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AN EXPERIMENTAL INVESTIGATION OF THE ROLE OF RESONANCE HEATING IN THE AUTOIGNITION OF FLOWING COMBUSTIBLE GAS MIXTURES

DISSertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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1970

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Studies in Physics. Professor K. N. Rao
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LIST OF SYMBOLS

\( a \) \hspace{1cm} \text{Local speed of sound}

\( A \) \hspace{1cm} \text{Cross sectional area}

\( C_p \) \hspace{1cm} \text{Specific heat at constant pressure}

\( d \) \hspace{1cm} \text{Diameter of fuel or oxidizer inlet lines}

\( f \) \hspace{1cm} \text{Frequency in Hertz (Hz)}

\( l \) \hspace{1cm} \text{Length of fuel line as measured from mixing tube}

\( \dot{m} \) \hspace{1cm} \text{Mass flow rate}

\( L \) \hspace{1cm} \text{Exposed length of fuel line windows}

\( M \) \hspace{1cm} \text{Mach Number}

\( M_1 \) \hspace{1cm} \text{Mach Number of the flow ahead of the shock relative to shock fixed coordinates}

\( M_2 \) \hspace{1cm} \text{Mach Number of the flow behind the shock relative to shock fixed coordinates}

\( \mathcal{M} \) \hspace{1cm} \text{Molecular weight of gas}

\( P \) \hspace{1cm} \text{Static pressure}

\( P_{\text{MAX}} \) \hspace{1cm} \text{The maximum value of the pressure fluctuations occurring within the resonating fuel line}

\( P_{\text{MIN}} \) \hspace{1cm} \text{The minimum value of the pressure fluctuations occurring within the resonating fuel line}

\( P_0 \) \hspace{1cm} \text{Total pressure}

\( P_R \) \hspace{1cm} \text{Instantaneous static pressure in resonating fuel line}

\( F_R \) \hspace{1cm} \text{Average static pressure in resonating fuel line}
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<td>$P_{RF}$</td>
<td>Reflected shock pressure as calculated from incident wave</td>
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<td>$R$</td>
<td>Universal gas constant</td>
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<td>$R$</td>
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<td>RPM</td>
<td>Drum camera speed in revolutions per minute</td>
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<td>$t$</td>
<td>Time</td>
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<td>$\nu$</td>
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<tr>
<td>$\gamma$</td>
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$X_1$
2 Conditions behind shock
R Conditions existing in resonating fuel line
P Conditions existing in primary (oxidizer) supply line

nth instrumentation location for the windowed mixing chamber (Figure 6)
I. INTRODUCTION

During recent years, because of the importance for aircraft and missile propulsion, a number of studies of the combustion process in subsonic and supersonic flows have been undertaken. In some of these studies, in which premixed flowing combustible gases were employed, the investigators reported the occurrence of accidental autoignition. These autoignitions occurred without warning, in the absence of any apparent ignition source, and at initial gas temperatures well below those believed sufficient for ignition. The purpose of this investigation was to explain the mechanism leading to these ignitions.

During attempts to produce standing detonation waves in flowing combustible mixtures, McKenna observed the occurrence of "accidental detonations". Detonation waves were transmitted head-on into a stoichiometric mixture of hydrogen and oxygen flowing in a constant area duct. The velocity of the flowing mixture was varied from subsonic up to a Mach Number of 4.0. The accidental detonation occurred in the flowing gas at random and before the initiation detonation tube was fired. It occurred at both subsonic and supersonic velocities, although more frequently in the
latter case. In the majority of instances the ignition occurred at the inlet of the flow test section so that the resulting combustion wave propagated downstream with the flow. However, occasionally ignition also occurred at the flow tube exit and propagated upstream into the flow. An explanation of these events was not offered.

Hamilton\(^2\) employed essentially the same apparatus as McKenna to study the initiation of detonation behind an incident shock wave in a stoichiometric mixture of hydrogen and oxygen flowing at subsonic speeds. For flow Mach Numbers of 0.8 or greater, spontaneous ignition occurred with a high degree of regularity. Only three instances of spontaneous ignition were reported in which the instrumentation was activated, and in these cases the author determined that the wave traveled from the exit of the tube moving upstream from that point. When the total mass flow rate was reduced, giving a flow Mach Number of approximately 0.78, the tendency to autoignite was not observed. In addition, the shock strength required to cause ignition, and subsequent detonation, of the flowing mixture decreased with increasing flow Mach Number, and the calculated ignition temperature in each case was well below that predicted by thermal explosion limit theory\(^3\). Hamilton discussed several possibilities as to the cause of the low ignition temperature phenomena. He concluded that a certain amount of ionization is produced in the flowing gas at a certain minimum velocity.
The ionization may be produced by frictional effects with the possible aid of solid or liquid impurities present in the gases. As the flow velocity is increased the amount of ionization increases until, finally, ignition ensues. At lower velocities the presence of this ionization causes the flowing mixture to be more sensitive to shock ignition i.e. a lower temperature is required than would be anticipated. He concluded that additional experiments were necessary in order to determine the extent and nature of flow induced ionization.

There are other studies in which the ignition temperatures of flowing combustible mixtures were less than anticipated. In a study of the combustion of hydrogen-air in a supersonic flow stream, Tomagno et al. varied the static temperature of the premixed flow and observed autoignition for temperatures above 500°K. They attributed these occurrences to nonuniformities and hot spots within the plenum chamber where the flowing mixture was heated.

Shepherd measured the ignition temperatures of methane-oxygen and ethylene-oxygen behind pressure driven incident shock waves at atmospheric initial pressures. A simple shock tube apparatus was employed. Ignition temperatures of 520°K were reported for methane-oxygen. Later, after installing a 15 cm air buffer section between the driver and the test gas to eliminate non-steady effects, the ignition temperature of ethylene-oxygen was found to be 390°K.
Steinburg and Kaskan\(^6\) studied the shock ignition of stoichiometric hydrogen-oxygen mixtures at initial pressures of 200 and 300 mm Hg. The shock tube employed contained a two foot long buffer section and special care was taken to insure that all interior surfaces matched. Ignition occurred at temperatures of 775°K to 800°K behind incident and reflected waves. For similar pressure the thermal explosion limit data are 760°K and 740°K respectively\(^3\).

Fay\(^7\), using an apparatus similar to that of Shepherd\(^5\), measured the ignition temperature of stoichiometric hydrogen-oxygen at initial pressures of one atmosphere. When a thin cellophane diaphragm separated the test gas and buffer gas an ignition temperature of 400°K was found, however if the diaphragm was removed just prior to the generation of the shock then the ignition temperature increased to 630°K. This temperature is less than that predicted by the thermal explosion limit theory which is 740°K\(^3\). In discussing Fay's results Steinberg and Kaskan\(^6\) voiced the opinion that for a test gas igniting close to a bursting diaphragm (as appeared to be the case for the 400°K ignition temperature) it was not possible to describe the state of the gas accurately. At a later date Fay and Hooker\(^8\) reported results obtained with an improved apparatus similar to that of Steinberg and Kaskan. The ignition temperatures for stoichiometric hydrogen-oxygen behind reflected waves were now found to be between 780 and 370°K. They further stated that the lower tempera-
tures reported earlier were due to a gas dynamic effect produced by a small clearance volume at the reflecting end of the shock tube. To demonstrate this effect a small hole $\frac{1}{16}$ inch in diameter by $\frac{1}{4}$ inch deep was drilled in the center of the end plate. The ignition temperatures observed under these conditions were lower than those of the early experiments. Calculations showed that the temperatures within this cavity reached 780 to $850^\circ$K.

Belles and Ehlers conducted experiments with hydrogen-air, and hydrogen-oxygen-argon mixtures. In a simple shock tube without buffer, stoichiometric hydrogen-oxygen gave consistent data for initial pressures of 25 mm Hg, but at initial pressures of 50 mm Hg spuriously low ignitions occurred resulting in an excessive scatter of the data. The authors concluded that in working without a buffer the initial pressure should be less than 50 mm Hg for stoichiometric mixtures. For dilute mixtures at the higher pressure this behavior did not occur. The experiments at 25 mm Hg gave the incident shock ignition temperature of stoichiometric hydrogen-oxygen as $780^\circ$K compared to the calculated explosion limit temperature of $810^\circ$K. However, the ignition temperature for hydrogen-air at 50 mm Hg was $150^\circ$K below the theory and for hydrogen-oxygen-argon mixtures was $100^\circ$K above the theory. Based on these results, Belles and Ehlers conclude that the agreement between shock ignition temperature and thermal explosion limit is fortuitous. They state
that there is no reason to expect agreement due to the differences in test conditions. Factors such as geometry, tube size, the nature of the surface, type of ignition source, the area to which the ignition source is applied, the existence of convection currents, and the rate of diffusion of active species to the wall all influence the ignition temperature.

Walker\textsuperscript{10} investigated the shock ignition characteristics of static and flowing combustible mixtures. The portion of the work concerned with the flowing mixtures was conducted in an apparatus similar to that of Hamilton\textsuperscript{2} discussed above. Shock waves generated in a conventional shock tube were transmitted through a buffer gas and thence head-on into the flowing mixture tube. Walker concluded that the shock ignition temperatures of methane-air and ethylene-air mixtures were relatively independent of the flow conditions. However, for hydrogen-air, ignition was found to occur behind incident waves in a shock tube and incident waves propagating into a flowing gas at temperatures considerably lower than for reflected waves or for that predicted by explosion limit theory. A summary of this and other data presented above is shown in Figure 1. He also found that over a certain range of flow rates and conditions autoignition was found to occur in a flowing mixture of hydrogen and oxygen. It was subsequently found that ignitions could be produced in the mixing tank, where the hydrogen and oxygen were in-
roduced before entering the constant area flow tube. Similar conditions would not produce ignition in hydrogen-air mixtures. In order to avoid large accumulations of a combustible mixture in the test bay area, it was usual practice to establish the oxidizer flow first, to which the fuel was then added. It was noted that if the oxidizer flow was operated for a period of time that hot spots would be formed in the fuel line close to the mixing tank inlet. The hydrogen-oxygen injection pattern into the mixing chamber consisted of opposed jets. This arrangement suggested that resonance was being set up in the fuel line and that localized resonance heating was a possible ignition source to be studied. Preliminary experiments indicated that the temperature rise due to resonance heating could be appreciable. For this reason a summary of some of the literature relating to resonance and resonance tubes is given below.

In its simplest form, a resonance tube consists of a cylindrical cavity with one end closed. When a supersonic flow is directed axially against the open end, large amplitude oscillations may be excited within the tube. The source of the supersonic flow may be the supersonic freestream in a wind tunnel, the free jet of a correctly expanded nozzle, or an underexpanded free jet issuing from a nozzle. A typical configuration is shown in Figure 2.

In his extensive work Sprenger noted that the intensity of the oscillations was affected by the ratio of the
free stream jet pressure to the total pressure, the ratio of the diameters of the tube and nozzle, the spacing between the nozzle and the tube, and ratio of the tube length to diameter (1/d). He further observed a high noise level of up to 115 decibels and appreciable heating at the base of the tube. With a tube of 0.3 cm diameter and 10.2 cm long Sprenger observed a temperature of 770°K at the tube base. The addition of fine particles increased this temperature to 1270°K. An 1/d of 34 appeared to produce the greatest temperature increase. By placing turbulence generating threads in the sonic nozzle a temperature increase was noted, but the same did not hold true for the case of a correctly expanded jet. Based on his observations Sprenger was the first to conclude that traveling shock waves were within the tube.

Beginning with studies in 1919 Hartmann produced resonance phenomena by placing a small "air jet oscillator" in a sonic underexpanded jet. He was concerned mainly with the high acoustical output from these devices and failed to observe any heating. The lack of thermal effects may in part have been caused by his use of very small resonators (d and 1≈1 or 2 mm) with corresponding very high frequencies (1=d=1 mm gave 65,000 Hz). Hartmann did observe however the "intervals of instability" of the underexpanded jet in which the tube must be placed in order to resonate. Simply stated, the tube must be placed within one of the compression regions of the periodic pattern formed by the jet. A very
extensive study of the nature and structure of free jets is given by Love et al.\textsuperscript{13}.

Similar effects can be observed in long tubes with one end closed while the other end is driven by a piston oscillating at small amplitude. Traveling shock waves are observed within the tube, and for piston frequencies near a higher harmonic than the fundamental, multiple shock waves traveling in opposite directions occur. This phenomenon was experimentally investigated by Lettau\textsuperscript{14}. Theoretical analyses have been performed by Betchov\textsuperscript{15}, Chester\textsuperscript{16}, Frederiksen\textsuperscript{17}, Saenger and Hudson\textsuperscript{18}, and Temkin\textsuperscript{19}. The analyses show the importance of nonlinear effects and that shock wave and boundary layer dissipation play an important role. However, the similarity to a resonance tube ceases when one attempts to account for the interaction phenomena taking place between the inner and outer fluid and the fact that the disturbances generated by the piston are small whereas in the resonance tube they are large.

Sibulkin\textsuperscript{20} has performed a careful investigation of the energy dissipation within a resonance tube. A water-cooled tube was employed in which the rise in coolant temperature was used to calculate the extent of the irreversible conversion of mechanical energy into thermal energy. On the basis of his measurements Sibulkin concluded that a simple shock wave model cannot completely account for the resonance tube phenomena.
Cassidy et al. studied the heating phenomena taking place within the tube with temperatures as high as $550^\circ \text{K}$ being reported. In addition, some stroboscopic shadowgraph pictures were taken showing the interaction of the tube with the jet. Hall and Berry observed shock waves traveling within the tube by means of a short-duration shadowgraph. Lloyd succeeded in obtaining high speed flash as well as streak shadowgraphs of the interior flow. A number of the still pictures show that for an underexpanded jet a series of shocklets may be observed entering the tube. With the aid of the streak photographs, a partial wave diagram for the internal flow was constructed.

In a recent work, Hall performed an extensive parametric study in which resonant frequency, base pressure, base temperature, and sound pressure level were determined as a function of the underexpanded jet supply total pressure for several different lengths and $l/d$'s. Photographs of the external flow phenomena were obtained. In work reported by Shapiro an approximately 1 cm resonance tube with an $l/d$ of 34 was employed. For a nozzle supply pressure of 6 atm., a peak pressure of 8 atm. with a time-mean pressure of 5 atm. was observed at the base of the tube. The external base temperature was $730^\circ \text{K}$; however, insulating the tube increased this value to $1090^\circ \text{K}$. Ackeret observed temperatures of $1040^\circ \text{K}$ in a resonance tube insulated with a vacuum jacket.

Vrebalovich observed resonance phenomena in tubes
placed in a supersonic wind tunnel free-stream. A square tube with glass sides was used to obtain spark pictures synchronized with the base pressure. The standing bow shock was observed to oscillate, but shock waves were not observed within the tube. When a tripping device was placed in front of the tube the oscillations of the bow shock increased in amplitude and shock waves were found moving within the tube. These studies all verify the hypothesis of Sprenger, that there is shock wave motion both internal and external to the tube.

Analytical studies of resonance tubes encounter formidable difficulties. As mentioned above, in the simpler case of a piston driven tube nonlinear and dissipative terms must be included. Hall\textsuperscript{24} and Vrebalovich\textsuperscript{27} employed simple shock-tube type analysis and were unable to predict pressure amplitudes or the maximum attainable temperature. The inability of a simple shock analysis to explain resonance tube phenomena was noted by Sibulkin\textsuperscript{20}.

Wilson and Resler\textsuperscript{28} obtained an expression for the maximum attainable temperature which involved the tube length and the rate of maximum pressure increase within a period, i.e., \( \frac{d}{dt} \left[ \frac{\Delta P(t)}{P_0} \right]_{\text{MAX}} \). However, they assumed small disturbances, (that is they assumed no shocks within the tube which was not true in the cases observed above), neglected reflections at the end of the tube, and assumed a uniform temperature distribution along the tube length (also measured
as untrue\textsuperscript{11}. Based on experiments showing that a near linear temperature distribution exists within the tube, Shapiro\textsuperscript{29} performed an approximate order-of-magnitude analysis to arrive at $\Delta T/T \approx 2(Y+1)$. This result shows that the temperature rise from open to closed end would be several times the mean tube temperature $\overline{T}$. However as $\overline{T}$ is not specified the equation is not practical. In addition, Shapiro postulated that the limiting mechanism of energy dissipation is probably a combination of 1) the average temperature increase within the tube causes waves to require a longer distance to steepen, and 2) a longitudinal temperature gradient itself inhibits wave steepening. However a complete theory must also take into account the external as well as internal flow.

Mørch\textsuperscript{30} has studied the oscillations of the bow shock in front of a plane resonator (i.e. a blunt body or resonance tube of zero length) in an underexpanded air jet. Such a configuration gives a higher frequency but a lower amplitude than an ordinary resonance tube. Earlier Thompson\textsuperscript{31} had shown that a plane resonator is stable in a correctly expanded jet, but that oscillations may arise in the case of a periodic jet. This resonance of the bow shock is perhaps similar to the mode of resonance tube operation observed both by Vrebalovich\textsuperscript{27} and Hall\textsuperscript{24} in which oscillations occurred only about the tube opening. In addition, Mørch obtained an instability model for the plane resonator case.
which allows the frequency of the oscillations to be predicted. However, the assumption of small amplitudes is made, and agreement between theory and experiment is poorer for the modes which involve more severe oscillations.

In a recent work Thompson investigated both the periodic and correctly expanded jet cases. Time resolved shadowgraphs of the external flow were obtained in conjunction with pressure transducer records from within the tube. He observed that the inflow and outflow phases were temporarily steady, and with the application of flow boundary conditions he succeeded in constructing wave diagrams of the internal flow which agree with the pressure transducer traces. As it is assumed that the entropy production within the tube is balanced by heat transfer, so that the overall process may be treated as isentropic, the diagrams are valid only for steady state operation. Based on observations the following scheme is proposed for one cycle of resonance tube operation:

1) a temporarily steady inflow phase in which all of the flow passes into the tube and the bow shock stands in front (37% of the period); 2) the transition from inflow to outflow in which a strong shock exits the tube advancing into the jet (6%); 3) a temporarily steady outflow phase in which the outflow becomes supersonic with the two jets colliding at an interface after each having passed through a strong shock (33%); and 4) a transition from outflow to inflow in which there is a gradual decrease in the outflow and the collision
system recedes into the tube (24%). Thompson also observed that for periodic jets the inflow and transition phases are somewhat shorter and the pressure amplitude is higher than that of the correctly expanded case. A certain portion of the fluid remains permanently trapped within the tube which Thompson calls the "indigenous fluid", and it is this fluid subjected to repetitive shock action whose temperature increases dramatically. Experimental pressure histories agree well with those predicted provided that empirical factors are employed. Unfortunately it is not apparent how these empirical factors may be predicted. In addition the theoretical analysis is valid only for a single wave within the tube. This is normally the case only for a correctly expanded nozzle. Thompson notes that for the periodic jet case multiple waves may be found within the tube, and that their presence is explained by the fact that the nodal structure of the jet is swallowed by the tube during the inflow phase. The appearance of occasional multiple waves in the correctly expanded case may be due to shock-contact surface interactions.

Kang\textsuperscript{32} has analyzed the problem of the stability of the resonance flow for the correctly expanded nozzle case. The analysis is based on vorticity being the probable cause of instability. Regions of instability are predicted in terms of the various physical parameters. The maximum attainable temperature is analyzed by the use of wave diagrams con-
structured in the same manner as those by Thompson. The
author cautions however, that because of the assumptions made,
the predicted maximum temperature of ten times the jet total
temperature is at best an order of magnitude prediction.
Experiments performed gave a maximum temperature of about
twice the jet total temperature.

From the above discussion it can be concluded that the
resonance phenomena is very complicated, and quantitative
analysis of even the simplest cases is at best only moderate­
tely successful. The qualitative aspects of the resonance
appear to be well defined. The maximum attainable tempera­
tures observed are above the ignition temperatures of many
combustible mixtures. Many authors have noted the hazards
possible if such a construction were accidentally included
in a pneumatic system. Indeed, the use of a resonance tube
ignitor for rocket engines has already been proposed.

The aims of this study are then 1) to investigate
further the phenomena of autoignition of combustible flowing
mixtures, 2) to ascertain the magnitude of flow induced
ionization in an apparatus in which ignitions were found to
occur, and 3) to undertake a systematic investigation of
resonance as observed in some preliminary configurations in
which ignition was observed to occur.
II. APPARATUS AND INSTRUMENTATION

Gas Supply

The gas supply system was built to accommodate the demands of high pressure and substantial mass flow rates required in the various experiments. Air was supplied from two 160 atmosphere, 21 cubic meter tanks which are part of the facilities of the Aeronautical Research Laboratory. The air is supplied by two compressors each supplying 21 cubic meters per minute; it is dried with activated alumina to within two parts in one million. Oxygen gas was taken from standard cylinders, individually filtered, and then connected to a common manifold. As many as ten cylinders could be connected in this manner. Hydrogen gas was supplied from a similar arrangement. The composition of these gases is given in Appendix A. These supply pressures were regulated to preset values by means of Grove Dome pressure regulators before entering the test bay area.

Flow Measurement

Sharp-edged flat-plate orifice flow meters of the "pipe tap design" were used to provide data required for calculation of the mass flow rate of the gases. The flow meters were constructed of stainless steel tubing with a
nominal inside diameter of 5.0 cm and conformed to the standards established by the American Gas Association (AGA) and the American Society of Mechanical Engineers (ASME). The flow rates were remotely controlled and monitored by means of Grove Dome pressure regulators, Annin flow regulators, Bourden type pressure gages, Barton differential pressure gages, small volume pressure regulators, and electric solenoid valves.

**Basic Mixing Chamber**

As reported above Walker noted that autoignition could be forced to occur in the mixing chamber alone, and that the opposed jet configuration appeared to be responsible. For these reasons the basic design was an opposed injection pattern. The scale was significantly reduced from that of Walker's in the hope that ignitions could be induced at lower total mass flow rates. Figure 3 shows the arrangement of the apparatus used to test the flowing mixtures for autoignition. The design consisted of individual fuel and oxidizer inlets of 0.8 cm inside diameter at the base of a 2.25 cm inside diameter mixture tube. All lines were made of stainless steel. The length of the mixing chamber was varied from 6.3 to 50 cm, and the position of the base plug was variable over a few cm. Check valves were located in each inlet line approximately 10-15 cm upstream of the mixing tube.

Upon occasion the fuel inlet line was capped and the
resonance occurring within the fuel line was studied. This arrangement simulated the presence of a check valve from which waves would be reflected. In the cases where the resonance was of prime interest air was used as the flowing gas. Kistler piezoelectric pressure transducers were used to measure the transient end wall pressure observed in this configuration. Available to display the output of these transducers were two Tektronix Storage Oscilloscopes (type 564) and a Dual Beam Tektronix Oscilloscope (type 555). A shielded junction chromel-alumel thermocouple was inserted through the endwall and the indicated temperature was read out directly by means of a Potentiometer Pyrometer (Thermo Electric Co., Inc.).

Variations of Basic Chamber

A number of alternate inlet configurations were also studied to determine their autoignition characteristics. These are depicted schematically in Figure 4. The dimensions and construction of these chambers are the same as those of the basic configuration with the exception that the mixing tube length was a constant 50 cm.

Ionization Apparatus

Two types of experiments were employed in an attempt to detect the presence of charged particles or ions. In the first case an electrostatic probe was inserted into the flowing stream at the exit of the mixing tube. A charge sensitive amplifier was attached to the probe. The second ap-
paratus consisted of a Lucite insulation piece which was added to the basic mixing tube increasing its total length to 61 cm. The interior diameter matched that of the mixing tube, and two diametrically opposed electrostatic plates were imbedded on the inner wall of the insulator. A d.c. potential voltage variable from 0 to 1200 V was applied across the plates. At a sufficiently high voltage a very small current was induced across the gap between the plates. This current was measured by means of a Keithley Model 410 Micro-Micro Ammeter. In this manner any change in the conductivity of the gap could be measured as the flow in the mixing tube was varied.

Windowed Mixing Chamber

In an attempt to better understand the resonance phenomena occurring within the fuel line a mixing chamber was fabricated in which the fuel line and mixing tube contained window sections. This necessitated that these two sections now have a square cross-section while the oxygen inlet line remained cylindrical. The mixing tube was constructed with two parallel sides being of Lucite. The interior dimension was 2.25 cm square, and the length remained approximately 50 cm. The fuel line consisted of an assembly containing schlieren-quality fused quartz windows, and the interior dimension was 0.84 cm square. The total window length was 10 cm with 9.2 cm visible for viewing. The entire height of the fuel line (0.84 cm) was visible. This apparatus is schemati-
cally represented in Figure 5. Instrumentation ports were provided at various locations along the fuel line for Kistler piezoelectric pressure transducers and for measurements with Bourdon type pressure gages. The location of these is shown in Figure 6.

**Variations of Windowed Chamber**

The windowed fuel line was fabricated so that interchangeable attachments could be affixed to the upstream end. The first of these attachments consisted of a plug which converted the fuel line into a closed end tube. A pressure transducer could be inserted into the end wall. The end wall at which the waves were reflected was visible through the quartz windows. The total length of the fuel line configuration as measured from the interior of the mixing tube was 10.8 cm giving an $l/d$ 12.9. Another configuration consisted of a round tube extension to the length of the square fuel line. The fuel line interior dimensions closely matched with the exception of the transition from round to square cross-section. For this case the total length of the tube, with the upstream side always being plugged, was 21.6 cm for an $l/d$ of 25.1. The final attachment, used with the windowed fuel line, allowed a gas flow to be superimposed upon the resonance. In this manner it was hoped to establish whether or not resonance could persist in a superimposed counter-flow. A Kistler type 606A piezoelectric pressure transducer was mounted in the end wall from which the waves could reflect.
The flow (air) entered the fuel line test section at a right angle slightly upstream of the windows. The necessity for this configuration is discussed in chapter IV. The length of this section was 12.9 cm giving an $l/d$ of 15.4. The window section and attachments are shown in Figure 7.

Schlieren System

A great many schlieren pictures were taken with a conventional Z-type apparatus depicted in Figure 8. Care was taken to maintain the angular displacement of the light source and camera from the parallel light path as small as possible and that the system was critically focused. Two types of pictures were taken, necessitating slightly different arrangements for each case. A 4x5 Graflex camera with Polaroid back was used in conjunction with a high-voltage spark source to obtain stop-action photographs of the wave phenomena in the resonating fuel line. The triggering of the spark was synchronized with the time-of-arrival of the main pressure wave at one of the Kistler transducer locations. By employing the Delayed Trigger Output from the Tektronix Type 555 Oscilloscope, the spark could be triggered at any portion of the resonance cycle with the transducer location being an arbitrary reference point. Due to a malfunction in the spark unit, a General Radio Type 1539-A Stroboslate was also employed as a light source. Unfortunately the flash duration of the Stroboslate (3 microsecond claimed) appeared responsible for a noticeable loss in picture quality as compared to
the spark. An Osram HBO Super Pressure Mercury Lamp was used as a continuous light source to obtain streak photographs of the resonance phenomena. The design and construction of the rotating-drum streak camera has been discussed elsewhere.\textsuperscript{35} The camera is driven by a variable speed air turbine with the rotational speed being detected by a magnetic pickup and displayed on a Beckmen Model 7370 R Events Per Unit Time Counter. Kodak 35 mm Tri-x Film was used. The camera contained a .79 mm slit which was aligned along the length of the window at the center of its height.

Small Scale Shock Tube

A number of experiments were conducted in which a single shock wave produced in a small conventional shock tube apparatus was directed into the windowed fuel line test section. The purpose of these experiments was to aid in the interpretation of the streak photographs obtained of the resonance phenomena. These experiments are discussed in Appendix B. Nominal inside diameter of the shock tube was 1.3 cm. Thin mylar and plastic (Saran Wrap) diaphragms were employed with the driver gas being compressed air. A few runs were made in which the oxidizer inlet was removed from the windowed mixing chamber, and the open driven section of the shock tube placed about 1 cm from the mixing tube (see Figure 9). The shock then left the shock tube, crossed the gap into the mixing tube, and thence into the square fuel line. This configuration did not produce a well-formed shock wave. For
this reason an extension was placed in the end of the shock tube which gradually reduced the inside diameter to 0.8 cm. This extension was then placed through the opening for the oxidizer inlet into the mixing tube so that only a 0.5 cm gap remained between the end of the shock tube and the inlet of the square fuel line (see Figure 9b). When taking spark pictures synchronization was as discussed above with the diaphragm being pressurized to the rupture point. In order to obtain streak photographs the breaking of the shock tube diaphragm had to be synchronized with the opening of the camera shutter. For this case the shock tube was pressurized and the diaphragm ruptured by means of an exploding wire.

**Ignition Study Shock Tube**

A small number of data were taken to determine the incident shock ignition temperature of stoichiometric hydrogen-oxygen mixtures in a conventional shock tube. This apparatus was identical to that used by Walker$^{10}$. 
III. EXPERIMENTAL PROCEDURES

Autoignition Studies

The various configurations discussed in Chapter II were all tested for autoignition characteristics. In order to avoid the accumulation of large quantities of an explosive mixture in the test bay area, it was usual practice to establish the oxidizer flow rate first and then introduce the fuel (hydrogen). In these studies it was necessary to employ additional observers to record the flow measurements as the ignitions would occur immediately upon introducing the hydrogen, before the hydrogen flow rate had stabilized. Even with the aid of electric solenoid valves, it was usually not possible to shut down the system rapidly enough to avoid partial or complete destruction of the mixing chamber. A smaller number of studies were also undertaken in which both flows were introduced simultaneously, or also, in which both flows were gradually increased up to the point where ignition resulted.

Resonance Studies with Basic Chamber Configuration

Resonance heating was observed in the fuel line for the basic configuration. With the fuel line capped, instrumentation was inserted into the end wall. A Kistler pressure
transducer was employed to measure the transient pressure phenomena, and a shielded chromel-alumel thermocouple was used to determine the average gas temperature within the line. Because of the large mass of the thermocouple, and due to heat transfer losses, several minutes were required for the temperature to stabilize. No attempt was made to insulate the fuel line. In order to avoid ignitions in these studies, air was the only flowing gas employed. Some additional studies were undertaken in which a Kistler transducer was placed in the fuel line side-wall, resonance was established by the primary (oxygen line) flow, and then a smaller amount of flow was passed through the fuel line to be superimposed upon the resonance. Such studies will hereinafter be referred to as resonance with counter-flow.

Ionization Studies

The ionization apparatus was tested with air, oxygen, and hydrogen individually, so as to avoid the possibility of ignition. To conserve the bottled gases, only short run times were employed with hydrogen and oxygen. To test the sensitivity of the conductivity apparatus different gases with different conductivities, such as HCl, were employed. In an additional test of sensitivity, a small quantity of ions were aspirated from a burner flame and introduced at the base of the mixing tube where they mixed with the main flow.

Resonance Studies with Windowed Chamber

As with the resonance studies enumerated above, only
air was used with the windowed chamber. Resonance was allowed to establish itself for five or ten seconds before any experimental measurements were made.

In the cases in which streak film records were obtained it was necessary to first bring the drum camera up to speed (up to 135 rps depending on the velocity of the waves being recorded), start the gas flow, and after the flow was established record the desired data. Synchronized streak film and pressure transducer traces were obtained in the following manner: With the opening of the camera shutter a pulse was supplied to trigger the scopes; In turn, an output pulse from the scope trigger was used to place a timing mark on the film. This procedure was necessary because during the interval the camera shutter was open, several resonance cycles would be recorded on the film, and it was desired to resolve at least one cycle in detail. In those cases in which spark schlieren studies were made, the triggering of the spark was synchronized with the arrival of the main pressure wave at one of the Kistler transducer locations. With the aid of the Delayed Trigger Output from a Tektronix Type 555 Oscilloscope, any portion of the resonance cycle could be recorded by selecting the appropriate time delay. The transducer location thus acted as an arbitrary reference point.

Streak photographs of a single shock wave, produced by a shock tube, required a different synchronization technique.
The shutter for the streak camera was of the guillotine type. As the shutter began to fall it tripped a variable position microswitch which in turn actuated the firing of the shock tube. The shock tube was pressurized to a preset value, and the diaphragm was then ruptured by an exploding wire. By proper placement of the microswitch, the shutter would be open when the shock arrived. Pressure transducer traces of the traveling wave were also obtained. Spark schlieren pictures were obtained by synchronizing the flash with a pressure transducer location as previously discussed above. In this case the diaphragm was merely pressurized to the burst point.
IV. RESULTS

Autoignition Studies

The basic mixing chamber design was initially evaluated for its tendency to produce autoignition. Hydrogen and oxygen were used to form the combustible mixture. In order to avoid the accumulation of large quantities of an explosive mixture in the test bay area, it was usual procedure to first establish the oxidizer flow then introduce the fuel. For oxygen flow rates of 350-400 gm/sec, or greater, ignition would occur immediately upon introduction of the hydrogen. As the ignition would occur during the transient period after the solenoid valve was opened and before the flow was well established, it was difficult to determine the exact hydrogen flow rate. In general it appeared that the ignition was relatively insensitive to mixture ratio changes although certainly the mixture was always lean as the hydrogen flow rate rarely exceeded 30 gm/sec. Ignitions were also found to occur if the flow rates were gradually increased up to the point of ignition rather than by opening solenoid valves. Even with the aid of electric solenoid valves, it was usually not possible to shut down the system rapidly enough to avoid partial or complete destruction of the mixing chamber.
A systematic reduction in the length of the mixing tube revealed that for a 6.3 cm or shorter length the ignitions no longer occurred. This result occurred in spite of the fact that the mass flow rates were as great, or greater, than before.

When air was used as the oxidizer autoignition could not be produced. Air mass flow rates of up to 500 gm/sec and hydrogen mass flow rates of up to 30 am/sec were employed. These flow rates are greater than those required for ignition of hydrogen-oxygen.

Of the variety of configurations tested (Figure 4) the basic opposed configuration (a) produced ignitions most readily. The opposed with check valve configuration (e) could also be forced to ignite with mass flow rates as high or higher than those listed above. In addition these ignitions did not occur immediately but only after the hydrogen and oxygen flows had been established for a matter of seconds. With the remainder of the configurations shown in Figure 4 it was not possible to produce ignitions.

Some additional experiments were also conducted with axial configurations such as (d). While this configuration did not lead to ignition a blunt object such as a cylinder or flat plate placed in the flow a few cm from the tube exit caused ignition at the exit. The ignitions occurred for mass flow rates higher than those discussed above but only after the flows were established for a few seconds.
Ionization Studies

The apparatus consisting of an insulated charge-sensitive probe was the first to be employed in the ionization studies. It was soon determined that this system was impractical as the probe responded equally well to moisture, temperature changes, and small concentrations of ions added to the main flow. The effect due to temperature seemed to be most pronounced however.

The apparatus consisting of parallel plates proved to be quite sensitive. It was able to detect differences in the conductivities of various gases. When a small quantity of ions was aspirated into the base of the mixing tube, allowed to mix with the flow, and then passed through the sensing plates a large difference in the current (up to three orders of magnitude) was observed.

The ionization studies were conducted with non-premixed gases to avoid the possibility of ignition. Over the range of flow rates which produced ignition no ionization or charge formation was observed.

Resonance in Basic Mixing Chamber Configuration

Early in the study it was observed that localized heating was occurring in the hydrogen feed line of the basic configuration when flow was established in the oxidizer line. The extent of the heating became even more apparent during the ionization studies when only the oxidizer flow would be used. The fuel line rapidly became so hot that a severe burn
could result from touching it. It was decided at this time to abandon the ionization studies and concentrate on the resonance heating aspects.

The fuel line was capped 10.7 cm upstream from the mixing tank giving a fuel line chamber with a length to diameter ratio of $l/d = 13.5$. This length corresponds to the distance from the mixing chamber at which a check valve would normally be located in the system. With the line capped it was possible to insert instrumentation through the endwall to observe the resonance. In all of the resonance studies air was used as the primary (oxidizer) flow.

With the fuel line capped very distinct audible tones were emitted which seemed to shift to different frequencies as the primary flow was varied. Pressure measurements made with a Kistler transducer placed in the fuel line endwall indicated the presence of large amplitude oscillations. Three discrete frequencies of approximately 600, 750, and 1900 Hz were observed to occur.

Measurements were taken with a microphone placed about 30 cm from the mixing tube exit. The output displayed on a Singer Panoramic Sonic Analyzer indicated that at the three resonant frequencies the noise output reached 130 db.

The third mode resonant frequency of 1900 Hz was of prime interest as it occurred at flow rates corresponding to those which produced the autoignitions. A shielded junction chromel-alumel thermocouple was inserted through the
endwall into the fuel line; fine base-wire thermocouples were unable to withstand the severe environment. Because of the relatively large thermocouple mass, several minutes were required for the thermocouple to reach an equilibrium temperature. The maximum temperature recorded in the fuel line for the basic mixing chamber configuration was 770°K. The length of the mixing tube appeared to have little effect on the resonance as the 6.3 cm length tube exhibited identical modes, but the temperature was even higher, in this case reaching 1075°K. In neither case was any attempt made to correct for losses due to heat transfer.

It was not yet possible to say that the resonance occurring here was identical to that discussed in the Introduction. There was need to determine if at some point within the current apparatus the flow was sonic or supersonic as in the case of a sonic or supersonic jet in a resonance tube. The fuel and oxidizer flows being diametrically opposed did appear to offer a configuration similar to a resonance tube set-up with, in this case, the mixing tube being an extra complicating factor. Static pressure measurements made within the basic configuration confirm that a sonic flow condition definitely could exist. Figure 10 shows the variation in static and total pressure as a function of mass flow rate within the oxidizer inlet line at a point 10 cm upstream of the mixing tube. The total pressure is a calculated value (Appendix C). The variation in the pressure at the base of
the mixing tube and the average pressure within the resonating fuel line are presented in Figure 11. Also depicted in Figure 11 is the mass flow range over which the various resonance modes occur. It is immediately evident from these two figures that the excess pressure between the supply line and the mixing tube is great enough so that the flow in the oxidizer line most likely may be sonic at its exit into the mixing chamber. In the reduced pressure region which is prevalent in the mixing tube, the jet can expand as an underexpanded free jet and reach supersonic velocities. The movable base plug served as another means to test this theory. If the free jet were restricted from expanding, then the resonance would be affected. When the base plug was positioned so that it was up flush with the inlet lines then the resonance was reduced to near extinction. In its normal position the top of the base plug was about 1.5 cm below the inlet lines. Further measurements made with the windowed mixing chamber, which was better adapted to making experimental measurements of this type, also tend to confirm this hypothesis. These results will be discussed in more detail later. From this it was concluded that the opposed fuel-oxidizer inlet configuration was acting as a resonance tube. A schematic of this proposed analogy is presented in Figure 12.

Figure 13 shows the average (due to filtering of the electrical signal) wave shapes present in the fuel line for the various modes of resonance. The peak-to-peak amplitude
of the resonance waves increases with each successive mode and further increases with increasing $\dot{m}_p$ within a mode. For the conditions where autoignition occurs the peak-to-peak amplitude reaches 10 atmospheres or more.

The above measurements were all made in a fuel line which was closed upstream with the transducer located at the closed end of the line. However, since ignitions were sometimes observed to occur even after the fuel flow was established, it was of interest to determine whether the same resonance conditions could exist with a gas flow in the resonance chamber (counter-flow). The measurements were repeated with various flow rates of air through the fuel line. As the flow rate in the fuel line increased, for a given oxidizer flow rate, the resonant frequency decreased. For a moderate amount of counter-flow the first two modes were eliminated. The third (1900 Hz) mode became intermittent for fuel line flow rates above 15 gm/sec. Figure 14 shows the decrease in frequency with counter-flow for the three modes. The average variations in wave shape for the three modes caused by various fuel line flow rates are shown in Figures 15, 16, 17, and 18 respectively.

The effect of counter-flow on the third mode resonance is rather surprising. The peak-to-peak amplitude of the resonance (Figures 17 and 18) in some cases is even greater than without counter-flow ($\dot{m}_R = 0$). When the average pressure in the fuel line, as measured by a Bourdon gage, is
shown as a function of the primary mass flow rate (Figure 19), the third mode again exhibits unusual characteristics. For oxidizer flow rates above 15 gm/sec the average fuel line pressure first increases then decreases. The point where the increase begins is where the frequency suddenly and dramatically decreases (Figure 14) and also where the peak-to-peak amplitude $P_{MAX} - P_{MIN}$ begins to increase. Even though the peak-to-peak amplitude of the waves increases, the pressure ratio $P_{MAX}/P_{MIN}$ across the waves remains fixed within a narrower range of from two to three atmospheres.

The experiments conducted with counter-flow indicated that in some cases not only did the resonance persist in the presence of this superimposed flow, but that the amplitude could possibly even increase.

**Resonance Studies With Windowed Chamber**

It was hoped that the windowed mixing chamber would resonate in a manner identical to that of the basic configuration. Initial experiments with a capped fuel line $1/d = 12.9$ indicated that it did not. While the first two modes appeared to be the same, the third mode which is most important from the standpoint of autoignition, was missing entirely. In addition, the complexity of the flow occurring in the center mixing chamber did not allow any meaningful pictures to be taken. When fillets were placed in the corners of the mixing tube this configuration behaved essentially as the basic mixing chamber. This observation again points out the im-
portance of the manner in which the freely expanding jet is formed and shaped.

Static pressure measurements were taken at various locations within the mixing chamber. In this case the pressure taken in the oxidizer supply line was only about 1.5 cm upstream of the point where it entered the mixing tube. The various pressures as well as the location of the various resonance modes occurring within the mixing chamber are essentially similar to the basic mixing chamber configuration. In comparison to the basic configuration the transition from mode to mode occurred much more abruptly without any overlapping of the frequencies. It was observed again that the excess pressure between the exit of the oxidizer line and the base pressure is more than sufficient to produce a critical pressure ratio. In addition, calculations show that for oxidizer mass flow rates of 18 gm/sec and above, the Mach Number in the inlet line at this point remains relatively constant at about 0.8. It must be remembered that in any flow in which a sonic condition exists the Mach Number increases most rapidly near the sonic point. As a point of interest it was seen that the first detectable resonance occurs for flow rates of about 18 gm/sec. A fourth lower frequency mode was observed to occur with this configuration at low mass flow rates. As this mode does not correspond to any of those occurring in the basic mixing chamber it is called the zeroth mode. Frequencies of approximately 450, 650, 750, and 2200 Hz
A summary of the resonant frequencies observed for this, and all the other configurations, is presented in Table 1. The calculated frequency is based on the closed organ pipe formula \( f \sim \frac{n^2}{L} \) which was first proposed by Sprenger as giving the fundamental frequency of a resonance tube. The speed of sound is based on the supply total temperature. In general the calculated and experimental values do not agree well.

Pressure transducer outputs were used as an aid in interpreting the streak films which are discussed below. It was usually possible to determine more about the structure of the wave by taking pressure measurements in the sidewall as opposed to the endwall. The pressure amplitudes for the first and second modes are comparable to those obtained in the basic mixing chamber, but unfortunately the third mode is less severe here.

A series of spark pictures were taken of each resonance mode. Three of these are presented in Figures 20, 21, and 22. As only one picture at a time was possible with the spark source used, each frame represents a different cycle. The light colored waves are moving into the tube while the dark colored waves (sometimes more difficult to observe) are moving out of the tube. As can be seen, the variation from cycle to cycle is excessive. The very complex nature of the resonance phenomena is also apparent. As few as one,
or as many as seven or more, shocks or shocklets may be seen moving within the tube. In addition a great deal of turbulence is observed. Turbulence was also observed by Kang in a sequential shadowgraph study. Continuous records of the shock patterns and motion is provided by the streak pictures obtained. A typical streak photograph for the second mode resonance is shown in Figure 23. A very startling feature of these records was the large number of lines which appeared to be tracing out the particle flow paths. It was subsequently determined that these lines were indeed representative of the particle motion which was made visible by turbulence (refer to Appendix B for a discussion of this problem). The extent of the penetration of the extraneous fluid from the mixing chamber into the fuel line is immediately evident.

A composite of streak pictures of the various modes is shown in Figure 24. Certain qualitative observations are immediately evident. In many cases a train of shocklets first enter the tube, rapidly coalesce, and then continue to propagate into the tube at constant velocity. The deepest penetration of the extraneous fluid, at approximately 60% of the tube length, occurs for the second mode, which also has the greatest peak-to-peak amplitude. In the lower three modes the inflow and outflow phases are well defined and fairly quiescent regions can be observed. However, the third mode is quite different from the others. An almost continual
progression of waves is seen to enter the tube; a single shock front is not well defined. The reflected wave has not exited from the tube before another wave enters. Little or no quiescent region exists. Only a small amount of fluid ever leaves the fuel line, the majority remaining trapped as indigenous fluid. One important means for lowering the trapped gas temperature is thus lost. The waves enter in such a rapid fashion that at certain instances in time the gas in different portions of the tube can actually be seen flowing in opposite directions. In addition a peculiar high frequency (22,000 Hz) resonance is superimposed upon the main pattern. It appears to be acoustical in nature as it does not alter the flow pattern, yet it is affected by the shock waves within the tube. Further, the waves must be traveling in a transverse or spinning manner rather than longitudinal as for the shocks, for if this were the case their slopes are steeper in the X-t or drum camera photographs than that of a shock which would imply a strong wave.

A similar series of experiments were undertaken in which the l/d of the capped fuel line was 25.1. It was hoped that the lower frequencies associated with the longer l/d would allow for more time to study a single wave.

This configuration exhibited three very distinct resonance modes of 300, 450, and 2400 Hz. The average pressure occurring within the resonating fuel line is nearly identical to the l/d = 12.9 configuration. The base pressure and
oxidizer inlet pressures are not affected by a change in the l/d of the fuel line. With the exception of the first mode, which is slightly stronger for this case, the amplitudes are comparable to the l/d = 12.9 case. The increase in the strength of the shock as it moves down the tube can be seen. Single shock waves which comprise a portion of a cycle were also visible.

A composite picture of the streak photographs for the various modes is shown in Figure 25. The features of the resonance waves are similar to those discussed above. The extent of the penetration of the extraneous fluid for the first two modes is deeper than the view through the window section can reveal. The structure of the third mode is almost identical to that observed before. This result is surprising since the length of the tube has been doubled. The pictures appear to show that the waves reflect as if an end-wall was still there. Some waves appear to penetrate into the extension while others appear to reflect. Apparently the change from a square to a circular cross section provides enough of an obstruction that reflections can take place.

The above apparatus was originally designed for a study of the effect of counter-flow on the resonance. However when a supply line was connected to the fuel inlet the configuration exhibited only very weak resonance in the third mode. As this mode is of prime importance, another configuration had to be fabricated. With the improved counter-flow
attachment discussed in Chapter II, a lower amplitude than desired, but nevertheless satisfactory third mode resonance occurred.

The average pressure within the resonating fuel line for this configuration is similar to that observed above, except that the transition to the third mode occurs at a somewhat higher mass flow rate.

When a fuel line counter-flow was superimposed upon the resonance the performance was similar to that obtained with the basic mixing chamber. With increasing flow rate in the fuel line, for a given primary flow rate, the frequency decreased. The first two modes were eliminated by moderate amounts of counter-flow. The variation in frequency with counter-flow is shown in Figure 26.

The effect of counter-flow on the third mode is again the most dramatic. When the fuel line flow rate exceeds a certain critical value the resonance abruptly changes and the peak-to-peak amplitude of the waves almost double. Superimposed on the large amplitude frequency is an approximately 4200 Hz resonance of smaller amplitude. Sudden and abrupt changes also occur in the average pressure in the fuel line as shown in Figure 27. The counter-flow evidently influences the structure of the free jet appreciably as even the base pressure (Figure 28) changes abruptly. The variation in the peak-to-peak amplitude for the three modes as a function of fuel line flow rate is
shown in Figure 29. The abrupt changes in pressure and amplitude occur for the same counter-flow mass flow rate.

In spite of the large increase in amplitude of the waves for the third mode with counter-flow the pressure ratio across the waves \( \frac{P_{\text{MAX}}}{P_{\text{MIN}}} \) remains about constant with a value of 1.5-2.0. As the counter-flow tends to destroy the first two modes, the pressure ratio across these waves decreases very rapidly.

A comparison of spark pictures taken with and without counterflow for the identical primary mass flow rates is shown in Figure 30. Most evident from these pictures is the great increase in observed turbulence in the case of resonance with counter-flow.

A series of streak photographs showing the influence of counter-flow on the wave patterns within the square fuel line for the various modes are shown in Figures 31, 32, and 33. The unusual disturbance occurring at \( X/L \approx 0.31 \) is due to a Bourdon pressure gage which was connected at (2). The gage can be seen alternately filling and discharging depending on the variation of the pressure within the fuel line. A number of unusual features are noted when counter-flow is present. For a moderate amount of counter-flow there appears to be a noticeable lack of reflected waves traveling back out of the tube. Those that are observed seem to be relatively weak as they have little effect on the flow lines. For those cases in which the counter-flow is appreciable it is very difficult
to distinguish where one cycle starts and another finishes.

Analysis of Strip Film Records

In addition to the qualitative information discussed above a number of quantitative measurements can be made. The shock Mach Number, as well as all the various property ratios such as \( \frac{P_2}{P_1}, \frac{T_2}{T_1} \), etc., which are functions of the Mach Number, can be found. In addition, the static and total temperatures of the gases can be determined from the films (see Appendix C for details). There are ten possible mode/configuration combinations that were studied. Multiple streak pictures were taken of each combination. Over 650 data points were obtained from fifty selected streak films. An enlarged print was made of each from which the various angles were carefully measured.

The calculations show that for all cases the Mach Number of a single shock, relative to the flow within the tube, is quite small. The Mach Numbers varied from slightly in excess of unity to a maximum of about 1.30.

The data scatter involved in calculating the temperature is somewhat large. A typical composite plot of the temperature distribution in the tube for the third mode resonance is shown in Figure 34. Temperature distributions for the other modes gave comparable but slightly lower temperatures. As little difference could be noted between the third mode resonances (\( \hat{m}_R = 0 \)) of the three configurations all three are shown. Temperatures in excess of 600°K are
attainable near the closed end of the tube. When compared to the temperature distributions for other modes the temperature near the open end is 50-100°K hotter. This observation is in agreement with the qualitative observations noted earlier; that in the third mode resonance very little of the indigenous fluid is spilled. Presenting the data in this manner has many shortcomings however. Since the streak films were taken at random, only sufficient time was allowed for the resonance to stabilize (it was usual practice to wait a minimum of ten seconds), each recorded resonance cycle has a different prior history. In addition such a plot does not take into account the prior history of a single shock within a particular cycle. The temperature distribution in the tube that is left by a single traveling shock is not the same as that left by a combination of as many as six shocks, all of which have interacted with each other in their passage into and out of the tube. Statistically speaking the sampling shown here is very small, being comprised of perhaps 30 cycles. In order to state with assurance what maximum values a random wave might produce, many thousands of samplings would quite likely be needed. At best the method provides an interesting optical means of determining the temperature within the tube. The average scatter in the temperature data is estimated to be ± 10%.

When counter-flow was superimposed on the resonance, the temperatures, even for the third mode, were found to be
much lower. The temperature distribution in the tube became quite uniform. For the third mode with counter-flow operating in the high amplitude resonance region, an average temperature of about 60°K above the supply stagnation temperature (\(\sim 290°K\)) was observed. The less severe resonances exhibited proportionately less of a temperature increase. When the primary mass flow rate is increased to 240 gm/sec the peak-to-peak amplitude of the resonance is greater as shown in Figure 29, and a number of temperatures as high as 460°K are recorded.
V. DISCUSSION OF RESULTS

Windowed Mixing Chamber

Studies with this configuration disclosed several new findings concerning resonance tube theory and operation which previously have not been known. The fact that resonance tube temperatures exceeding the supply total temperature are observed is not new. The method of obtaining resonance tube temperatures from streak pictures of the internal flow phenomena proved to be an interesting but somewhat cumbersome technique. A maximum temperature of about 700 K was recorded. It cannot be stated with certainty however, that this is the maximum instantaneous temperature which this configuration could produce. The statistical sampling involved is very small in comparison to the total number of cycles occurring in the tube in even a few seconds operation.

The very random nature of resonance tube operation, especially for the case of underexpanded jets as present in these configurations, is amply demonstrated both by the stop action pictures as well as the streak films. At present it would appear that a theory to predict the maximum attainable temperature for such modes of operation is not possible. It is not even possible to 'a priori' predict the
number of shocks present in the tube for a given cycle. In his analysis of the maximum attainable temperature Kang assumes a single shock. It appears that such an analysis may be more nearly correct for the case of a correctly expanded nozzle. However, a correctly expanded flow is unlikely to occur in configurations similar to those discussed herein or those of other researchers investigating the deleterious effects of an accidental inclusion of a resonance tube configuration in a flow system.

Previously both Thompson and Kang succeeded in constructing wave diagrams of the internal flow processes within a resonance tube based on the external flow phenomena. Again, their results are correct only for the correctly expanded jet. The streak film technique has the additional advantage that wave diagrams of the internal flow are directly obtained.

The existence of several modes of operation for a single configuration may at first seem somewhat unusual. In the original work on resonance tubes Hartmann noted zones of instability corresponding to the nodal pattern of an underexpanded jet. The observed resonance depended on where the tube was placed within this nodal structure. It was already pointed out above how filleting the square corners of the mixing tube allowed the third mode resonance to appear. As would be expected, the fillets would influence the shape of the free jet. If the base plug is removed from the mixing
tube the resonance is dramatically changed. This result is not unexpected as removal of the base plug acts to reduce the back pressure present in the mixing tube as well as providing another path for the flow to escape. The systematic variation in modes with primary mass flow rate is readily explained in terms of the free jet structure. For increasing primary mass flow rate, and corresponding increasing supply line pressure, the underexpanded condition of the jet continues to be increased. The nodal structure of the jet is thus displaced (see for example Love et al.\textsuperscript{13}) as the mass flow rate is increased. As jet structure changes, the mouth of the fuel line is effectively changing position within the jet accounting for the sudden and abrupt changes in mode.

The performance of the third mode resonance with counter-flow is somewhat startling. Undoubtedly the counter-flow is affecting the free jet expansion, compressing the jet structure so that it more nearly resembles conditions that exist at a lower \( m_p \) without counter-flow. This fact would explain the drastic change in resonant frequency for the third mode. It is also interesting to note that the high amplitude resonant frequency with counter-flow agrees well with the first and second mode resonant frequencies (Figure 26).

The exact structure of the free jet with counter-flow is speculative. Photographs were not helpful because of great amount of mixing and turbulence associated with the
abrupt change in flow direction in this area. The pressure ratio at the exit of the fuel line may be great enough that this flow is also sonic. Figures 27 and 28 show that at the point where an abrupt change in resonant conditions for the third mode exist, the ratio $\frac{P - q}{P_0}$ is two or greater. Hall and Thompson both observed that the discharge phase of an ordinary resonance occurred as sonic flow and that a double shock system was thus set up. The first of these shocks is the ordinarily present Bow Shock set up when an object is placed in a supersonic stream. Such an arrangement is represented in Figure 35. It is possible that similar conditions could exist almost continuously for sufficient amounts of counter-flow. It is also possible that the two standing shocks could interact to form the large amplitude waves observed. The possibility that the large amplitude waves could interact with the oxidizer line flow, in effect setting up a coupled oscillation in both lines, was also investigated.

When a Kistler transducer was placed a few cm upstream of the mixing tube in the oxidizer line, and when both fuel line and oxidizer line flow rates were established such that large amplitude resonance was occurring in the fuel line, no change was observed in the supply line pressure. This observation verifies the statement that the primary flow is sonic at its entrance into the mixing tube. Calculations furthermore show that the flow in the mixing tube is not sufficient to cause frictional choking.
If the primary mass flow rate is increased to sufficiently high values then spurious high temperature waves appear in the fuel line in spite of appreciable counter-flow. Although about 460°K was observed for a primary mass flow rate of 240 gm/sec it is again not possible to say this is the maximum that could be attained.

Relationship of Windowed Mixing Chamber to Basic Configuration

One of the problems encountered in this study was that the windowed chamber did not resonate in a manner identical to that of the basic configuration. The problem appeared to be due mainly to differences existing in the free jet expansion process. Satisfactory agreements between the various resonant modes was finally achieved by filleting the corners of the mixing chamber. Unfortunately the amplitude of the important third mode resonance was much less for the windowed configuration. As this resonance occurred in the flow regime for the basic chamber where autoignitions were found to result, the inability to exactly duplicate these conditions with the windowed chamber was disappointing. Nevertheless certain important observations were made.

The third mode resonance observed here is fundamentally different from other observed resonance tube modes. Hall and Vrebakovich observed a mode of resonance which occurred only about the mouth of the tube. However no shock waves were observed traveling within the tube. The most common
The mode of resonance observed by the various authors is the same as observed here for the lower frequency modes. This mode consists of distinct inflow and outflow phases where a considerable portion of the resonance tube fluid is exchanged with the external jet. During the venting portion of the cycle an absence of shock waves is noted. However with the third mode this absence of shock waves is not observed. Before the reflected shock can exit from the tube another is entering. As a result the fluid within the tube is almost entirely indigenous fluid. The temperature distribution for this mode (Figure 34) shows that the temperatures near the open end are higher than for the others. The behavior for this mode is somewhat anomalous as the instantaneous pressures do fluctuate about a mean value, yet a cycle appears to exhibit no venting phase.

In the light of these experiments the temperatures measured in the basic mixing chamber (770-1075 K) appear to be reasonable. The resonance amplitude in the basic tube is greater, so higher temperatures would be anticipated. The actual instantaneous values of temperature could be even higher as the thermocouple measured only the average gas temperature and heat transfer losses are not accounted for. A rough estimate of the radiation losses from the heated fuel line shows that the gas temperature may be 100-150 K higher. The remaining discussion must show if the various observed autoignition phenomena can be explained in light
of these results.

Autoignition

There seems little doubt that the temperatures achieved by resonance heating are sufficient to cause ignition of combustible mixtures. For the basic configuration ignition occurred immediately upon introduction of the hydrogen when a staggered start sequence was used. However ignition did not occur for hydrogen-air, nor did it occur for hydrogen-oxygen when short mixing chamber lengths were involved. This implies some other phenomena must also be accounted for. It is felt that the ignition delay time of the reacting mixture must also be taken into account. Since the percentage of oxygen is greater for a hydrogen-oxygen mixture than for a hydrogen-air mixture the ignition delay times for hydrogen-oxygen would be about five times shorter, all other conditions being equal. The following order-of-magnitude analysis indicates the importance of delay time. Assume that a certain volume of reactants is heated to $700^\circ$K while the components mix at the base of the mixing tube or within the fuel line near the exit. A slight cooling of the hot gas probably does occur as it expands out of the resonating fuel line. As the reactants proceed up the mixing tube, further cooling is accomplished by mixing with the primary mass flow which is unheated. A further reduction in temperature occurs as the gases exit the mixing chamber. Presume ignition must occur before the gases exit the mixing tube or the reaction
will be quenched. If the average pressure in the mixing tube were about 2.5 atmospheres then according to Walker the ignition delay time of hydrogen-air for these conditions is around 8000 μsec. The corresponding delay time for hydrogen-oxygen would be about 1600 μsec. Calculations based on the average velocity within the mixing tube show that the residence time is about 1700 μsec. Therefore based on these crude estimates the hydrogen-air mixture quite possibly would not ignite while the hydrogen-oxygen would. Now if the mixing tube length were shortened by say a factor of 8 then the residence time would not be sufficient for even the hydrogen-oxygen to ignite. This relationship has been verified experimentally. This is in spite of the fact that the shorter chamber actually produced higher resonance temperatures. The importance of ignition delay time in explaining the anomalous ignition behavior of hydrogen-air as compared to ethylene-air and methane-air was discussed by Walker. He felt that since hydrogen-air possessed a lower ignition delay time than the other gases in his study, that it was more susceptible to non-steady effects (such as the resonance discussed here). The role of ignition delay time in these experiments may explain some of the low ignition temperatures in flowing hydrogen observed by him and other investigators (Hamilton, Tomagno, Sheperd, and Fay).

The possibility that the phenomena occurring in resonance tubes may also play a role in shock tube experiments
should not be overlooked. Fay and Hooker noted the effect of a small cavity in their shock ignition studies of stoichiometric hydrogen-oxygen. They observed ignition temperatures of 780 to 870°K. However if a small hole 1/16 inch in diameter by 1/2 inch deep was drilled into the end plate of the shock tube the ignition temperature was found to be up to 200°K less. Great care must therefore be exercised in the construction of shock tube apparatus to avoid unsteady effects in cavities.

In the present study some autoignition experiments were performed in which the flows were gradually increased up to the point where ignition occurred. These cases usually required that the flows be established for a matter of seconds before ignition took place. Based on the studies with counter-flow this behavior might seem quite likely. The average resonance temperature with counter-flow is greatly reduced, however, waves producing high temperatures do exist. With the flows being established gradually, the occurrence of ignition would be dependent upon whether or when these random waves would be strong enough to produce ignition conditions. Such strong waves were only found in the resonance studies for high oxidizer line flow rates. When auto-ignition studies were performed in this manner, the ignitions did not take place until the flow rates were even greater than those which produced ignitions by introducing oxygen first then hydrogen.
Another configuration which produced ignition is the 'Opposed with Check Valve', Figure 4(e). The check valve was placed physically as close as possible to the mixing tube. Audible resonance was reduced with this configuration. Ignitions could be produced however after operation of both flows for a period of a few seconds. The flow rates required were very large. Again, ignition is probably brought about by high temperature waves associated with resonance with counter-flow.

When the alignment of the inlet lines was such that resonance could not occur then ignition did not occur. This seems to suggest that resonance is the only mechanism that for these configurations produced ignition. The mechanism of flow-induced ionization could not be detected in any of the mixing chambers.

Experiments requiring further discussion are those in which ignitions were produced by placing blunt objects in the expanding gases exiting from the mixing chamber. In the configurations used for these studies the gases were introduced in a parallel manner at the base of the mixing chamber. Flat plates and blunted cylinders were placed in the flows about 1-1.5 cm from the mixing tube exit. Ignitions appeared to occur somewhat randomly and only at high mass flow rates of 600-700 gm/sec. The ignitions took place only after the gases had been flowing for several seconds. The ignitions appeared to be occurring on the face of the blunt objects as
the burning appeared to be entirely external and the mixing chamber was usually not even warm. As noted both by Mørch\textsuperscript{30} and Thompson\textsuperscript{31} a resonance tube of zero length can resonate in an underexpanded jet. Due to the very high mass flow rates, the pressure in the tube was undoubtedly high so that an underexpanded jet could be set up. It is thus quite likely that resonance was occurring in the gap between the blunt body and the mixing tube exit. Very little is known of the heating effect of this type of resonance. As there is no trapped gas as in the ordinary resonance tube one might expect the temperature to be lower. The amplitude of such resonance vibration, as reported by Mørch\textsuperscript{30} is also less for a plane resonator. The frequency may be quite high however, Mørch reported values up to 45 KHz. It is thus possible that the gas on the face of the blunt body may be traversed many times by the shocks before spilling over the sides.

It appears that the autoignition observed by McKenna\textsuperscript{1}, Hamilton\textsuperscript{2}, and Walker\textsuperscript{10} may be explained by resonance heating phenomena. McKenna observed the occurrence of "accidental detonations" in an apparatus which consisted of a constant area flow tube in which subsonic or supersonic stoichiometric flows of mixtures of hydrogen and oxygen were ignited by detonation waves fired head-on from another tube into the flow. Upon occasion the flowing mixture ignited without any apparent source and before the initiation detonation tube was fired. The ignitions occurred at high subsonic as well
as supersonic Mach Numbers. For the majority of cases the ignition occurred at the inlet of flow test section and propagated downstream. In other cases however ignition occurred at the flow tube exit and propagated upstream. It should be pointed out that the injection pattern for the hydrogen and oxygen consisted of opposed jets. According to McKenna ignition occurred sometimes immediately upon introduction of the gases or after a rather short time delay. Since the two jets were opposed, it is highly likely that for appropriate flow conditions ignitions took place in the mixing chamber. The open end of the initiation detonation tube was axially aligned with the flow tube. Such a configuration almost identically resembles the classical resonance tube configuration especially when supersonic or highly underexpanded subsonic flow is discharging from the flow tube. Resonant oscillations occurring in the initiation tube are almost certain to occur. Such conditions would lead to the downstream ignitions McKenna observed.

The statements that apply to McKenna's apparatus apply equally well to Hamilton's as the systems were nearly identical. However Hamilton studied only subsonic flows and fired incident shocks into the flowing mixture. The mixing chamber in both cases, made use of opposed jets. Hamilton observed that autoignition occurred both after the flow was established and also during the transient flow start procedure. It is quite interesting to note that ignitions occurred
In Hamilton's study for \( M = 0.8 \), but if the mass flow rate was reduced slightly so that a Mach Number of 0.78 resulted, ignitions no longer resulted. This suggests the possibility that these flow rates were on the boundary between the transition from one resonance mode to another.

It should be pointed out at this time that a resonant condition existing in these configurations could quite likely go unnoticed. Both McKenna and Hamilton used high volume blowers to supply dilution air for the combustible mixtures. In general the operation of their flow systems quite likely produced large volumes of noise itself. More important however is the fact that resonance in the presence of counter-flow becomes less noisy. Small amounts of counter-flow reduce the noise level of the resonance greatly although large amplitude waves may still be present. The remaining noise is primarily that of the flowing gases.

In experiments conducted with Walker\(^10\) this author observed that for the appropriate flow conditions audible resonance could be induced in his initiation shock tube. The walls of the shock tube became extremely hot. Even for those cases in which a diaphragm was placed over the open end of the shock tube resonance could occur in the gap. The diaphragms used by Walker did not remain plane but did form a slight cavity as they were bent back into the mouth of the shock tube by the action of the flow. In pictures taken of the gap between the shock tube and flow tube there is strong
evidence of resonance. It has already been noted that Walker was the first to verify that ignitions could be produced in the mixing chamber alone. The injection pattern of his mixing chamber was that of opposed jets.

Even in those cases where resonance does not cause ignition its effects may not be negligible. The low ignition temperatures found by Hamilton and Walker for flowing hydrogen-oxygen and hydrogen-air systems respectively are a case in point. The susceptibility of the hydrogen system to unsteady wave phenomena has already been discussed in light of its short ignition delay time. Walker gives a very extensive discussion of this topic. The results of the present study indicate that local non uniform temperatures and hot spots may be produced by resonance heating which could produce an apparently lower ignition temperature for flowing gas systems.

In conclusion it may be stated that the autoignition phenomena observed herein and by other investigators are a consequence of the design configuration producing resonance heating. Further, the occurrence of low temperature ignitions observed by Hamilton and Walker may to a great extent be dependent on resonance phenomena.
VI. CONCLUSIONS

1. The inadvertent use of resonant configurations in flowing gas systems may result in dangerous explosions. Localized regions at high temperature and high pressure may result from the resonance phenomena. If combustible gas mixtures are involved spontaneous ignition may result. Great care should be exercised in designing mixing chambers for combustible gas mixtures.

2. Autoignitions of hydrogen and oxygen mixtures were found to occur quite readily in mixing chambers in which opposed jets were employed. Resonant conditions existing in the fuel inlet line created temperatures of 770$^\circ$K and higher. Resonance heating may also be partially responsible for the ignition at low apparent temperatures as reported by several authors for flowing hydrogen-oxygen and hydrogen-air mixtures.

3. Streak schlieren photographs are obtained of the fuel line resonance phenomena. On the basis of this information the minimal flow rates necessary to produce autoignition can be predicted. The results indicate that the resonance phenomena is so complex that a workable theory for predicting the maximum attainable temperature is presently not possible. A technique is devised whereby the instantaneous
temperature occurring within any portion of the resonating fuel line may be determined. Further study of the resonance phenomena by streak photographs and other means is necessary to obtain a better understanding of resonance tube operation. This is especially true for those cases where the resonance in the tube is generated by an underexpanded jet.
## APPENDIX A

## COMPOSITION OF TEST GASES

### Hydrogen Gas:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Burdett Manufacturing Co.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Commercial</td>
</tr>
<tr>
<td>Purity</td>
<td>99.8%</td>
</tr>
<tr>
<td>Dew Point</td>
<td>-75°F</td>
</tr>
<tr>
<td>Impurities</td>
<td>He, N₂, O₂, CO₂, H₂O, CO</td>
</tr>
</tbody>
</table>

### Oxygen Gas:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Liquid Carbonic Co.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Commercial</td>
</tr>
<tr>
<td>Purity</td>
<td>99.5%</td>
</tr>
<tr>
<td>Impurities</td>
<td>Ar = 0.04%</td>
</tr>
<tr>
<td></td>
<td>N₂ = 0.20%</td>
</tr>
<tr>
<td></td>
<td>CO₂ = 20 PPM</td>
</tr>
<tr>
<td></td>
<td>H₂O = 20 PPM</td>
</tr>
<tr>
<td></td>
<td>CH₄ = 25 PPM</td>
</tr>
</tbody>
</table>

### Air:

- Pumped at this laboratory
- Dew Point: -140°F
- Oil: none

### Nitrogen Gas:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Liquid Carbonic Co.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>High Purity</td>
</tr>
<tr>
<td>Purity</td>
<td>99.995 + %</td>
</tr>
</tbody>
</table>
APPENDIX B

INTERPRETATION OF THE STREAK PHOTOGRAPHS

The first streak photographs obtained revealed at once that the resonance phenomena taking place within the fuel line were quite complicated. Somewhat baffling were the lines which seemed to result from the particle flow paths. There was no previous record which indicated that the particle flow paths should be visible. Minute particle contaminants, deposits on the windows, and turbulence were considered as possible sources of these lines. However it is quite unlikely that deposits on the windows could cause the streaks observed on the photographs because the lines interact with shock waves in an abrupt manner with sudden changes in direction. In addition, the displacement of the lines may be as much as 60% of the fuel line length, which is definitely not a characteristic of particles adhering to the windows. As for contaminants, it would require very small particles to execute the observed changes in direction so rapidly. Also against this theory is the fact that light as well as dark lines are observed, an indication that light path has been deflected rather than just obstructed as would be the case with a solid particle. The most probable cause then
appeared to be free stream turbulence which would be carried along at nominally the free stream velocity. The fact that turbulence can be viewed optically is well known (see for example the discussions on optical turbulence measurements in reference 36). With this in mind several experiments were conducted to determine how well these lines could predict a known flow velocity and if their exact nature could be determined.

Early experiments involved flowing gases at low Mach Numbers (M ~ .1 to .3) through the fuel line window section to see if the schlieren system could detect the presence of motion. Since it was possible that the air might contain some oil vapor contaminants, high purity nitrogen was also used. Flow lines were visible for both nitrogen and air. A typical streak film record of this flow is shown in Figure 36. When the velocity is calculated from the known mass flow rate and compared to that measured from the film the agreement is quite good. Table 2 is a summary of some of the data obtained in this manner for air. The high purity nitrogen was fed from the supply bottle via a short line directly into the fuel line test section. This arrangement was used so that if any contaminants were in the fuel flow system, they would not be picked up by the nitrogen. The strip film traces obtained in this manner appeared identical to those obtained with the air flow. From this set of experiments it was concluded that contaminants were not responsible for the
flow lines observed on the streak films. Further, as the tabular data show, the actual velocity can be predicted a fair degree of accuracy from the streaks. The maximum recorded error of approximately 9% involves the accumulative errors of mass flow measurement, camera speed measurement, and measurement of the slope of the line on the streak photograph. Further, the inclusion of frictional effects would increase the calculated velocity so that, in general, a better agreement would be reached. For a flow velocity of 100 m/sec the Reynolds number in the square fuel line is:

\[ R_d = \frac{Vd}{y} = 55,300. \]

This number when compared to the critical Reynolds Number for transition to turbulent flow which according to Schlichting is 2300, shows that the flow within the tube is indeed turbulent.

It was also desired to see whether the flow induced by a single shock wave propagating into the fuel line could be observed. A small shock tube (see Chapter II) was used as the source for a single shock wave. For the configuration shown in Figure 9a the shock front was not well formed. This lack of uniformity is probably caused by the path the shock must traverse before entering the square fuel line test section. A streak photograph obtained with this configuration is shown in Figure 37. By adding an extension to the shock tube (see Figure 9b) the shock entered the fuel line through a simpler path. The improved results can be seen in Figure
38. Both streak photographs show that within a short time after the shock enters the tube the flow lines appear. The transient flow behind the shock wave appears to set up resonance waves within the fuel line. This behavior is especially evident in the case of the shock tube without the extension. However, this result perhaps had to be expected as the flow leaving the shock tube is underexpanded and could behave in a manner similar to that of the flow exiting from the oxidizer inlet line.

Flow lines begin to appear 100 - 200 microseconds after the shock wave is first visible in the test section. Calculations show that these times are an order of magnitude shorter than the time-of-arrival of the contact surface. By extrapolation of the slope of the shock and flow lines backward to their intersection point, it appears that the lines are formed very close to the exit of the shock tube in the gap between the exit and the entrance to the fuel line. It is further noted that a great many additional lines are formed when the reflected shock collides with the incoming flow. The rather layered appearance of a great number of these lines indicates the presence of turbulent eddies. A series of time-delayed strobe photographs are presented in Figure 39. The striking resemblance between these photographs and the streak film records is apparent.

The streak photographs present another opportunity to test how well this technique can record flow velocities. The
shock velocity can be determined from the film. Knowing the
temperature gives the shock Mach Number, from which the flow
velocity can be calculated readily. A summary of calculated
and experimental velocities obtained in this manner is pre­
sented in Table 3. The first three experiments given in this
table are calculated for multiple shocklets entering the
tube (as in Figure 37). Agreement between calculated and
measured values is very good.

On the basis of these experiments it was concluded that
the particle flow was made visible due to its turbulent
nature, and further, that its velocity could be calculated
very well from the streak film photographs. The measured
values of velocity were usually within ± 4% with a maximum
deviation of ± 9% from those calculated.

Also shown in Table 3 are various calculated and mea­
sured pressure ratios. In general the agreements between the
experimental values measured by the Kistler piezoelectric
transducers and those calculated from the film is satisfac­
tory. The reflected pressure behaved in a slightly more
erratic manner. It should be noted however that transducer
measurements at such low pressure ratios are more difficult
than at higher pressure ratios as small errors are magnified.
APPENDIX C
DATA REDUCTION AND CALCULATIONS

Flow Mach Number and Total Pressure in the Oxidizer Inlet Line

Since the inlet lines were quite small, total pressure measurements of the flow in the lines were not attempted. However since the mass flow rates for a given condition and for the tube area are known, and the static pressure is readily measurable, it is possible to calculate the total pressure and Mach Number within the tube at any point where the static pressure is measured. For this simple flow in a tube conservation of mass requires:

\[ M = \frac{\dot{m}}{P A} \left( \frac{\gamma RT}{P A (\gamma RT)^{\frac{1}{2}}} \right) \]

The constant terms may be grouped so that:

\[ M = C \frac{\dot{m}}{P} \left( \frac{T}{T_o} \right)^{\frac{1}{2}} \]

where the total temperature (approximately the temperature of the gas supply tanks) has been included in the constant \( C \). With the aid of tables such as reference 38 this equation can be readily solved by iteration on \( M \) and \( T/T_o \). The solution for \( M \) allows \( P/P_o \) to also be obtained from the tables.

68
Data Reduction from Strip Films

The wave speed and particle speed within the test section are directly related to the camera rotational speed and the tangent of the inclination angle shown on the strip film.

\[ W \text{ RPM} \tan \phi \] (3)

An arbitrary sign convention was assigned so that waves or particles traveling upstream (from the mixing chamber up the fuel line) were taken as positive velocities, while those which were leaving the fuel line were taken as negative velocities. The constant of proportionality involves the drum camera circumference and the minification of the optical system. Since the camera remains in a fixed laboratory position the velocities obtained from the strip film are velocities relative to laboratory fixed coordinates. However, as discussed previously, particle velocities before and after the shock as well as the shock velocity itself, can be read from the film. Conversion to the shock fixed coordinate system is accomplished by:

\[ U_1 = W_1 - W_3 \] (4)

and \[ U_2 = W_2 - W_3 \] (5)

Since the fuel line is of constant area the density ratio across the shock is given simply by:

\[ \frac{\rho_2}{\rho_1} = \frac{U_1}{U_2} \] (6)

Knowing the density ratio, the shock Mach Number \( M_1 \) can be calculated from the normal shock equation. However since both \( M_1 \) and \( U_1 \) are now known, the speed of sound, and hence
the temperature $T_1$, can be found directly. Knowing $M_1$, the
temperature ratio $T_2/T_1$ can be calculated from the normal
shock relations and thus $T_2$ is also known. Or alternately,
$M_2$ can be found from $M_1$ and thus knowing $M_2$ and $U_2$ the tem­
perature $T_2$ can be calculated. The two different methods
gave excellent agreement. The normal shock relations can al­
so furnish the total temperature and the pressure ratio. The
absolute pressure however cannot be calculated but must be
measured.

The total temperature relative to the laboratory fixed
coordinate system was calculated from the conservation of
energy equation, assuming a calorically perfect gas:

$$T_o = T + \frac{W^2}{2\ c_p} \quad . \quad (7)$$

Due to the large number of data points obtainable by
this method, the data reduction procedure was programmed to
make use of the Ohio State University Computer Center IBM 360.

In some instances it was of interest to compare the
strength of the reflected shock measured from the streak
film records with the reflected shock strength predicted
from the incident wave. The reflected shock pressure in terms
of the initial Mach Number is:

$$\frac{P_{RF}}{P_2} = 1 + \frac{\gamma}{2} \frac{\gamma+1}{\gamma-1} \left( \frac{2 \gamma}{\gamma-1} \frac{M^2-1}{M^2-1} \left( \frac{\gamma-1}{2} \frac{M^2+1}{M^2-1} \right) \right) \left\{ 1 + \left[ \frac{\varepsilon(\gamma-1)}{\gamma+1} \left( \frac{2 \gamma}{\gamma-1} \frac{M^2-1}{M^2-1} \left( \frac{\gamma-1}{2} \frac{M^2+1}{M^2-1} \right) \right) \right]^2 \right\}^{1/4}$$
Table 1

Calculated and Measured Frequencies for the Various Configurations

<table>
<thead>
<tr>
<th>Experimental Configuration</th>
<th>Approximate Measured Frequency (Hz)</th>
<th>Calculated Fundamental Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mode 0</td>
<td>mode 1</td>
</tr>
<tr>
<td>Basic Chamber</td>
<td></td>
<td>600-650</td>
</tr>
<tr>
<td>$1/d = 13.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windowed Chamber</td>
<td>450</td>
<td>650</td>
</tr>
<tr>
<td>$1/d = 12.9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windowed Chamber</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>$1/d = 25.1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windowed Chamber Counter-flow ($\dot{m}_R = 0$)</td>
<td></td>
<td>330</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2

Calculated and Measured Flow Velocities

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$W_{meas}$ (m/sec)</th>
<th>$W_{calc}$ (m/sec)</th>
<th>$W_{calc} - W_{meas}$</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>96</td>
<td>-4</td>
<td>-4.0</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>80</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>126</td>
<td>120</td>
<td>-6</td>
<td>-5.0</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>131</td>
<td>-9</td>
<td>-6.9</td>
</tr>
<tr>
<td>5</td>
<td>165</td>
<td>151</td>
<td>-14</td>
<td>-9.3</td>
</tr>
<tr>
<td>6</td>
<td>176</td>
<td>175</td>
<td>-1</td>
<td>0.6</td>
</tr>
<tr>
<td>7</td>
<td>190</td>
<td>185</td>
<td>-5</td>
<td>-2.7</td>
</tr>
<tr>
<td>8</td>
<td>208</td>
<td>201</td>
<td>-7</td>
<td>-3.5</td>
</tr>
</tbody>
</table>
Table 3
Calculated and Measured Values for Single Shook Studies

<table>
<thead>
<tr>
<th>Run No.</th>
<th>( M_i )</th>
<th>( \frac{P_2}{P_1} )\text{calc} from ( M_i )</th>
<th>( \frac{P_2}{P_1} )\text{meas} (Kistler)</th>
<th>( \frac{P_{RF}}{P_2} )\text{calc} from ( M_{RF} )</th>
<th>( \frac{P_{RF}}{P_2} )\text{meas} (Kistler)</th>
<th>( W_2 )\text{calc} (m/sec)</th>
<th>( W_2 )\text{meas} (m/sec)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-9-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>205</td>
<td>210</td>
<td>-2.4</td>
</tr>
<tr>
<td>9-11-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>233</td>
<td>233</td>
<td>0.0</td>
</tr>
<tr>
<td>9-11-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>195</td>
<td>209</td>
<td>-7.2</td>
</tr>
<tr>
<td>9-14-2</td>
<td>1.61</td>
<td>2.86</td>
<td>2.66 (3)</td>
<td>2.35</td>
<td>2.47</td>
<td>2.73 (3)</td>
<td>2.28 (2)</td>
<td>2.2</td>
</tr>
<tr>
<td>9-14-3</td>
<td>1.55</td>
<td>2.64</td>
<td>2.71 (3)</td>
<td>2.22</td>
<td>2.36</td>
<td>2.90 (3)</td>
<td>2.27 (2)</td>
<td>3.0</td>
</tr>
<tr>
<td>9-15-7</td>
<td>1.456</td>
<td>2.30</td>
<td>2.22 (3)</td>
<td>2.12</td>
<td>2.10</td>
<td>2.54 (3)</td>
<td>2.40 (2)</td>
<td>-1.4</td>
</tr>
<tr>
<td>9-15-5</td>
<td>1.52</td>
<td>2.53</td>
<td>2.27 (3)</td>
<td>2.25</td>
<td>2.26</td>
<td>2.27 (3)</td>
<td>2.61 (2)</td>
<td>3.8</td>
</tr>
<tr>
<td>9-16-1</td>
<td>1.34</td>
<td>1.93</td>
<td>1.94 (3)</td>
<td>2.07</td>
<td>1.82</td>
<td>2.35 (3)</td>
<td>2.25 (2)</td>
<td>-4.1</td>
</tr>
</tbody>
</table>

Note: Numbers in Parenthesis Refer to Transducer Locations as Shown in Figure
Figure 1 Comparison of Incident Shock Ignition Temperatures and Thermal Explosion Limits For Hydrogen-Oxygen and Hydrogen-Air
Figure 2 A Typical Resonance Tube During The Inflow Phase
Figure 3  Basic Mixing Chamber
Figure 4 Variations of Basic Mixing Chamber
Lucite Windows

Quartz Windows

Removable End Plates to Accommodate Transducers, Extensions, or Adaptor for Cross Flow Studies

Figure 5 Windowed Mixing Chamber
Figure 6 Location Of Instrumentation
Figure 7  Windowed Mixing Chamber and Attachments
Figure 8  Schematic of Schlieren System
Figure 9  Schematic of Arrangement for Single Shock Study
Figure 10 Oxidizer Line Inlet Pressures for Basic Mixing Chamber
Figure 11 Fuel Line and Base Pressure for Basic Mixing Chamber with Capped Fuel Line
Figure 12 Schematic of Proposed Resonance Tube Analogy in Basic Mixing Chamber
Figure 13 Oscillograph Traces of Pressure Variations in Fuel Line of the Basic Mixing Chamber
Figure 14: The Effect of Counter-Flow on Resonant Frequency
Figure 15 The Effect of Counter-Flow on the First Mode Resonance ($\dot{m}_p = 100$ gm/sec) in the Basic Mixing Chamber
Figure 16 The Effect of Counter-Flow on the Second Mode Resonance 
\( \dot{m}_p = 115-135 \text{ gm/sec} \) in the Basic Mixing Chamber
Figure 17 The Effect of Counter-Flow on Third Mode Resonance ($\dot{m}_p = 270$ gm/sec) in the Basic Mixing Chamber

\[ \dot{m}_R = 0 \text{ gm/sec} \]
\[ \dot{m}_R = 10.5 \text{ gm/sec} \]
\[ \dot{m}_R = 18.9 \text{ gm/sec} \]
\[ \dot{m}_R = 24.0 \text{ gm/sec} \]
\[ \dot{m}_R = 44.2 \text{ gm/sec} \]
\[ \dot{m}_R = 81.0 \text{ gm/sec} \]
Figure 18 The Effect of Counter-Flow on the Third Mode Resonance (\( \dot{m}_R = 429 \, \text{gm/sec} \)) In the Basic Mixing Chamber
Figure 19 Variation in Fuel Line Pressure with Counter-flow in Basic Mixing Chamber
$\tau = 0$ For Shock at End Wall

End Wall

Figure 20 Stop Action Schlieren Photographs of First Mode Resonance In Square Fuel Line, $1/d = 12.9$
Figure 21 Stop Action Schlieren Photographs of Second Mode Resonance in a Square Fuel Line, $l/d = 12.9$
\( \tau = 0 \) For Shock at End Wall

<table>
<thead>
<tr>
<th>( \tau ) (( \mu )sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>450</td>
</tr>
<tr>
<td>500</td>
</tr>
</tbody>
</table>

Figure 22 Stop Action Schlieren Photographs Of Third Mode Resonance (\( \dot{m}_p = 225 \) gm/sec) In Square Fuel Line, \( l/d = .12.9 \)
Figure 23 Portion of Typical Streak Photograph, Second Mode Resonance, $l/d = 12.9$
Figure 24 Composite of Streak Photographs For the Various Modes, $l/d = 12.9$
Figure 25 Composite of Streak Photographs for the Various Modes, l/d = 25.1
Figure 26 Variation in Resonance Frequency with Counter-Flow For Windowed Mixing Chamber
Figure 27 Variation in Average Fuel Line Pressure with Counter-flow in Windowed Mixing Chamber
Figure 28 Variation in Base Pressure with Counter-flow in Windowed Mixing Chamber
Figure 29 Variation in Resonance Amplitude with Counter-flow in Windowed Mixing Chamber
$\gamma = 0$ for wave at $\Re$

\begin{align*}
\dot{m}_P &= 59.1 \text{ gm/sec} \\
\dot{m}_R &= 0.0 \text{ gm/sec} \\
\dot{m}_P &= 60.3 \text{ gm/sec} \\
\dot{m}_R &= 18.8 \text{ gm/sec} \\
\dot{m}_P &= 69.3 \text{ gm/sec} \\
\dot{m}_R &= 0.0 \text{ gm/sec} \\
\dot{m}_P &= 70.0 \text{ gm/sec} \\
\dot{m}_R &= 12.9 \text{ gm/sec} \\
\dot{m}_P &= 146.2 \text{ gm/sec} \\
\dot{m}_R &= 0.0 \text{ gm/sec} \\
\dot{m}_P &= 146.2 \text{ gm/sec} \\
\dot{m}_R &= 33.8 \text{ gm/sec}
\end{align*}

Figure 30  Stop Action Schlieren Photographs in Square Fuel Line With and Without Counter-Flow
Figure 31 Composite of Streak Photographs Showing Variation
In First Mode Resonance With Counter-Flow
Figure 32 Composite of Streak Photographs Showing Variation In Second Mode Resonance With Counter-Flow

\[ \dot{m}_R = 0.0 \text{ gm/sec} \]
\[ t = 153 \mu \text{sec/cm} \]

\[ \dot{m}_R = 0.9 \text{ gm/sec} \]
\[ t = 151 \mu \text{sec/cm} \]

\[ \dot{m}_R = 14.8 \text{ gm/sec} \]
\[ t = 140 \mu \text{sec/cm} \]
Figure 33 Composite of Streak Photographs Showing Variation in Third Mode Resonance With Counter-flow
Figure 34 Temperature Distribution in Fuel Line as Measured From Streak Photographs for Third Mode Resonance
Figure 35 Discharge Phase of Resonance Tube Operation
Figure 36 Typical Streak Photograph of Flow ( $W \approx 100\text{m/sec}$) in Square Fuel Line
Figure 37 Streak Photograph of Shock Tube Generated Shock Wave in Square Fuel Line
Figure 38 Streak Photograph of Improved Shock Tube Generated Shock Wave In Fuel Line
\[ \tau = 0 \text{ for Wave at } \Theta \]

- \( \tau \) (\( \mu \text{sec} \))
  - 1
  - 50
  - 70
  - 100
  - 140
  - 150
  - 180
  - 210
  - 240
  - 270
  - 300
  - 340
  - 370

End Wall

Figure 39 Stop Action Photographs of Shock Tube Generated Shock Wave in Fuel Line
REFERENCES


