Part II

Laminar Flat Flame Dynamics
Chapter 4

Flat Flame Study: Technical approach and Experimental Setup

4.1 Rationale and Objectives

Discussions in Chapter one, and the literature reviewed in Chapter three have clearly highlighted the need to study the dynamics of flames, and build simple reduced order models that would describe the response of the flame to perturbations in the velocity of the incoming reactants. The dominant characteristics of the reduced order model need to be correlated with the physics so as to enable the extrapolation of the results to other combustor geometries and operating conditions. Since a large number of physical parameters influence the flame dynamics in a full scale gas combustor, it is virtually impossible to develop a physically correlated reduced order model for flame dynamics by directly studying these reacting flows. The logical procedure would be to start with studying a simplest possible system, having a lower number of physical variables involved, and build physically co-related reduced order models. These reduced order models could then be expanded upon by adding complexities, (hopefully one at a time), to the combustion process.

With this philosophy in mind, it was decided to experimentally study the dynamic response of a premixed laminar flat flame to controlled velocity perturbations imparted to the reactants. This initial study was formulated to analyze the effects of flame speed oscillations and the
chemical kinetics involved in the combustion process, on the flame dynamics. For this purpose three different fuels were studied. Instrument grade methane, propane and ethane were selected as fuels for the study because natural gas, the most widely used gaseous fuel for land-based gas turbines, primarily consists mainly of these three fuels. The methodology used for such an analysis and the experimental setup built, to conduct the study are described in this chapter.

4.2 Technical Approach

4.2.1 System Description

Any combustion process along with the acoustic characteristics of the combustor, is essentially a closed loop system when analyzed from the thermo-acoustic instabilities point of view. Therefore in general, a combustor burning a premixed charge of gaseous fuel and oxidizer can be represented by a system level block diagram shown in Figure 4.1. Here $F_d$ represents the dynamics of the combustion process while $A_d$ represents the dynamics of the plant acoustics. $u'_a$ is the velocity perturbation imparted to the reactants due to some exter-
nal source, and $u'_a$ is the feedback component of the acoustic perturbation due to coupling of the combustion dynamics with the plant acoustics. The effective fluctuating velocity $u'$ to which the flame responds is an algebraic sum of $u'_a$ and $u'_s$. Fluctuations in the velocity of the incoming reactants produce fluctuations in the heat release rate occurring in the combustor. These oscillations in the heat release rate couple with the dynamics of the plant acoustics to generate velocity perturbations upstream of the flame, thus affecting the velocity of the reactants reaching the flame, and effectively closing the loop. Such a closed loop system, is potentially capable of becoming self-excited when the coupling of the heat release rate with the plant acoustics amplifies the incoming velocity perturbation. Linear stability analysis, when applied to this loop can predict the frequencies at which the system will become unstable, assuming the dynamics of the combustion process and the plant acoustics is well known. Since this study concerns with understanding the dynamics of the combustion process, it is essential to design an experiment which is thermo-acoustically stable in the frequency bandwidth of interest and it is possible to break open the loop and measure the open loop dynamic response of the flame to incoming velocity perturbations.

It is seen in the literature that the flames normally respond as a low pass filter to acoustic perturbations. Considering this, the present study was limited to the frequency bandwidth of 20-400 Hz. The laminar flame dynamics were studied in a rig that was designed to produce premixed laminar flat flames and a thermo-acoustically stable environment within the frequency range of 20-380 Hz. Measurement techniques were developed to obtain the open loop dynamic character of the laminar flat flame. Velocity disturbance were imparted to the system using an external source. By measuring the dynamic heat release, $q'$, and the effective velocity perturbation, $u'$, the goal of breaking the loop and obtaining the open loop dynamic response of the flame is achieved. This is mathematically proven below.

The effective fluctuating velocity, $u'$, to which the flame responds is a sum of the externally imparted perturbation, $u'_s$, and the feedback component $u'_a$.

$$u' = u'_s + u'_a$$ (4.1)
Closed loop analysis of the system shown in Figure 4.1 results in

\[ q' = F_d (u_s' + q'A_d) \]  \hspace{1cm} (4.2)

\[ q'(1 - F_dA_d) = F_d u_s' \]  \hspace{1cm} (4.3)

and

\[ u_a' = q'A_d \]  \hspace{1cm} (4.4)

Substituting equations 4.1 and 4.4 into equation 4.3, we get

\[ q' = F_d u' \]  \hspace{1cm} (4.5)

Thus, by measuring the frequency resolved \( u' \) and \( OH^* \) chemiluminescence, a measure of \( q' \), the goal to obtain an open loop transfer function of the dynamics of burner stabilized flames is achieved.

### 4.2.2 Energy Flow Description

Section 4.1 discussed the need to study laminar flat flames with an objective to understand how the flame speed oscillations and the chemical kinetics effect the dynamic response to velocity perturbations in the reactant stream. The ultimate goal is to map over the results of this laminar flat flame dynamic experiment to turbulent swirl stabilized flames in full-scale gas turbines. Therefore, it is paramount that the flat flame experiment be conducted at flame temperatures close to those seen in full-scale gas turbines. Normally, laminar flat flames are stabilized by losing a significant amount of energy to the flame holder that acts as a heat sink. Flames stabilized over such heat sinks are normally rather cool flames with flame temperatures almost 50% to 75% of the corresponding adiabatic flame temperatures. Such flames are quite useless for the present study. The present study mandates that non-adiabatic laminar flat flames are studied, yet the flame temperatures should be close to the adiabatic flame temperatures for the corresponding flow conditions and mixture strengths. This can be achieved by applying the concept of excess enthalpy flames, which was used
in the present burner design. Figure 4.2 shows the flow of energy in the designed laminar flat flame burner. Here the flame stabilizer plays the role of a heat exchanger rather than a heat sink and re-circulates most of the energy it draws from the flame front by heating up the incoming reactants. Thus, the flame is stabilized not by significantly lowering the laminar flame speed but by increasing the speed of the reactants entering the flame front. The thermal loses from the flame front to the environment, $q_l 1$, and from the flame stabilizer to the environment, $q_l 2$, ensure that a non-adiabatic burning condition is achieved, which is very essential for the success of the experiment, as there shall be no fluctuations in the flame speed unless there are oscillations in the flame temperature. The above described requirements of the flame stabilizer can be fulfilled by a ceramic honeycomb with high percentage of volumetric porosity.

### 4.3 Experimental Setup

The experimental setup used to study the dynamics of laminar flat flames is schematically shown in Figure 4.3. The system consisted of mass flow meters, a mixing chamber that thoroughly mixed the oxidizer and the fuel prior to their injection into the laminar flat flame burner where a flat flame was stabilized using a ceramic honeycomb. Thermocouples embedded in the top and bottom surface of the honeycomb monitored its temperature,
while the two microphones were used to measure the effective velocity perturbations. Controlled velocity perturbations were imparted using a 5”, 60 watt, 8 ohm speaker. An $OH^*$ signal measured from the top of the burner using a monochrometer and a photomultiplier tube,(PMT) was taken to be the measure of the dynamic heat release rate. The dynamic signals and the flow parameters were recorded using a data acquisition system.
4.3.1 Laminar Flat Flame Burner

A schematic of the flat flame burner built for this experiment is shown in Figure 4.4 and its photograph is shown in Figure 4.5. The burner consists of a plenum, a bell reducer, ceramic honeycomb flame stabilizer and a quartz combustion chamber. The plenum is made from a 100 mm diameter tee. A speaker needed to impart controlled velocity perturbations to the flow is mounted on the side branch of the tee. The bottom end of the plenum is closed with a blind flange which accommodates the velocity probe holder. The premixed charge of air and fuel was injected just downstream of the tee through four equi-spaced injectors. Each injector is a \( \frac{1}{4} \)” copper tube with \( \frac{1}{64} \)” diameter holes that are equi-spaced in the radial direction. There are three rows of the \( \frac{1}{64} \)” holes on each injector that are 90 degrees apart. The assembly is such that the jets forced out of the \( \frac{1}{64} \)” holes are directed radially in the plane of injection, and axially upstream of the injector. The \( \frac{1}{64} \)” diameter holes provide high acoustic impedance, which coupled with the fact that the injectors are connected to the mixing chamber with \( \frac{1}{4} \)” tubing that is 6 meters long, ensure that the mixing chamber is isolated from the acoustic disturbances generated in the laminar flat flame burner. Thus, the complexities of equivalence ratio oscillations are totally eliminated.

Downstream of the injector, a bell reducer is welded that reduces the pipe diameter from 100 mm to 65 mm. The reducer ensures that the flow entering the flame stabilizer is radially uniform and is purely in the axial direction. Flow through the bell reducer enters a ceramic honeycomb, which functions as a flame stabilizer. A photograph of the honeycomb used is shown in Figure 4.6. The honeycomb is 68 mm in diameter and 17.8 mm in thickness. It is embedded in the carbon-steel flange to which the bell reducer is welded. This ensures that a cross-section having a diameter of 65 mm is open to the flow coming from the bell reducer. The honeycomb structure consists of square channels that are 1.2 mm wide and the walls separating the channels are 0.05 mm thick. This configuration generates an area blockage of about 15%. The low percentage of area blockage results in the honeycomb exhibiting negligible acoustic impedance, thus ensuring that the acoustic velocity perturbations measured
Figure 4.4: Schematic of the burner
Figure 4.5: Photograph of the burner

Figure 4.6: Photograph of the honeycomb
upstream of the honeycomb are not damped out by the honeycomb. Around the ceramic honeycomb is a long quartz tube functioning as a combustion chamber. It has an outer diameter of 75 mm and a wall thickness of 2 mm. The length of this tube was designed to be 150 mm so that the axial position of the flame just above the honeycomb when compared to the entire length of the burner ensured that Rayleigh’s criteria was not satisfied and the system was stable with regards to thermo-acoustic oscillations in the bandwidth of 20-380 Hz. Further, the above length of the quartz tube ensured that the ambient environment around the burner did not influence the stability and the dynamics of the laminar flat flame.

4.3.2 Flow Control System

The burner requires a controlled flow of air and fuel. The flow of both air and fuel are controlled independently using metering valves, and are measured using hasting series HFM 200 mass flow meters that are powered by 0-5 volt DC supply. The capacity and the accuracy of these flow meters is discussed in Appendix C. The performance of both the flow meters is linear, and they produce an output voltage signal of 0-5 volts, proportional to the flow being measured. The output voltage of the mass flow meters was measured by two of the channels used by the process control data acquisition system and displayed on the PC using LABVIEW program.

4.3.3 Mixing System

A mixing chamber designed and built for the Rijke tube combustor [51] was used to ensure that the fuel and air streams were well mixed prior to injection into the burner. A schematic of the mixer is shown in Figure 4.7. It consists of a backplate and a mixing chamber that is necked down to an outlet of $\frac{1}{2}''$ using a bell reducer. The fuel is injected through a single port in the center of the back plate. The air is let into the mixing chamber through four swirling ports in the back plate. The swirling air jets generate enough swirl and turbulence that a well mixed fuel-air mixture leaves the mixing chamber.
4.3.4 Dynamic Heat Release Measurement

It is well accepted in literature that OH* chemiluminescence is a measure of the dynamic heat release rate within the flame. This has also been recently shown to be a valid assumption by Haber [70]. Therefore, dynamic OH* chemiluminescence signal was used as a measure of the dynamic heat release rate. The OH* chemiluminescence was collected from the top of the burner using lenses, a fiber-optic cable, and a monochromator. The light was converted to a voltage signal by a photomultiplier tube, (PMT) and a current to voltage amplifier. A schematic demonstrating the major components of this system is shown in Figure 4.8. Chemiluminescent light was collected by a two lens optical train that focused the captured light on to a fiber-optic cable, which then transported it to a monochromometer. The captured light was filtered by the monochromator so as to allow passage of only 309 nm wavelength of light onto a PMT, which then generated a current. A current to voltage amplifier finally converted the current generated by the PMT to a measurable voltage.
4.3.5 Optical Capture and Transmission System

The optical light collection and transmission system was designed using lenses and a fiber-optic cable. The system design was based on the thin lens approximation and basic optical equations. The system was set up on the basis of the design procedure, detailed by Haber [70]. In the design process, it was assumed that the flame was flat with no depth, a reasonable assumption based on a large object distance to object thickness ratio. The chemiluminescence was assumed to be diffuse and the flame was assumed to be optically thin, i.e., it does not re-absorb any of the emitted chemiluminescence.

Based on the optical design, two fused-silica lenses of 25.4 mm diameter were selected. These lenses allow transmission of near ultra-violet wavelength of light. The focal length of the selected lenses is 25.4 mm. The design calculation showed that the two lenses were to be kept 10 mm apart and the first lens should be assembled 640 mm away from the flame stabilizer. This setup was expected to focus the light from a round flat disc having a diameter of 57 mm, onto a 1 mm diameter fused-silica core fiber-optic cable. The fiber-optic cable has a numerical aperture of 0.48 and SMA-type terminations at both the ends. Fused silica was a preferred material for both the lenses and the fiber-optic cable, because this material ensured high transmission (more than 98%) of incident near ultra-violet light around the 309 nm wavelength. The fiber-optic cable is mounted on a Newport series fiber-optic positioning...
module, that has the freedom of movement along the three Cartesian axis and also rotation about two of the Cartesian co-ordinates. The lenses are held together in place by lens holders, maintaining a small separation distance as stipulated by the design. Figure 4.9 shows a photograph of the collection optics setup. The far end of the fiber-optical cable is attached to the collimating lens assembly. The purpose of the collimating-beam lens is to align the incident light beams to be parallel to each other when the rays exit the collimating lens.

4.3.6 Optical Filtering System

A Jarrel-Ash 0.5 m Ebert defraction grating scanning monochrometer, model 82-020, was used to filter the captured and the collimated light prior to its incidence on the photomultiplier tube. The monochrometer is fitted with a grating that is etched for 400 nm. Figure 4.10 shows a schematic of the monochrometer setup. The monochrometer has a micrometer fitted on both the entrance and the exit slits so as to accurately control the opening of the slit widths, an important parameter that determines the amount of light handled by the monochrometer as well as the wavelength resolution of the monochrometer.
For finer resolution, the slit width should be narrowed.

Inside the monochrometer, the collected light is further collimated by a concave mirror. This collimated light beam is then made incident on the diffraction grating, which reflects different wavelengths of light at different angles. Some of the light beam is incident on a second concave mirror from which the light is reflected onto the exit slit. Rotation of the diffraction grating changes the wavelength of light that is made incident on the second concave mirror and hence seen at the exit. A manual crank or a motor, connected to a sine-bar rotates the diffraction grating. The sine-bar is used to linearize the relationship between the motor and the center wavelength in the exit slit. The monochromometer manual [71], describes in detail the wavelength calibration procedure.

The gratings of the monochromometer are blocks of reflective material that contain grooves. The angle at which the grooves are cut into the material is called the blaze angle. The spacing of the grooves determines the wavelength resolution of the grating. For the Jarrel-
Ash monochrometer being used, the grating has 1180 grooves per mm and is biased for 400 nm. The efficiency of the monochrometer grating varies with the wavelength. Therefore, a 400 nm grating reflects the maximum amount of optical signal onto the second concave mirror for a wavelength of 400 nm. The efficiency of the grating decreases on either side of 400 nm on the light spectra. This can be seen from Figure 4.11.

### 4.3.7 Optical Measurement System

The filtered light from the monochrometer is made incident on the photomultiplier tube (PMT) that converts the incident light flux into a linearly proportional current. The PMT used in this study was the Hamamatsu R955 with fused-silica windows for ultra-violet light intensity measurements. The R955 has ten dynode stages and is operated by a 1000 volt power source. It has a large dynamic bandwidth with a cut off frequency in GHz range.
The photocathode within the PMT, which determines the quantum efficiency of PMT, captures the incident photons and emits electrons in direct proportion to the incoming light flux, which then impact the first dynode stage. The dynode functions as an electron multiplier, emitting a number of electrons for each incident electron. To amplify the electron flux to a measurable current, several dynode stages are arranged in series. Similar to the monochrometer grating, the PMT also has a peak quantum efficiency of performance at a particular wavelength. On either side of this wavelength on the light spectrum, the efficiency drops. This is seen from Figure 4.11.

The current signal output from the PMT is then fed to a current to voltage amplifier, which is driven by two 9 V batteries and was designed with 2 K Ω input resistance and achieved a 60 dB gain in the output signal. The instrument amplifier is equipped with a DC-output adjustment.

4.3.8 Dynamic Velocity Measurement system

As discussed in section 4.2, the aim is to measure the effective velocity just upstream of the flame. For this purpose, a velocity probe was designed and built based on the two microphone technique [72]. The details of the underlying theory, the design methodology, the electronic circuit used and the calibration process are described in detail in Appendix A. Particularly for this experimental setup, two Radio Shack ultra miniature, tie clip microphones, model number 33-3003 are spaced 55 mm apart using a spacer. A photograph of the final assembly of the velocity probe sensor containing the two microphones and the spaces mounted in a \( \frac{1}{4} \)" stainless steel tube can be seen in Figure 4.12. The positioning of the microphones was such that its sensing elements were always perpendicular to the flow direction. The choice of the microphone model was based on its large bandwidth of response (well above the 20-400 Hz range that was of interest for this experiment) and its small size. The dynamic velocity signal was generated by processing the two spatially distinct dynamic pressure signals, through a differencing and an integrating circuit. The circuit was built to simulate the integral form of
the momentum equation for inviscid flow with no body forces. The final form of the equation is

$$u'(t) = \int_0^T \frac{1}{\rho} \frac{\partial p'}{\partial x} \, dt$$  \hspace{1cm} (4.6)

### 4.3.9 Temperature Measurement System

For the evaluation of velocity from the velocity probe, the temperature at the plane of velocity measurement was required. This was achieved by inserting a ‘Type K’ thermocouple of 0.01” wire diameter, into the flow that measured the temperature at a plane 70 mm below the top surface of the flame stabilizer. A ‘Type R’ thermocouple of wire diameter 0.003”, was imbedded in the center of the top surface of the honeycomb and the bead was covered with a ceramic coat that matched the thermal and radiative properties of the ceramic material out of which the honeycomb was made. A photograph of the top surface of the honeycomb along with the location where the ‘Type R’ thermocouple was embedded is shown in Figure 4.13. Similarly, a ‘Type K’ thermocouple of wire diameter 0.003” was imbedded in the center of the bottom surface of the honeycomb. The wires of these two thermocouples were then cemented
Type R Thermocouple (0.003” Dia) embedded on the top surface of the Honeycomb

Figure 4.13: Photograph of honeycomb with ‘Type R’ thermocouple

Thermocouple wires cemented to channel walls

Figure 4.14: Photograph of the honeycomb bottom with the thermocouple wires cemented
to the channel walls on the bottom surface of the honeycomb, as shown in Figure 4.14. This was done to ensure that the wires do not disturb the flow and also decreases the chances of their breaking due to flow disturbances. All of the three thermocouples were referenced to zero degree Celsius by using a reference junction that was embedded in a water/ice bath.

4.3.10 Data Acquisition System

The data acquisition system is primarily responsible for collecting, displaying and storing all the relevant information essential to evaluate the outcome and success of an experiment. This system registers the incoming time trace of data, interprets it, organizes and displays the relevant information and stores the required data files in a format that eases the process of post processing and post experiment analysis. The data acquisition system used in the present experiment could be classified as a ‘process control system’ and ‘research data collection system’. Both these systems are P.C. based and use LABVIEW as the front end software, although their hardwares are quite different.

Data Acquisition Software

The LABVIEW, a P.C. based graphical programming language by National Instruments [73] was used for all of the data acquisition needs. A program written in LABVIEW processes all the data collected on the A/D data acquisition boards, and displays and stores all the relevant information. LABVIEW allows the program to include easy to use graphical user interface called ‘front panel’, making the procedure of using the program very easy and self-explanatory. The front panel can contain windows that display the required process information such as flow rates, rate of data collection, A/D boards used etc. It also contains control buttons, that help the user to control the process of data collection and processing.
Process Control System

Figure 4.15 shows a schematic of the process control system. The signals from the two mass flow meters were collected using a Data Translation 2801-A type board. The 2801-A board has a 12 bit A/D converter and collects data sequentially from the connected channels. A special DTV-LINK software was used to interface between the LABVIEW and the 2801-A board. DTV-LINK supplies analog routines to the LABVIEW for use with the Data Translation data acquisition board. flowDT.vi, a program written in LABVIEW was
used for acquisition and display of the process control data. The sampling rates for data acquisition can be varied from the front panel of the data acquisition program flowDT.vi.

**Research Data Collection System**

Figure 4.16 shows a schematic of the research data collection system. The data acquisition system consists of a Hewlett Packard frequency analyzer, model number 35665A, an instrumentation amplifier manufactured by Peavey, model number CS 800X, 4 dual channel 8 pole anti-aliasing filters manufactured by Frequency Devices, model number 9002, a National...
Instruments 8 channel 16 bit simultaneous sample and hold card SC2040, a GPIB card, a voltmeter. fd-da2lev.vi a program written on LABVIEW was used to control the frequency and the amplitude of the acoustic forcing applied by the speaker and to collect, organize and store the dynamic time traces generated by the velocity probe, $OH^*$ chemiluminescence, the ‘Type K’ and ‘Type R’ thermocouples, and the microphones.

The data collection using fd-da2lev.vi was automated to change the frequency and amplitude of the excitation and collect the various time traces. The anti-aliasing filters have the options of amplifying the input signal prior to filtering as well as post filtering in the range of 1 and 13.5. Each of the filtered signals can also be amplified independently during their collection by the SC240 simultaneous sample and hold card. The amplification setting for each of the channels can be adjusted between 1 to 800 using dip switches provided on the card.