under both hydrogen and simulated reformate (1%CO). In addition, the thermal profile of the stack was measured as a function of current load and cathode stoichiometric.

**Version 2 Design:** The flow field of Version 2 was designed for lower pressure drop, and to optimize cooling by varying the cathode stoichiometry. Using what was learned
from the Version 1 design, the backing plates of the Version 2 design were modified so that the cathode air would first cool the stack, and then cross the MEA to react with the cathode electrocatalyst. After heating to 160ºC and gradually increasing the load, the stack was run almost continuously over 400 hours. Not all the data was recorded because our life-test software was locking up periodically and not writing data to the file, however, the stack was still running under load. The overall life test is shown in Figure 5.7. After about 130 hours the stack was shut down so that the test station software could be upgraded to include internal mixing of reformate gas and to debug stack testing software.

During the course of this life-test, the effect of cathode stoich and current load on thermal profile was studied, as well as performance at low anode stoich. As expected,

Fig. 5.5. Life test of the first Version 2 design stack (left), voltage vs. load (center) and power vs. current density (right).

increasing the cathode stoich resulted in a cooler stack and lower voltage, while increasing current density resulted in higher stack temperature. Figure 5.7 shows the voltage at different loads (center), with the data repotted as a traditional polarization and power curve (right).
The most pressing issue in stack development from a system perspective concerns the fuel utilization on the anode. A simple energy balance of a 20W scale RMFC system quickly reveals that an optimized fuel processor should require only ~10% of the energy required by the fuel cell stack. This results in a system design based on 90% fuel utilization on the anode. In other words, it is critical to demonstrate stable stack performance operating at anode stoichiometry of 1.1 in order to achieve an optimum efficiency of the RHFC system. Since the hydrogen reduction reaction is so facile when pure hydrogen is used as the fuel source, we investigated the effect of anode channel geometry on stack performance using reformate gas. It was found that when the flow field channels are shallow, higher anode stoichiometry is needed in order to maintain stack voltage at acceptable levels. Figure 5.8 shows Version 2 stack performance at the lowest achievable stoichiometry (1.5) when anode channel depth is shallow, compared when the flow field channels are deeper (1.1). We have consistently operated our 25W stacks at these low reformate stoichiometries when the optimized channel geometry is used.

![Reformed Hydrogen (75% H2, 25% CO2) Stack Life Test](image1)

**Fig 5.6.** Effect of anode channel geometry on stack performance under simulated reformate gas (75%H₂: 25%CO₂). Shallow channels (left) and deeper channels (right).
**Version 3 Design:** Version 3 stack employs the same bipolar plates and MEAs as the Version 2 design but integrates a new fuel manifolding design. The first test run with this new design utilized the same stack “core” (MEA’s and bipolar plates that had not been taken apart) from an earlier Version 2 stack test in order to demonstrate the effect of changing only the backing plates. Figure 5.9 shows the power comparison of Version 2 & 3 stacks. The new backing plates produced an average of 25 Watts when fed an anode stoichiometry of 1.1 ($S_a=1.1$) and a cathode stoichiometry of 6.5 ($S_c=6.5$).

![Power Curve at $S_a=1.1$ (75%H2, 24%CO2, 1%CO) at Load=2.2 Amps](image)

**Fig 5.7.** Power output comparison of Version 2 & 3 stacks.

In the tests of the Version 3 fuel cell stack, it was necessary to run the cathode at very high stoichiometry (>6) in order to maintain the stack temperature below 180ºC. Unfortunately, these high flow rates caused a significant pressure drop (~1psi) through the cathode. It is desirable from a system perspective to have as low a pressure drop through the cathode as possible so that a more efficient fan or blower can be used instead of a high pressure head air mover such as a compressor or diaphragm pump. Fortunately,
the flow through the cathode (and thus the pressure drop) can be reduced significantly by integrating the fuel vaporizer into the thermal envelope of the stack so that much of the waste heat from the fuel cell is used to vaporize the incoming fuel instead of being carried out with the cathode exhaust. Figure 5.10 compares the thermal profile of the Version 3 stack without vaporizer, with vaporizer alone (i.e., not operating), and with an operating vaporizer. The effect of an integrated vaporizer on thermal profile is quite dramatic, improving the thermal profile in the stack significantly.

Fig. 5.8 Integration of a vaporizer with the Version 3 stack and the effect on thermal profile.

Integrating the vaporizer with the stack also enabled the use of much lower cathode stoichiometry ($S_c<2$) to maintain the desired stack operating temperature. The impact of this result on the system is that a smaller and more efficient blower can be used for the cathode feed. Figure 6 shows the effect of cathode stoichiometry on the thermal profile of the Version 3 stack with vaporizer. During these experiments the anode was fed reformate at stoichiometry 1.1. We found that it was possible to run the stack with air
flows as low as 1.5 stoich on cathode side. The low pressure drop measured during these experiments (<0.1psi) will enable us to use the lower power pump for feeding the cathode of the fuel cell stack.
Chapter 6

Conclusion & Recommendation

6.1 Conclusions

This work has been performed on characterizing the vortex structure in sinusoidal wavy channel, which can used as interconnect or bipolar plates in high temperature fuel cells. It will provide uniform cooling of fuel cell stack, which will enhance the durability of the system. The salient features of this work can be summarized as below:

6.1.1 Compact Heat Exchanger

1. Experimental characterization of swirl flow in a sinusoidal wavy channel was performed by injecting very fine aluminum dust (63 µm) in the flow field for a wide range of steady laminar flows (135 ≤ Re ≤ 700) and duct-geometry variations (0.25 ≤ γ ≤ 0.5, and 1.0 ≤ ε ≤ 1.5). The experimentally visualized flow fields amply validate the computational stream function simulation. The wavy-wall curvature induces lateral vortices in the trough region, which grow in magnitude and spatial flow coverage with increasing Re and/or γ. The inter-plate separation, however, is critical for the development of this flow structure. With small separation (ε ≤ 0.5), viscous forces dominate and a streamline, fully developed duct flow type behavior prevails. With larger inter-plate gap (ε ≥ 1.0), this effect diminishes and the boundary-layer separation downstream of corrugation peaks gives rise to a vortex flow structure in the valley region. The recirculation is enveloped in the near-wall axial flow separation bubble, and its spatial growth is governed by Re, γ, and ε.

2. LDV measurements were performed in phase wavy channel at vertical plane crossing the mid point of crests and troughs to capture the velocity profile. It validates the results
obtained from the flow visualization in wavy channels. The flow is still periodically full
developed as the flow profile is parabolic but it is shifted from the center because of the
waviness of the test section. As the Reynolds number is increase the wall induced effects
dominates the viscous effects, as a results we see the recirculation in the trough of the
wavy channel.

3. The recent interest in various fuel cell systems including portable electronics,
automotive and stationary power has resulted in increased understanding of the relevant
mechanisms controlling performance, but each system has unique barriers which must be
overcome. Future performance enhancements, environmental regulations and incentives,
and increased conventional energy costs should provide ample financial impetus for
continued research. In general, future fuel cell research will result in reduction in
manufacturing and component cost, increased system longevity, and enhanced system
modeling for use as a design optimization tool. In addition, high performance and
longevity must be demonstrated in real world systems, as the transition from laboratory
steady state operation to commercial product is made. The main goals specific to H2 PEM
fuel cell research include finding membrane-electrode assemblies with increased CO
tolerance, better performance in dry conditions, and reduced catalyst loading. Finally,
future SOFC research will likely result in performance increases through reduced internal
component resistance and novel design, lower operating temperatures, and ease of
manufacturing.

4. Reformed Hydrogen Fuel Cells system: A successful experiments was performed on
25W elevated temperature fuel cell stacks operating at 160°C using reformate fuel at high
utilization (anode stoichiometry 1.1). By integration with a working fuel vaporizer we
have shown that low cathode stoichiometry is sufficient for thermal management. These results enable a compact, lightweight power source that is a key component towards demonstration of a net 20Wc reformed methanol power system for portable electronic applications.

**6.2 Recommendations for future work:**

The characterization of flow behavior in a wavy channel will help in optimizing the performance of plate heat exchangers. The following are recommended for future research to advance the understanding in the flow behavior in wavy channels.

1. As increase in friction factor is one of the penalties of flow through a wavy channel, a detailed study of measurement of pressure drop at different Reynolds number in different duct-geometry variations ($0.25 \leq \gamma \leq 0.5$, and $1.0 \leq \varepsilon \leq 1.5$). These results will help in optimizing the design of wavy plate heat exchangers.

2. To study the behavior of flow in out of phase wavy channels. The phase angle can be considered as a variation parameters along with the corrugation ration and fin spacing ration.

3. To understand the instability of flows at high Reynolds number a detailed study of LDV measurements can be done. A Turbulent intensity measurement will provide the magnitude of the instability in the flow which will help in characterizing the flow at high Reynolds numbers.

4. An exhaustive numerical study can be performed on sinusoidal wavy channel with the variation of fin spacing ratio ($\varepsilon$) and corrugation ratio ($\gamma$). It will help in optimizing the wavy channel configuration.
5. In case of PEMFC stack design the wavy shape can be used to optimize the stack design. The traditional designs of PEMFC (Proton Exchange Membrane fuel cells) stacks have been based on planar, repetitively stacked a structure which consist of repetitive units of plates and MEA (Membrane electrode assembly). A new stack design is based on the waved tube cell (WTC) concept. This design is the physical embodiment of a novel fuel cell architecture aimed at developing high power density stacks that utilizes non carbonaceous materials and easily manufacturability components.

![Fig 6.1 wavy tube cell concept with three-dimensional, non-planar MEA structure](Merida 2001).

In planar stack configuration only a portion of the active area is exposed to the flow of reactants in the flow channels. At the point of contact, the porosity of the gas diffusion layer is reduce by the clamping pressure required to ensure perimeter sealing, prevent reaction contact resistance. As consequences this particular design represents a trade off between larger exposed areas and larger contact area. To achieve the higher volumetric density the planes of oxidant and fuel distribution channels must be collapse onto a single plane. This can be possible with a non planar MEA as shown in Fig 6.1. This stacks has been proposed to be used for high temperature fuel cells.
REFERENCES:


W. J Wepfer, M.H Woolsey, ‘High Temperature Fuel Cells for Power Generation,”


P. Hendrisken, SOFC Modeling 2: Unit cell, Materials Departmetns, Riso National Laboratory, Denmark (1996).


Maloney, T.S.” Computer Modeling of Solid Oxide Fuel Cells” PhD. Dissertation, Cleveland State University, March 1990.


APPENDIX A RENOYLD'S NUMBER CALCULATION

Reynolds number calculation for different test section:

1. spacing ratio \( \varepsilon = S/2A = 1 \), flow cross-section aspect ratio \( \alpha = S/H = 0.5 \)

\[
\text{Cross section area} = 15 \times 1 = 15 \text{ cm}^2 \\
\text{Perimeter} = 2 (15+1) = 2 \times 16 = 32 \text{ cm}
\]

Hydraulic diameter
\[
D_h = \frac{4A}{P} = \frac{4 \times 14}{32} = 1.75 \text{ cm} \text{ or } 0.0175 \text{ m}
\]  

(1)

Reynolds number is given by:
\[
Re = \frac{\rho UD_h}{\mu} 
\]  

(2)

Multiplying numerator and denominator of eq 1 by \( A \) we get:
\[
Re = \frac{\rho UD_h A}{\mu A}
\]  

(3)

From mass continuity equation
\[
m = \rho UA
\]  

(4)

Inserting eq (4) into eq (3) we get:
\[
Re = \frac{m D_h}{\mu A}
\]  

(5)

For water \( \rho = 1000 \text{ kg/m}^3 \), \( \mu = 0.799 \times 10^{-3} \)

Inserting the values of in \( \mu, D_h, A \), eq (5):
\[
\text{Re} = m \times 1.46 \times 10^4
\]

or
\[
m = \text{Re} \times 0.6849 \times 10^{-4} \text{ Kg/sec}
\]  

(6)

Conversion of \( \dot{m} \) (Kg/sec) to \( \dot{m} \) (ml/min)

\[
\dot{m} = \text{Re} \times 0.6849 \times 10^{-4} \times 60 \times 1000 \text{ mil/min}
\]

\[
\dot{m} = \text{Re} \times 4.1094 \text{ mil/min}
\]

or
\[
\text{Re} = \dot{m} \times 0.2433
\]  

(7)

using eq (7) Reynolds was calculated using the calibration chart of the FLT-115 Rotameter.

Calculation of Average velocity:
From eq (7):
\[
\text{Re} = \dot{m} \times 0.2433
\]  

(7)

Where,
\[
\text{Re} = \frac{\rho \dot{U} D_h}{\mu}
\]
APPENDIX B UNCERTAINTY ANALYSIS

Since laser-Doppler Velocimetry is an nonintrusive measurement technique, the prospect of obtaining accurate results is good. The major source of error is not the velocity measurement themselves: they are correct within 1% or so. The major difficulty is to position the measurement volume correctly in the duct. The overall uncertainty is composed of overall fixed and random errors. According to Moffat [], the overall random error may be deduced from the observed multiple–sample data set. In the present study a measure of the overall random error is obtained from the rms values of the velocity measurements.

Fixed error due to calibration

The flow are primarily calculate the Doppler frequency. To obtain the velocity, the Doppler frequency is multiplied by a calibration factor that is determined by the wavelength of the incident laser beams and angle between them. The uncertainty in the determination of the angle gives an estimated fixed error \( \delta V / V \) of 1%. Here \( V \) stands for measured velocity components \( u_y \) and the notation \( \delta V \) means that with 95% confidence the true velocity is within \( V \pm \delta V \).

Fixed error due to Determination of Re

The Reynolds number for a square duct can be calculated from \( Re = \frac{mD_h}{\mu A} \), where the mass flow is determined by weighing the amount of water collected in a timed interval and \( \mu \) is determined at the fluid temperature. The uncertainties in the determination of the mass and the hydraulic diameter are most important, and the overall uncertainty in Re is estimated to be \( \delta Re / Re \approx 4\% \). Depending on which point in the duct is being considered,
a given uncertainty in the Reynolds number will give rise to varying uncertainties in the velocity components.

**Random Errors**

The overall random error is estimated from the rms values of the velocity measurements. The rms value of a measurement is denoted by $V_{\text{rms}}$ and $2V/\sqrt{N}$ by $\delta V_{\text{rms}}$. Then with approximately 95% confidence, the true velocity is within $V_{\text{mean}} \pm \delta V_{\text{rms}}$ if there are no fixed errors. $N$ is the number of observations of the velocity in a measurement and should at least 30 or so for the above estimate to be valid. The random errors were pronounced in the vicinity of the wall of the ducts.

The major contribution to the rms value comes from so-called gradient broadening, which is due to the finite size of the measurement volume. This is especially important at the outer wall, where the velocity gradient is large and the measurement volume is oriented along the gradient. Other contribution to the rms values could come from scattering particles that do not follow the flow exactly “optically noise” due to, for example particle passing the laser beams ahead of the measurement volume and vibration in the Laboratory. The accuracy of the floware is given as 0.1% of the selected bandwidth for a record length of 64 samples. According to Dantec, this is a random error, which for the present bandwidth and numbers of bursts is completely negligible.

**The Overall Uncertainty**

The overall uncertainty in a measurement is obtained as the root- sum square combination of all fixed errors and the random error $\delta V_{\text{rms}}$. The value found out is 1%.
APPENDIX C LDV Velocity Data

Normalized velocity and distance calculation for wavy channel $\alpha=0.25$, $\varepsilon = 1.0$ at Re=248

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Velocity magnitudes for wavy channel $\alpha=0.25$, $\varepsilon = 1.0$ at $Re=135, 248, 390, 600$

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Comparison of LDV measured velocities and Numerical values at channel $\varepsilon =1$, $\gamma =0.25$ at $Re =350$.

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