Part III

Swirl Stabilized Turbulent Flame Dynamics

Chapter 8

Swirl Stabilized Study : Technical Approach and Experimental Setup

8.1 Rationale and Objectives

Discussions in Part I have clearly highlighted the need to develop reduced order models that describe the dynamic response of swirl stabilized flames to perturbations in the velocity of the incoming reactants. These models are expected to be simple and yet, exhibit all the dominant dynamic characteristics of the combustion process. Since a large number of physical variables are involved in the combustion process occurring in complex swirl stabilized combustors, simple systems were initially studied and are described in Part II. Having understood the dynamics of laminar flat flames and developed methodologies to build reduced order flame dynamic models, an experimental setup was designed and fabricated to study the dynamics of turbulent swirling flames. This chapter describes the details of the experimental setup of the turbulent variable swirl combustor.

8.2 Technical Approach

The system level description of the dynamics involved in a combustion process, described in Chapter 4 Section 4.2.1 is also valid for turbulent swirl stabilized flames. Therefore,

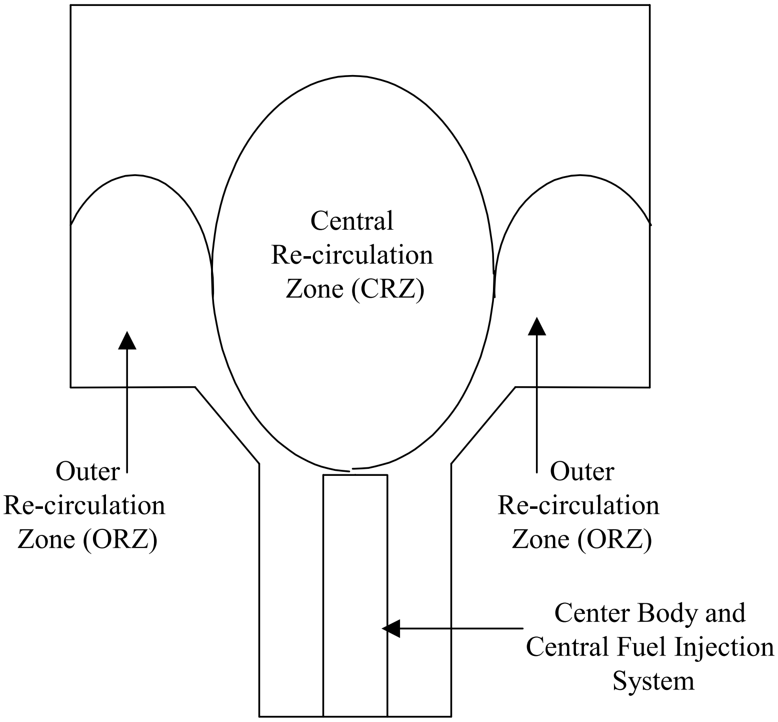

Figure 8.1: Sketch of a swirling flow showing the various re-circulation zones

the technique developed to measure the open loop transfer function of laminar flat flame dynamics will be used for developing the transfer function for the flame dynamics (within the linear range) of swirl stabilized turbulent flames. The flames in the turbulent variable swirl combustor were hydrodynamically stabilized due to the presence of the central re-circulation zone (CRZ) and the outer re-circulation zone (ORZ), as shown in Figure 8.1. The CRZ and the ORZ re-circulate the products of combustion back to the inlet of the combustor, thereby enabling the transfer of energy from the hot products of combustion to the incoming reactants. This hydrodynamic feature of swirl stabilized flames that creates a continuous ignition source, eliminates the need for an external energy re-circulator as was required for laminar flat flames. By altering the flow field and hence, the strength of the re-circulating zones, the flame could be forced to reside in either of the re-circulating zones or on the shear layer between the re-circulating zones. Such a variation in the flow field could be achieved by changing the swirl number and hence, the swirl strength of the flow

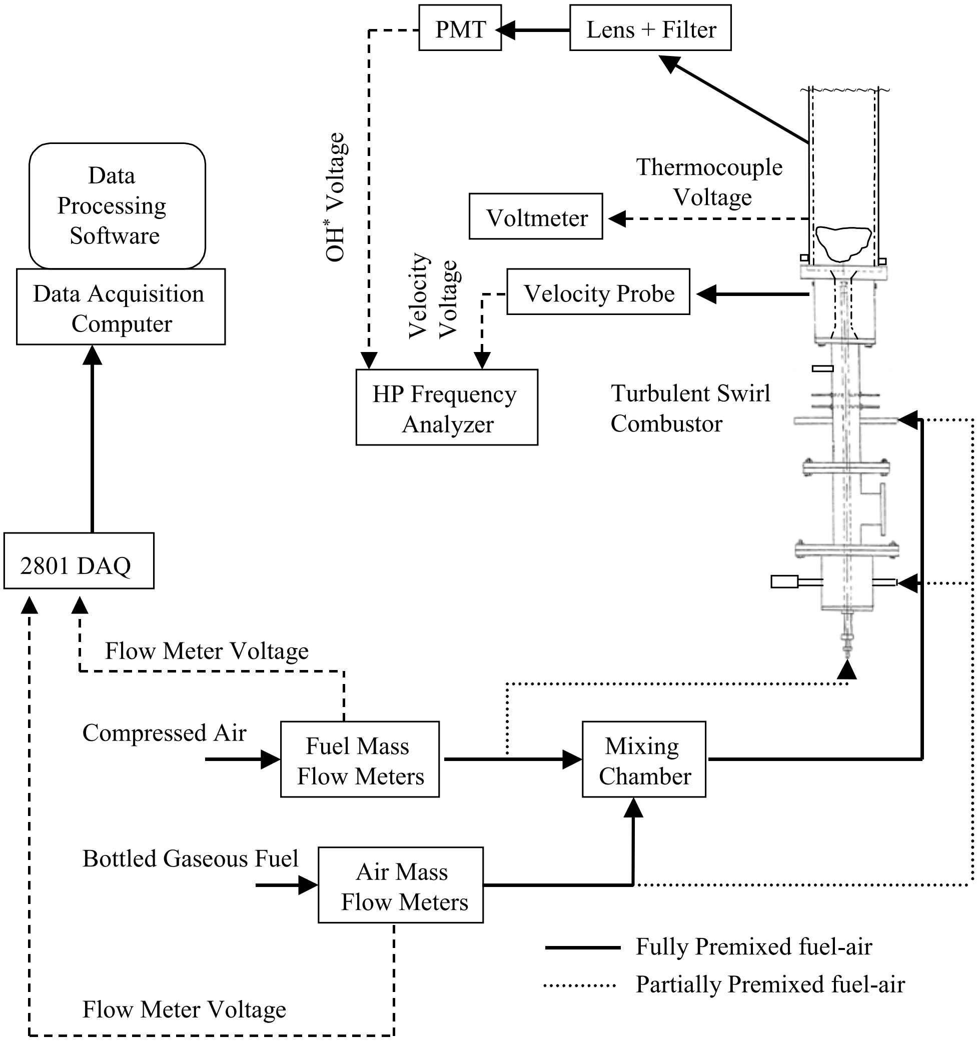

Figure 8.2: Experimental setup for turbulent swirl stabilized flame dynamic study

entering the combustion chamber.

8.3 Experimental Setup

The experimental setup used to study the dynamics of turbulent swirl stabilized flames is schematically shown in Figure 8.2. The system consists of mass flow meters, a mixing system that was used for the study of premixed swirl stabilized flames, the flow control system, a turbulent variable swirl combustor, the dynamic velocity measurement system, the dynamic

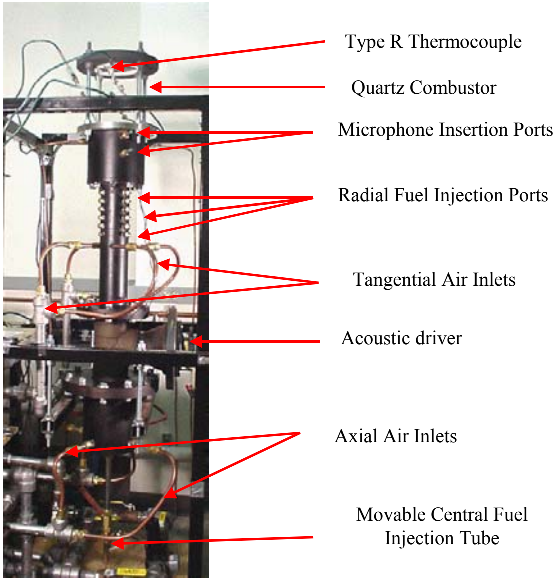

Figure 8.3: Photograph of the variable swirl turbulent combustor

OH^* measurement system, and the data acquisition system. The fuel flow measured using an array of mass flow meters, could be injected directly into the swirling air flow within the rig, generating partially premixed condition, or fed into a premixer that thoroughly premixed the fuel and air prior to the injection of the premixed charge into the combustor, henceforth termed as fully premixed condition. Thermocouples measured the gas temperatures near the wall of the combustion chamber. Microphones were used to obtain dynamic velocity signal, while the OH^* chemiluminescence captured by viewing the entire flame from the side was taken as the measure of the dynamic heat release rate. Controlled acoustic perturbations were imparted to the flow using a $6\frac{1}{2}$", 160 watt, 8 ohm speaker. The dynamic signals were analyzed using the Hewlett Packard frequency analyzer, while the flow parameters were recorded using a data acquisition system.

8.3.1 Turbulent Variable Swirl Combustor

The variable swirl turbulent combustor was designed with a maximum pressure rating of 150 psig, has a maximum thermal rating of 400 KW and is capable of accommodating 200

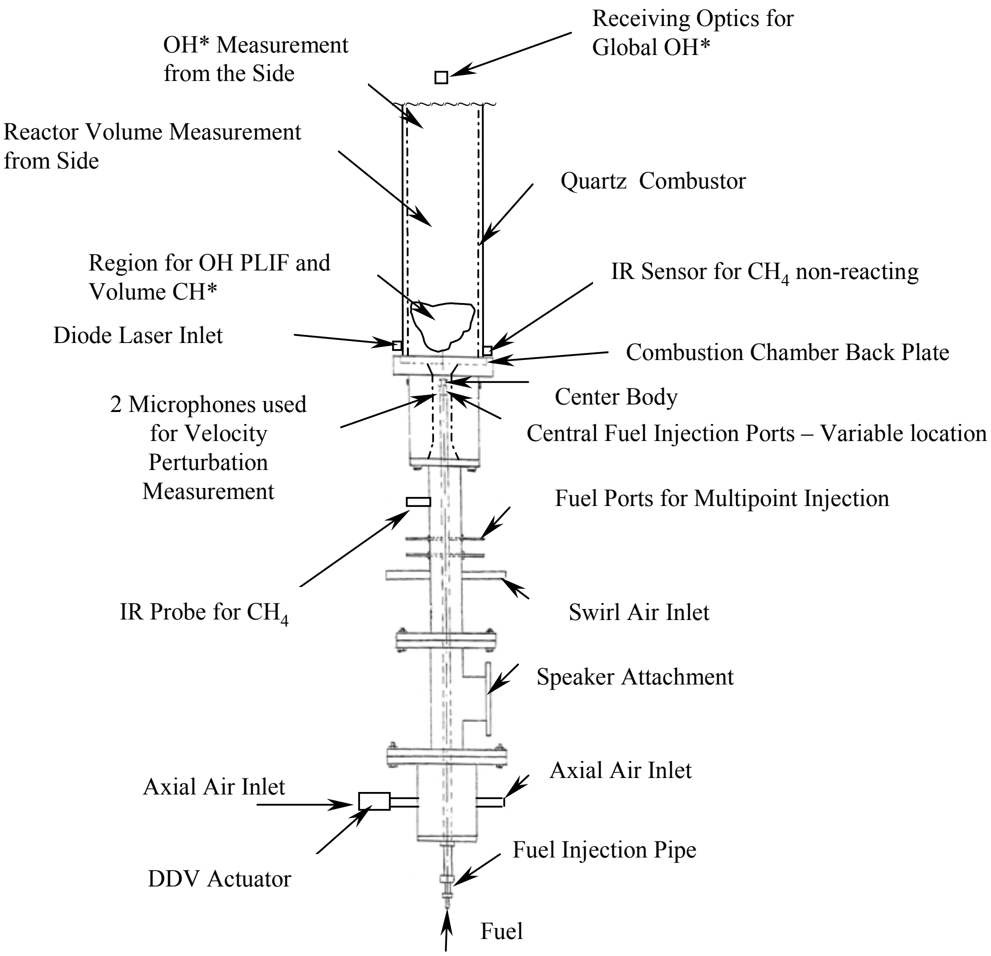

Figure 8.4: Schematic of the variable swirl turbulent combustor

scfm of total flow. It has a variable swirl generation arrangement that generates a maximum swirl number (S), of 1.86. A photograph of the turbulent variable swirl combustor built for this experiment is shown in Figure 8.3 and its schematic is shown in Figure 8.4. A dimensioned assembly drawing of the rig can be found in Appendix G. The combustor consists of a plenum, a swirl generator, a fuel injection system, an acoustic driver, a burner head and a quartz combustion chamber. The plenum is made of a 150 mm diameter pipe that has a plate welded at its bottom. The bottom plate supports the $\frac{3}{4}$" stainless steel fuel line, which feeds the movable central fuel injection nozzle. Four angularly equispaced axial ports are provided in the plenum which house the axial air injectors. Each injector is a $\frac{1}{2}$"

stainless steel tube with one of its ends capped and is drilled with $\frac{1}{16}$" diameter holes that are equispaced in the radial direction. There are three rows of the $\frac{1}{16}$" diameter holes on each injector which are 90 degrees apart. This assembly ensures that the jets forced out of these holes are directed radially in the plane of the injection and axially upstream of the injection. The holes provide high acoustic impedance that effectively decouples the rig from the influence of the acoustic characteristics of the piping system. Downstream of the axial injectors, the plenum supports an aluminum honeycomb and a perforated plate that act as flow straightening devices. Attached to the downstream end of the plenum is a fabricated tee. The tee has a through branch of 75 mm diameter, while its side branch consists of a bell reducer which supports a speaker having a diameter of 130 mm.

Flow through the tee enters the swirl generator, which consists of a long pipe having a diameter of 75 mm. At its upstream end, the swirl generator supports the apparatus responsible for the alignment of the central fuel injection system with the axis of the combustion chamber. The swirl generator has four copper tubes, $\frac{1}{2}$" in diameter, attached tangentially to its walls. These are the tangential air ports. The design is such that the air enters the swirl generator through these ports tangentially with reference to the upcoming axial air.

Inside the swirl generator, the tangential and the axial air stream mix to generate a swirling flow field. The swirl intensity can be varied by controlling the percentage split of total air flow rate into the axial and the tangential ports. Downstream of the tangential ports are $\frac{1}{4}''$ ports at six different axial locations. At each axial location, there are four ports 90 degrees apart. The distance between the two axial locations is 25.4 mm. These ports are made available for insertion of radial fuel injection spokes. This design feature enables the injection of fuel at multiple axial locations, that are different from the location of the central fuel injector described in Section 8.3.2. Thus, it is possible to simulate dynamic conditions analogous to the presence of multiple injectors in full-scale gas turbines. This feature is especially useful to study the effects of multiple time delays, generated due to equivalence ratio fluctuations, on the dynamics of the combustion process. The radial fuel injector ports can also be used in the study of the combustion dynamics using dual fuels. In such a study, the radial fuel injection ports will be used for the injection of gaseous fuel, while the liquid fuel will be injected through the central fuel injection system.

Downstream of the swirl generator is the combustor head. It houses a converging flow passage that reduces the cross sectional diameter of the flow from 75 mm to 38 mm. Beyond the converging section, a straight section having a L/D ratio of 2 is present. The microphones and the 'Type K' thermocouples used for the velocity measurement are housed in this section with their respective sensors mounted flush to the walls of the flow passage. Downstream of the burner head is the combustion chamber back plate, which has the diverging quarl and the arrangement to mount the combustion chamber. This plate is replaceable so as to be able to vary the cone angle of the quarl and also the diameter of the mounted combustion chamber. For the present experiment, the combustion chamber back plate was designed to have a quarl with a half cone angle of 35 degrees and was able to accommodate combustion chamber of 125 mm diameter. Presently, the combustion chamber mounted on the back plate, is made up of quartz and is 125 mm in diameter and 190 mm long. To support the combustion chamber, a steel flange was placed at its downstream end. The flange was supported by connecting it to the combustion chamber back plate and thus, did not apply any stress on the quartz tube. All contacts between the quartz tube and metal surfaces were insulated by using $Fiberfrax^{TM}$ gasket material. The combustion chamber is open to the atmosphere at its downstream end, but to conduct pressurized combustion experiments, it can be easily connected to a back pressure regulator that would maintain a specific pressure in the combustion chamber.

8.3.2 Central Fuel Injection System

Figure 8.5 shows a sketch detailing the design of the central fuel injection system. The central fuel injection system consists of a set of coaxial stainless steel tubes, that are inserted from the bottom of the combustor. The fuel injection system itself is coaxial to the centerline of the combustor. The outer most tube is $\frac{3}{4}$" in diameter and has the fuel injector welded to its

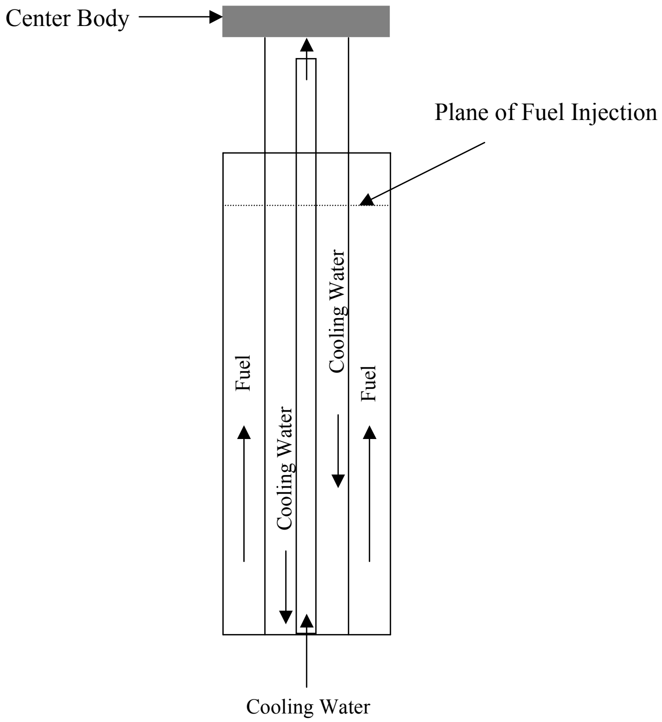

Figure 8.5: Sketch of the central fuel injection system

downstream end. This outer tube is capable of sliding along the length of the $\frac{3}{8}$" inner tube, which has a $\frac{3}{4}$" center body welded to its downstream end. This design enables the axial movement of the outer $\frac{3}{4}$" tube relative to the $\frac{3}{8}$" tube. Thus, by maintaining the center body at the inlet of the quarl, the plane of the fuel injection could be varied in the axial direction. This important feature makes it possible to study the effects of unmixedness and the degree of premix on the dynamics of the combustion process. The fuel injector itself has 24 equispaced holes of $\frac{1}{32}$" diameter for radial injection of the fuel into the swirling air flow. The fuel flows in the annulus of the $\frac{3}{4}$" tube and the $\frac{3}{8}$" tube. The innermost $\frac{1}{4}$" stainless steel tube in the central fuel injection system is used for impinging a jet of cooling water onto the undersurface of the center body plate. The water, then flows out of the combustor through the annulus between the $\frac{3}{8}$" and the $\frac{1}{4}$" stainless steel tubes. In the process, it also cools the fuel flow, thus maintaining the fuel temperature at the point of injection almost constant for all the tests conducted.

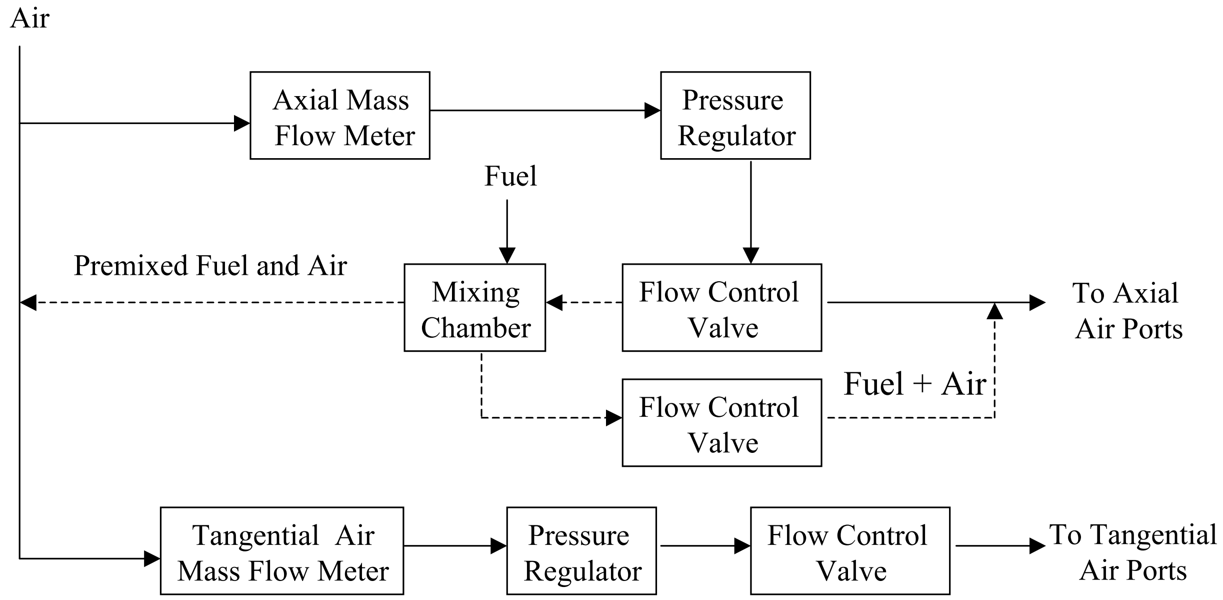

Figure 8.6: Piping and instrumentation diagram for the air supply system

8.3.3 Flow Control System

The combustor requires a controlled flow of air and fuel. The fuel supply system was expected to have the capability of either injecting the fuel directly into the swirling air stream inside the combustor through the central injection system or premixing it with the air outside the combustor in a premixer. The air supply system was expected to have the capability to monitor and control independently the amount of air flow through the axial and the tangential ports. To achieve all of the above mentioned flow capabilities along with the ability to regulate the pressure of the flow, a flow system was designed and built. The piping and the instrumentation diagrams for the air and the fuel supply systems are shown in Figure 8.6 and Figure 8.7 respectively. The fuel flow was monitored by a bank of four Hastings flow meters. Each flow meter had a different flow range and depending on the amount of flow at any given time, one of the flow meters was used. This arrangement ensured good accuracy of the fuel flow measurement over a wide range of flow rates, thus limiting the uncertainty of the measured equivalence ratio. The details of the flow meters can be found in Appendix C. The fuel flow stream has its own pressure regulator and a flow control valve. Using a

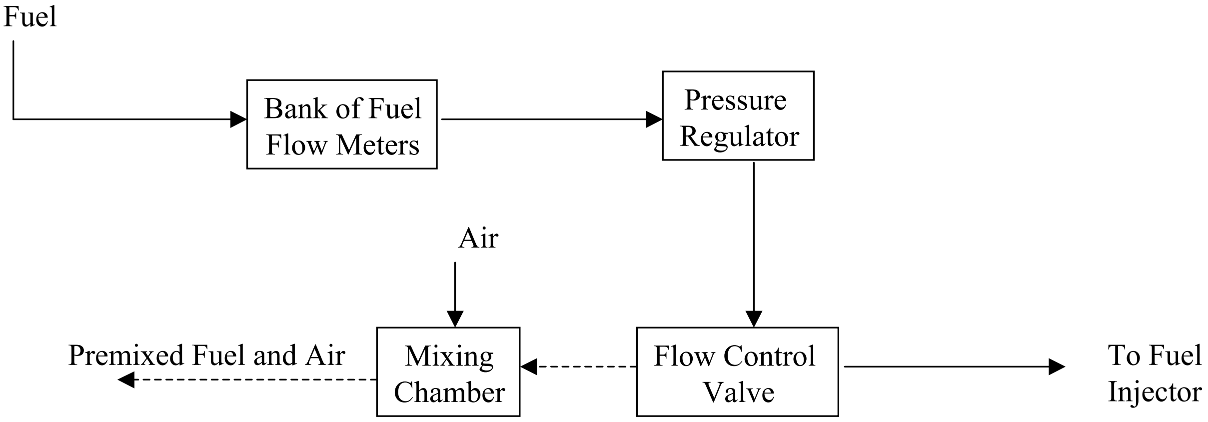

Figure 8.7: Piping and instrumentation diagram for the fuel supply system

combination of the shut off valves, the fuel flow could be diverted either to the central fuel injection system or to the premixer.

The incoming air was split into two flow streams termed as the 'Axial flow stream' and the 'Tangential flow stream'. Each of the streams had an Eldridge flow meter to monitor its flow. These flow meters are powered with a DC power supply and produce an output voltage signal of 0-5 volts, proportional to the flow measured. The details of the flow meters are discussed in Appendix C. Each of the flow streams has its independent flow control and pressure regulating valves.

The air flow piping was designed such that when running experiments under fully premixed condition, the flow meter on the axial stream monitored the total air that went to the premixer. The premixed stream of fuel and air was then split and piped into the axial and the tangential ports, with each of the flow trains having its own flow control valves. However, only the flow rate of part of the premixed air-fuel mixture that was fed into the tangential port was monitored, while the flow rate of the part piped to the axial port was deduced by performing a mass balance on the system.

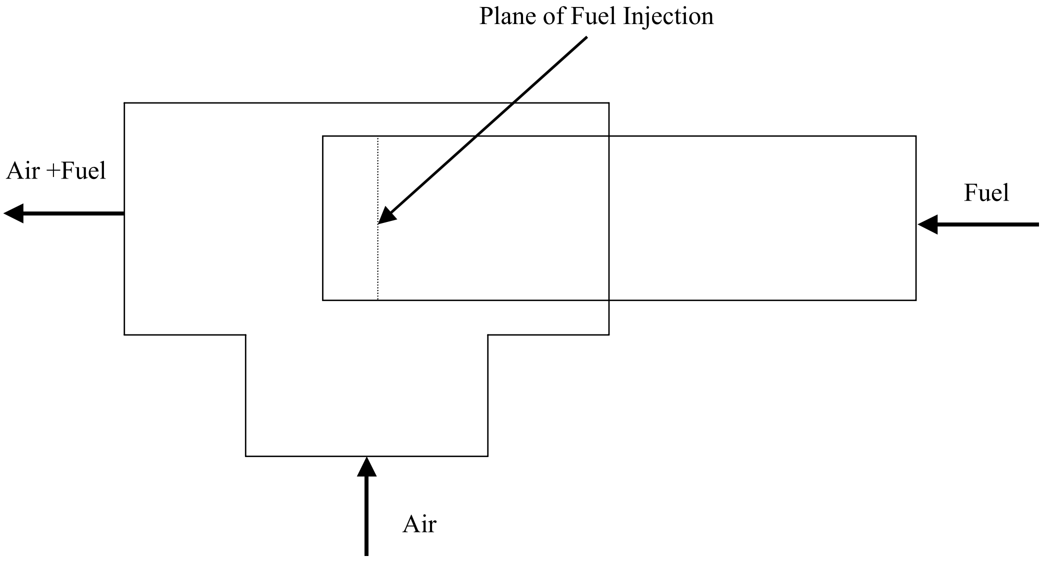

Figure 8.8: Schematic of the mixing chamber

8.3.4 Mixing System

A mixing chamber was designed and built to ensure that the fuel and the air streams were well mixed prior to the injection into the burner. A schematic of the mixer is shown in Figure 8.8. It consists of a $1\frac{1}{2}$" stainless steel tee and has a $\frac{3}{4}$" stainless steel tube inserted through one of the run-through ports. The stainless steel tube has one of its ends capped and has 24 equispaced holes of diameter $\frac{1}{32}$" for injection of the fuel. The fuel injection tube is placed within the tee such that the plane of the fuel injection is in the center of the tee. The air is injected through the side branch of the tee. The premixed mixture then leaves the mixing system from the downstream end of the tee. This design ensures that the high air velocity hitting the tee wall generates intense turbulence, and the circumferentially uniform injection of the fuel into this air stream leads to almost uniform mixing. The mixing process is completed in the piping just downstream of the mixing chamber.

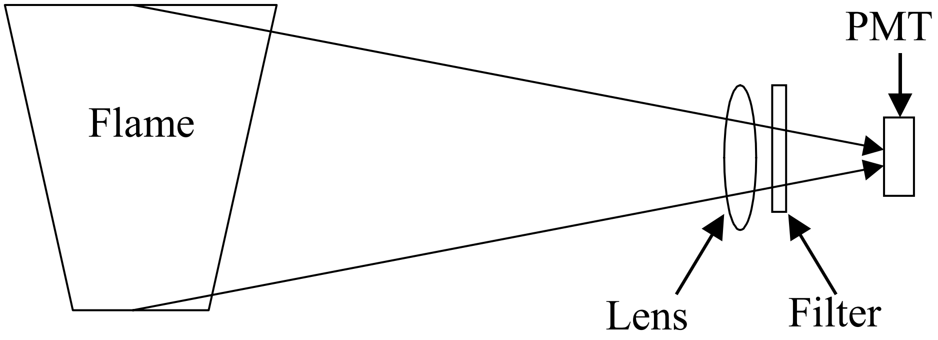

Figure 8.9: Schematic of the OH^* chemiluminescence measurement system

8.3.5 Dynamic Heat Release Measurement

Dynamic OH^* chemiluminescence was recorded and used as a measure of the dynamic heat release rate. OH^* chemiluminescence was collected from the side of the quartz combustion chamber by viewing the entire flame using a single lens. The collected chemiluminescent light was focused on to the PMT after passing it through a 307.81 nm filter. The light incident on the PMT results in a current that was converted to a measurable voltage using a current to voltage amplifier. A schematic of the major components of this system is shown in Figure 8.9.

Optical Capture and Filtration System

The lens used for optical collection was chosen based upon the calculations made using a thin lens approximation and the basic optical equations. The calculation process assumed the chemiluminescence was diffuse and the flame was optically thin i.e. it does not reabsorb any of the emitted chemiluminescence. Based on the calculations, a fused silica lens of 50.8 mm diameter and a focal length of 75 mm was selected. The lens allows transmission of near ultraviolet wavelength of light. The calculations indicated that when the lens is kept 1981 mm away from the flame, an image having a height of 8 mm is produced at a distance of 78.5 mm away from the lens.

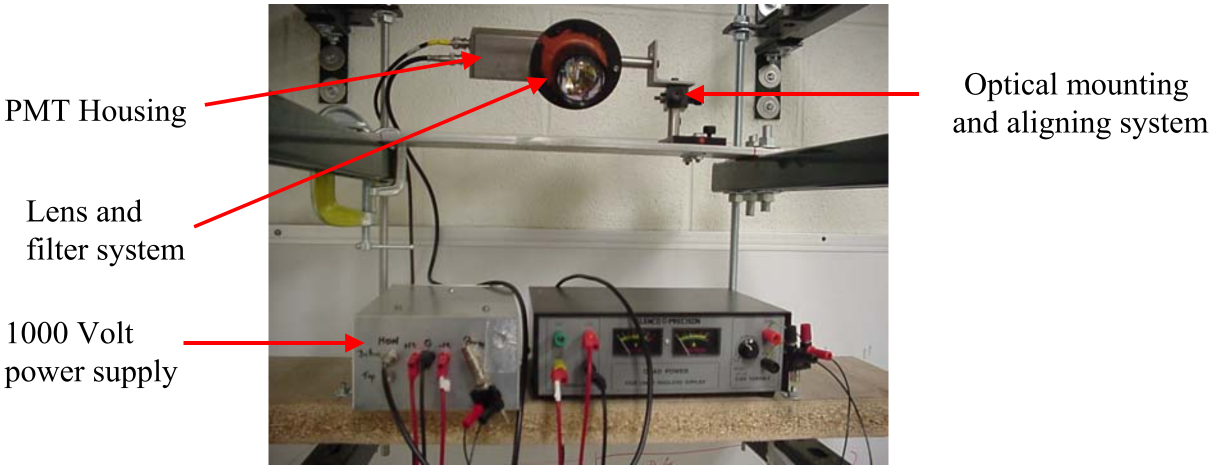

Figure 8.10: Photograph of the optical capture system

The light focused by the lens was filtered using a 307FS10-50 filter manufactured by Andover Corporation. The filter has a center wavelength of 307.81 nm, a full width half maximum of 19.03 nm, and a peak transmittance of 15.04 %. The lens and the filter were mounted on the lens and filter mounts that were then attached to the face of the PMT housing. The setup ensured that a distance of 78.5 mm was maintained between the lens and the PMT. The filter was mounted in between the lens and the PMT. The entire optical assembly was mounted on optical mounts so that it could be moved axially in the horizontal direction and rotated about the horizontal axis. This enabled the maximization of the collected chemiluminescent signal. Figure 8.10 shows a photograph of the optical capture system.

Optical Measurement System

The filtered light from the flame was made incident on the PMT, which converts the incident flux into a linearly proportional current. The PMT used in this study was the Hammatsu R955 with fused silica windows for ultraviolet light intensity measurements. It has a large dynamic bandwidth with a cutoff frequency in GHz range. Details of the PMT operation are given in Chapter 4, Section 4.3.7.

The output current from the PMT is fed to a current to a voltage amplifier, which is driven

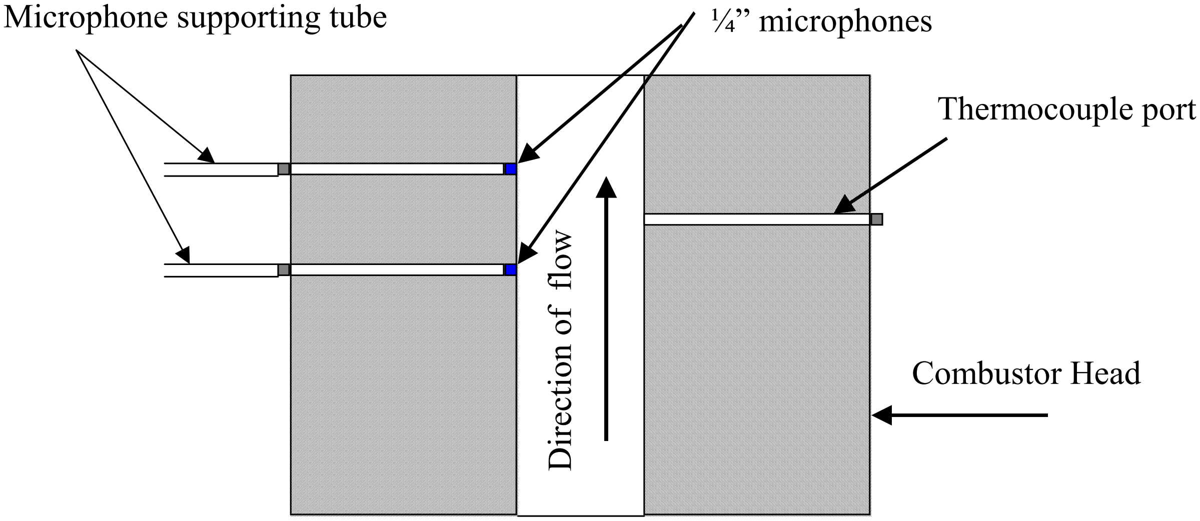

Figure 8.11: Schematic of the velocity probe setup

by a 15 volt DC source. The amplifier was designed with a 56 Ω input resistance, and amplified the incoming voltage by 60 dB. The instrument amplifier is equipped with a DC output adjustment.

8.3.6 Dynamic Velocity Measurement System

As discussed previously in Chapter 4, the aim is to measure the effective velocity perturbations in the axial flow direction just upstream of the flame. For this purpose, a velocity probe consisting of two microphones and an electronic circuit was built. Details of the design and its underlying theory are given in Appendix A. The electronic circuit used for the laminar flame dynamic experiment was also used here. However, a different sensing probe was built. Two Radio-shack ultra miniature microphones, model number 33-3003 were inserted into the microphone housing provided in the combustor. The design ensured that the microphones were kept 50 mm apart and their sensing elements were flush with the walls of the flow cavity. A sketch of the setup is shown in Figure 8.11. The electronic circuit consisted of a differencing element and an integrating circuit, such that the integral form of the momentum equation for inviscid flow with no body forces is simulated. The final form of the equation used is

$$u'(t) = \int_0^T \frac{1}{\rho} \frac{\partial p'}{\partial x} \, dt \tag{8.1}$$

Thus, two spatially distinct dynamic pressure signals were processed to generate a dynamic velocity measurement.

8.3.7 Temperature Measurement

For the evaluation of the velocity from the voltage generated by the velocity probe, it is essential to know the temperature at the plane of the velocity measurement. This was achieved by inserting a ‘Type K’ thermocouple of 0.005” diameter wire into the flow at a plane 45 mm below the entrance of the quarl. This axial location was defined as the plane of the velocity measurement. The temperature of the combustion chamber was monitored using five ‘Type R’ thermocouples of 0.005” diameter wire. The thermocouples were passed through a $\frac{1}{8}$” outer diameter two holed ceramic tube to insulate the two wires from each other. The ceramic tube was held in a quartz tube that was attached to the combustor wall using Ultra-Torr fittings. Four of the thermocouples could be moved radially to measure the temperature at various radial locations in the plane of the measurement. These four thermocouples were located at a distance of $1\frac{3}{4}$”, $2\frac{3}{4}$”, $4\frac{5}{8}$”, and $5\frac{5}{8}$” above the top of the combustion chamber back plate. The fifth thermocouple was inserted at an angle of about 30 degrees to the vertical axis and was either used to measure the gas temperature near the wall of the combustor at an axial location $\frac{1}{2}$” above the combustion chamber top plate, or was used to measure the temperature of the combustion chamber top plate.

8.3.8 Data Acquisition System

The process control data acquisition system used for the turbulent flame dynamic experiment was PC based and used LABVIEW as the front end software, while the research data acquisition system used the Hewlett Packard frequency analyzer for data collection and analysis. Cold flow field characterization used a four channel hotwire anemometer, while the reacting flow visualization was achieved using a ICCD camera.

Process Control System

The signals from the four fuel mass flow meters and the two air flow mass meters were collected using a National Instruments PSI-6034E board. This board has a 16 bit A/D converter and collects data sequentially from the connected channels. The National Instruments data acquisition software is used to interface between the LABVIEW and the PCI-6034E board. "$Gasflow\_swirl\_PCI\_pm.vi$", a program written in LABVIEW was used for acquisition and display of the process control data while running experiments under fully premixed conditions. For process control of partially premixed experiments, "$Gasflow\_swirl\_PCI.vi$" was used. The sampling rate of the data acquisition can be varied from the front panel of both the data acquisition programs.

Data Collection System

The data acquisition system consists of a Hewlett Packard frequency analyzer, model number 35665A, an amplifier manufactured by Peavey, model number CS800S and a voltmeter. The frequency analyzer was used as a source to generate controlled sinusoidal voltage signals at various frequencies. The generated signal was applied to the speaker after amplification using the instrumentation amplifier. The dynamic time traces generated by the dynamic velocity probe and the OH^* chemiluminescence were collected and analyzed by the Hewlett Packard frequency analyzer. The results of the analysis in the frequency domain were displayed on the screen of the frequency analyzer, from which the relevant data could be recorded manually.

Cold Flow Characterization

A four element constant current hotwire was used to characterize the flow field at the inlet of the combustor by measuring the velocity profiles under various operating conditions. The measurement equipment consisted of a four element hotwire, a hotwire anemometry system and a data acquisition system.

The hotwire anemometry system, model number AN-1003, is manufactured by AA labs, Israel, and consists of four anti-aliasing filters, low noise amplifiers and a 4 channel simultaneous sample and hold card. The signal generated by each of the wires of the probe is fed to a separate channel. The data was collected and stored in a computer using a C program written specifically for this application by Stephen D. Lepera. The collected data was later analyzed using a program written in Matlab. Details of the theory and the operation of the Hot wire anemometry can be found in [79].

Reacting Flow Visualization

Images of the flame were captured by visualizing the chemiluminescence in the visible spectrum from the flame using an ICCD camera (4Quick05), manufactured by Stanford Computer Inc.,CA. The camera has sensitivity of $1 \times 10^{-7} fc$ and a dynamic range of 50 - 500,000 ASA. The time and the delay of the gate pulse was digitally programmed using a separate program written specifically for the camera operation. Images were collected and stored in the computer as *.irs files that were later converted to *.tif files.