Part IV

Conclusions and Recommendations

Chapter 11

Summary and Conclusions

11.1 Background and Motivation

Environmental pollution concerns drove the land based gas turbine manufacturers to devise ways and means to reduce NO_x and other pollutant levels in exhaust of these gas turbines. Out of a number of techniques devised to achieve the above goal, the one most widely implemented is lean-premixed combustion. However, this technology is often susceptible to thermo-acoustic instabilities which manifest as pressure and heat release oscillations within the combustor.

Research in the area of thermo-acoustic instabilities and their potential control has progressed considerably over the past few years, with efforts being directed towards physically understanding and properly modeling the underlying phenomena that lead to these instabilities. Recently, linear stability theory has been applied to combustion systems for prediction of thermo-acoustic instability. The success of this approach hinges on the availability of simple, yet accurate models that would describe the behavior of each dynamic block within the loop.

Considerable knowledge and understanding has been gained in modeling the plant acoustics, both for simple systems and full scale gas turbine systems, but relatively little is known about the flame dynamics. From the systems perspective, it is essential to understand the dynamic response of the flame in terms of the fluctuating heat release rate, q', for a velocity disturbance upstream of the flame, u', since it is the rate of fluctuating heat release rate that couples with the acoustics of the plant to produce thermo-acoustic instabilities. Prior research in this area has been largely limited to simplified analytical models and computations using simplified finite-rate chemistry models. However, these models capture the flame dynamics only qualitatively. Therefore, it is important to provide the modeling community with relevant experimentally based models that fully describe the key input-output relationship and allow corroboration of reacting flow CFD calculations.

11.2 Research Philosophy

Due to the complexities brought about by the nonlinear aspects of the dynamic response of the flame, it is very difficult to build a simple, yet effective model from first principles to describe the flame dynamics in full scale gas turbines. The empirical models developed on simple test combustors cannot be applied to full scale gas turbine combustors, unless the effect of physical parameters on the behavior of these models is well understood to enable the mapping over to full scale gas turbines. To be able to understand the impact of each of the involved physical variables on the flame dynamics, it is essential to devise experiments that reduce the set of interdependent physical parameters, and to be able to vary the parameter of interest without effecting the other physical parameters. Therefore, it is essential to first understand the dynamics of a simple flame system, and to develop the techniques for experimental study and subsequent data analysis, along with a correlation which links the behavior of the empirical model with related physical parameters. This could later be applied to more complex combustors.

With this philosophy in mind, it was decided to experimentally study the linearized 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, instrument grade methane, propane and ethane were studied. Comparing the flame dynamics of the three different fuels, the author has tried to predict the trends that the combustors would be expected to show with regard to thermo-acoustic instabilities, if different blends of the three pure fuels are used. The techniques developed during the laminar flame dynamic study were later applied to the experimental study of the dynamics of swirl stabilized turbulent flames under atmospheric conditions. Finally, the complexity of unmixedness generated due to the fuel injection in swirling flow just upstream of the combustor, was added to the problem.

Reduced order models were developed for both the laminar and the turbulent fully premixed flames and an attempt was made to provide an insight to the influence of the various physical parameters on the flame dynamics. The reduced order dynamic models could then be used in the systems level linear stability analysis of similar combustors, and help the controls community to build effective control methodologies and algorithms for the purpose of active combustion control. This research effort, has attempted to provide a better understanding of the physics related to the combustion dynamics as defined in the scope of thermo-acoustic instabilities. The author also hopes that this research will lead to a methodology, that the industry could use to experimentally characterize the dynamics of an injector-burner design, and reduce the number of prototype experiments and hence the development cost and cycle time.

11.3 Laminar Flat Flame Dynamics

Laminar flat flame experiments were conducted with bottled instrument grade methane, ethane and propane as fuel, for five equivalence ratios ranging from 0.5 to 0.75, and four flow rates ranging from 145 cc/sec to 200 cc/sec. The analysis was done by measuring the frequency resolved velocity perturbations u', and the OH^* chemiluminescence, as a measure of unsteady heat release q', to determine an open loop transfer function of the dynamics of a burner stabilized flame. The experimental data showed that for the test conditions studied, the FRF is fourth order in nature with a pure time delay. For the purpose of further analysis, of the two resonances, the one that occured at a lower frequency was termed as '1^{st} resonant response', while the other was termed as '2^{nd} resonant response'.

11.3.1 1^{st} resonant response

The FRF (magnitude) plots indicated that for changes in Φ and Q_{Total}, the frequency of the 1^{st} resonant response varied between 25 Hz and 50 Hz. The 1^{st} resonant response' was lightly damped for fuel-air reactant mixtures having lower mean energy content. Its damping increased linearly with an increase in the net heat transfer potential of the flame. These characteristics of the 1^{st} resonant response' have been shown to represent the pulsation of the flame location caused by fluctuation in the flame speed and fluctuating heat losses to the ceramic honeycomb. It was deduced that the 1^{st} resonant response was responsible for the amplitude modulating side bands seen in the power spectrum of the Rijke tube combustor. Therefore, apart from being a low frequency thermo-diffusive oscillation, the 1^{st} resonant response directly impacts the thermo-acoustic instability in a combustion process by modulating its amplitude. This unique feature could have implications for active control systems, as these are low frequency sources that could be used to lower the amplitude of the high frequency thermo-acoustic instability.

11.3.2 2^{nd} resonant response

The frequency of the 2^{nd} resonant response increased significantly with increasing Φ, for all the total flow rates studied. This movement of the frequency of the 2^{nd} resonant response was primarily responsible for the broadening of the bandwidth of the FRF, which led to higher FRF magnitudes at the upper end of the investigated frequency range. The movement of the 2^{nd} resonant response to higher frequencies was predominantly dependent on the Φ and very weakly dependent on Q_{Total}. It was further deduced that the resonant frequency of the 2^{nd} resonant response varied exponentially with the flame temperature.

The fore mentioned observations indicated that the 2^{nd} resonant response was primarily dependent on the reaction rate and thus, represented the chemical kinetics involved and captures all of the important dynamic characteristics of finite rate chemistry. Therefore, while modeling reacting flows, if the dynamics of the chemical kinetics are important and need to be studied, then the use of at least a two step chemical kinetic model having a minimum of two reaction rates is advised.

11.3.3 Time Delay

Since acoustically a standing wave was generated within the rig, there was no phase change between the plane of u' measurement and the flame front. Therefore, there was no time delay, τ, due to the acoustics of the rig. The only time delay that occured in the laminar flame dynamic experiment detailed in this document, was the delay between the u' that was felt at the flame front and the corresponding q' signal. This delay was due to the finite rate chemistry of the combustion process. The chemical time delay, τ_{chem}, was evaluated from the results of modeling the experimental conditions using 'Burner Stabilized Premix' code. The time delay compared well with the delay predicted by the reduced order model.

11.3.4 Comparison of the Dynamics of Propane, Methane and Ethane

One of the most significant conclusions of the laminar flame dynamic experiments was that the chemical kinetics and the flame speed oscillations dominated the dynamics of burner stabilized laminar flat flames in the bandwidth of 30 to 250 Hz. Both these parameters are very much fuel dependent. Since natural gas is primarily a mixture of methane, propane and ethane, changes in its composition are expected to effect the dynamic characteristics of the combustion process. Therefore, the dynamics characteristics of methane, ethane and propane flames were compared, and conclusions were drawn on the effect of the variations in the composition of natural gas on the occurrence of thermo-acoustic instabilities.

From the experimental results it was concluded that for all equivalence ratios studied, burning of propane instead of methane increases the likelihood of thermo-acoustic instabilities. For ultra lean conditions, burning propane increases the dynamic gain in the system and also effects the phase characteristics. Changing fuels from methane to propane at higher equivalence ratios increases the chances of occurrence of thermo-acoustic instabilities, purely due to an increase in dynamic gain. Thus, marginally stable systems burning methane as fuel will demonstrate thermo-acoustic instabilities upon burning propane.

Burning of ethane instead of methane, in flames that are stabilized at ultra lean conditions, is expected to lower the dynamic gain in the system at frequencies greater than 100 Hz and in most cases, increase the dynamic gain in the system for frequencies below 100 Hz. But, the change in phase caused by switching to ethane will almost certainly shift the phase cross over frequencies of the closed loop combustion system. Thus, stable or marginally stable systems could exhibit instabilities at some other frequency. On the other hand, depending on the dynamic characteristics of the closed loop combustion process, burning ethane could have a stabilizing effect.

Furthermore, the comparison of the experimental results highlighted that at higher Φ of about 0.75, switching from methane to ethane air flames in most cases would have no effect on the thermo-acoustic instabilities. For intermediate equivalence ratios such as $\Phi = 0.65$, the marginally stable system could be made unstable by burning ethane due to slightly higher gain and small changes in phase. The likelihood of such an occurrence is greater for systems that exhibit marginal stability at frequencies within the range of 35-180 Hz.

Comparing the dependence of the 2^{nd} resonant response to the flame temperature for the three fuels, it was noted that, each of the three fuels exhibit their own distinct exponential fits between the resonant frequency and the flame temperature. The three fits seemed to merge at higher flame temperatures and spread apart at the lower range of flame temperatures. This behavior indicated that at higher equivalence ratios, the 2^{nd} resonant response was almost independent of the fuel composition being burnt. But at lower equivalence ratios, injection of propane or ethane into methane flames will increase the bandwidth of the dynamic flame response by 30-40 Hz. This could increase the susceptibility of the combustion process to thermo-acoustic instabilities.

The above discussion led to the conclusion that at higher equivalence ratios, changes in fuel composition would have negligible effect on the dynamics of chemical kinetics involved. However, the dynamic stability of the combustion system could still be affected via the dynamic gain. At ultra-lean conditions, the composition of the fuel being burnt plays an important role in defining the dynamics of the chemical kinetics, and thus the stability of the combustion system.

11.4 Swirl Stabilized Turbulent Flame Dynamics

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 swirl stabilized flames.

A variable swirl turbulent combustor was designed with a maximum pressure rating of 150 psig and is capable of accommodating 200 scfm of total flow. It has a variable swirl generation arrangement that generates a maximum swirl number (S), of 1.86. The combustor is capable of running under fully and partially premixed conditions and the degree of unmixedness of the reactant mixture can be changed very easily. It is also capable of operating under dual fuel conditions and can generate multiple time delay scenarios.

In the present research effort, the velocity profiles were generated using a hotwire anemometer, and the swirl number was obtained by integrating the experimentally generated velocity profiles. Experiments were conducted using bottled commercial grade methane. The experiments included both, totally and partially premixed conditions and were performed for Q_{Air} of 15 scfm and 20 scfm, Φ of 0.55, 0.6, and 0.65 and S of 0.79 and 1.19.

Totally premixed conditions were generated by mixing the fuel with the air outside the combustor and injecting the premixed charge into the combustor. This setup ensured that no oscillations were generated in the equivalence ratio when the flow was imparted acoustic perturbations using the speaker.

Under the partially premixed conditions, the fuel was injected into the swirling air stream within the combustor. For partially premixed flames, any pressure oscillation at the plane of injection was not expected to effect the fuel injection, but only effect the air stream, and thus generate equivalence ratio oscillations. Therefore, partially premixed flames were subjected both to variation in the equivalence ratio across the cross-section of the flow and also to equivalence ratio oscillations.

11.4.1 Fully Premixed Conditions

Results of the fully premixed experiment showed that the flame, when subjected to u' perturbations, behaved as a low pass filter which was 8^{th} order in nature. For the frequency range of 100-400 Hz, small changes in Φ had a measurable impact on the dynamics of the combustion process. For the frequency range of 20-100 Hz, small changes in Φ around the lower equivalence ratios such as $\Phi = 0.55$ significantly effect the dynamic response of the flame, but at operating conditions with $\Phi \geq 0.6$, the effect of changes in Φ on the flame dynamics could be considered to be negligible. Therefore, well tuned stable combustors operating under ultra lean conditions are likely to exhibit thermo-acoustic instabilities, for small changes in the overall Φ.

The results also showed very little dependence of the dynamic response on S, but demonstrated a broadening of the bandwidth with increase in Φ and Q_{Air}. Thus, upon correlating this phenomenon to the conclusions of the laminar flat flame, it was deduced that the broadening in the bandwidth is controlled by the reaction rate and the thermal interaction between the flame front and its surroundings.

11.4.2 Partially Premixed Conditions

The partially premixed conditions were generated by injecting fuel into the swirling air stream in a plane that is 150 mm upstream of the inlet of the quarl. Determination of the effects of variation in the unmixedness of the reactant stream were not conducted and left for future studies.

The results indicated that the dynamics of partially premixed flames exhibit a rich spectra, that attempts to maintain its bandwidth over the entire range of frequency studied. An increase in Q_{Air} tends to increase the bandwidth of the response and also made the peaks occurring at the acoustic modes of 270 Hz and 460 Hz more pronounced.

The FRF of the dynamic response shows the presence of zeros at low frequencies. Q_{Air} and Φ moved the zeros in the opposite directions on the frequency axis, while increasing S tends to diminish their presence. It should be noted that under fully premixed conditions, these zeros were not prominent in the data. All of the above observations indicated that the location of the zero and probably also its damping, was influenced by the local instantaneous species distribution across the cross-section of the flow, as it arrived at the flame front. The net result as seen from the dynamic plot was an integrated effect of all such local variations.

11.4.3 Comparison of Fully and Partially Premixed Conditions

In the frequency range of 200-400 Hz, comparing the results of the fully and the partially premixed experiments, the magnitude plots indicated that at overall lean conditions the dynamic gain of the totally premixed flames was almost an order of magnitude lower than that of the partially premixed conditions. This primarily occured due to the fact that partially premixed flames exhibited a broad bandwidth of response which extended right up to 400 Hz, while the fully premixed flames showed a low pass filtering response with the corner frequency around 100 Hz. Increase in Φ tends to lower this difference in the dynamic gain. Yet, at the acoustic modes, the magnitude of the peaks for the fully premixed conditions were still around 10 dB lower than that for partially premixed conditions.

The comparison of the results concluded that combustors with fully premixed flames have a higher probability of being thermo-acoustically stable than those with partially premixed flames, purely by the virtue of having a lower dynamic gain. Thus, to prevent the occurrence of thermo-acoustic instabilities, active control methodology must be primarily targeted towards minimizing both spatial and temporal variations in Φ. The author expects that such control methodologies would invariably include active control of the mixing process upstream of the flames.

11.4.4 Effects of Near Field Acoustics

The dynamic results of fully and partially premixed conditions showed that independent of the operating conditions, there was a sharp increase in the dynamic gain around 275 Hz and 460 Hz, the longitudinal acoustic modes of the combustor. Furthermore, detailed investigations using phased locked images taken at an excitation frequency of 275 and 105 Hz concluded that the planar acoustic waves when subjected to the temperature and density gradients generate evanescent waves in the radial and azimuthal direction. These evanescent waves were primarily responsible for enhancing the OH^* signal by generating greater heat release, but were not accounted for in the velocity measurement upstream of the flame. The effect of the evanescent waves was prominent at the longitudinal modes of the combustor and could be neglected at off resonant frequencies. Thus, there was a sharp increase in the magnitude of the flame response at the longitudinal modes of the combustor. The above discussion concludes that the three-dimensional nature of the near field acoustic effects needs to be accounted for in the system level description of the combustion process, so as to accurately predict the occurrence of thermo-acoustic instabilities.

Chapter 12

Future Work and Recommendations

The research effort described in this dissertation was aimed at developing from experimental results, systems level reduced order models for the response of the combustion process to incoming velocity perturbations. During the course of this research, a number of areas were highlighted where a better in-depth knowledge would immensely help in solving the problem of thermo-acoustic instabilities. These research topics are discussed in this chapter and the author recommends that they be looked into in the near future.

12.1 Quantification of the Dynamic Heat Release Rate

12.1.1 Calibration of the Dynamic OH^* Signal

Although OH^* chemiluminescence is presently considered as the most accurate measure of the dynamic heat release rate, q', its signal generates only qualitative results. The systems level analysis of the combustion process, however requires a quantitative result for q'. Furthermore, the results using OH^* chemiluminescence assume that the response of the OH^* signal is independent of the frequency at least in the low frequency range of 0-1000 Hz. However, this may not be entirely accurate. Thus, there is an urgent need to characterize the OH^* signal and acquire capabilities to extract quantitative values of the dynamic heat release rate from the OH^* signal. A study aimed at achieving the above goals would involve

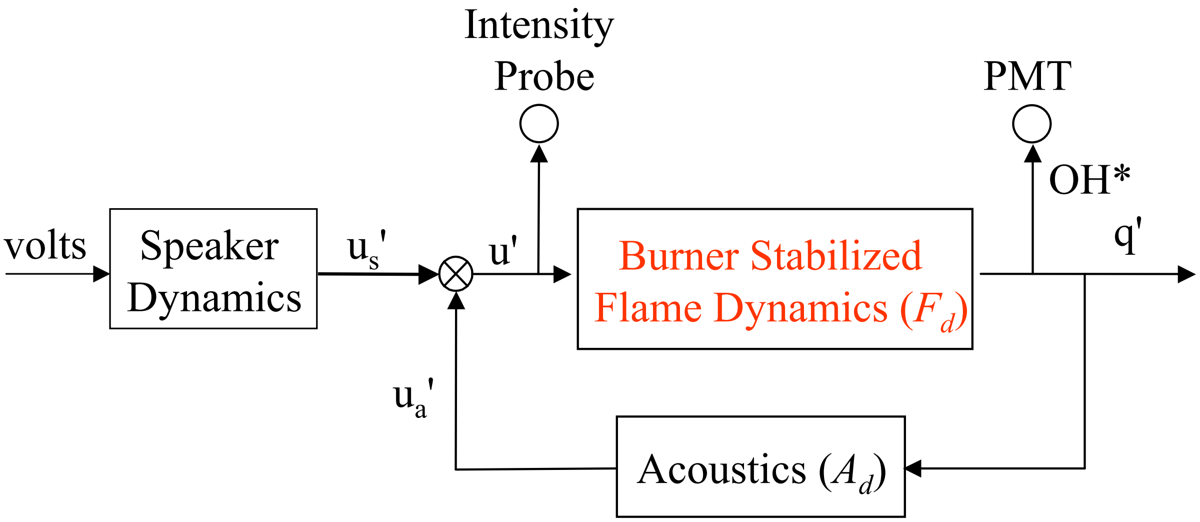

Figure 12.1: System level description of controlled combustion dynamic experiment

experiments on simple laminar combustors and physics based modeling or CFD analysis of the combustor. The comparison between the experimental and the computational results would then provide the calibration of the OH^* signal. However, as the OH^* signal is a line of sight measurement, methodologies must also be decided to make the OH^* calibration insensitive to the experimental setup so as to avoid the need for calibration with changes in geometry of the combustor.

12.1.2 Deduction from the System Level Closed Loop

Another possible method of obtaining the quantified dynamic heat release rate is by conducting a detailed study of the plant acoustics and evaluating the closed loop of a thermo-acoustically stable combustor for both cold and reacting flow conditions, as shown in Figure 12.1. Thus, by knowing the dynamics of the speaker, the coupling between the speaker voltage and the velocity perturbation and the coupling between the heat release rate and the plant acoustics, it is possible to deduce the dynamic heat release rate.

12.2 Reduced Order Chemical Kinetic Models that Satisfy Dynamic Requirements

The flame dynamic study conducted on laminar burner stabilized flat flames showed the dependence of the heat release dynamics on the chemical kinetics involved, especially at lean ($\Phi << 1$) conditions. The corresponding reduced order models developed showed that the dominant characteristics of the chemical kinetics involved was second order in nature, thus indicating that atleast a two step reduced order chemical kinetic model with atleast two reaction rates would be required to be modeled, to capture the dynamic characteristics of the chemical kinetics. The reduced order chemical kinetic models presently available in literature were developed to satisfy the steady state combustion characteristics measured during experiments. These reduced order models may not satisfy the dynamic response characteristics of the flame. Therefore, there is a need to study and evaluate the dynamic characteristics of presently available reduced order chemical kinetic models and if required, efforts must be directed in developing reduced order chemical kinetic models that satisfy the dynamic characteristics of the combustion process. This research effort will be very helpful in the advancement of the computational work in the area of thermo-acoustic instabilities.

12.3 Dependence of the Dynamic Response of Flames on the Degree of Premixing

The dynamic study of turbulent swirl stabilized flames concluded that both temporal and spatial fluctuations in the concentration of the fuel strongly influenced the flame dynamics. To gain further insight to the behavior of the partially premixed flames, it is recommended that a detailed study of the species distribution for various swirl numbers and for various degrees of premixing be conducted in the near future.

The present work also showed that fully premixed flames are more likely to be thermo-acoustically stable than the partially premixed flames. This conclusion amplifies the importance of the mixing process with regard to solving the thermo-acoustic instability problem. Therefore, it is proposed that future research should concentrate on understanding and controlling the mixing process, and predicting its effect on the flame dynamics. While making the above recommendation, the author is aware of the vast amount of research work conducted by Samuelsen et al. [88] in mapping the effects of various mixing and combustor geometric parameters on NO_x emissions. However, their work is primarily directed towards reducing pollutants on the mean basis, while the author feels that studies must be devised to understand the dynamics of the mixing process and evaluate its dynamic influence on both thermo-acoustic instabilities and emissions. These studies could have far reaching influences on the design of active combustion control systems that could accurately control the species distribution in the flow, thus minimizing both the emission and the occurrence of thermo-acoustic instability.

The partially premixed experiments indicated the presence of low frequency zeros, which were not observed in the results of the fully premixed experiments. Their presence is expected to effect the performance of the active control algorithms used in sub-harmonic controllers. Thus, while studying the effects of the degree of premixing on the flame dynamics, it is recommended that the response of these low frequency zeros be studied in detail, with an aim to predict their occurrence based on measurable parameters. Such predictive tools developed, based on the above study, could then be incorporated in the algorithms used in sub-harmonic controllers, so as to actively shift the actuation frequency of the controllers away from those at which the zeros were present.

12.4 Near Field Acoustic Effects on Flame Dynamics

The present research effort highlighted the influence of the near field acoustic effects on flame dynamics at the longitudinal acoustic modes of the combustor. Although, the near field acoustics are present at all frequencies, the experimental data presented in this dissertation indicates that these evanescent effects do not influence the flame dynamics at all

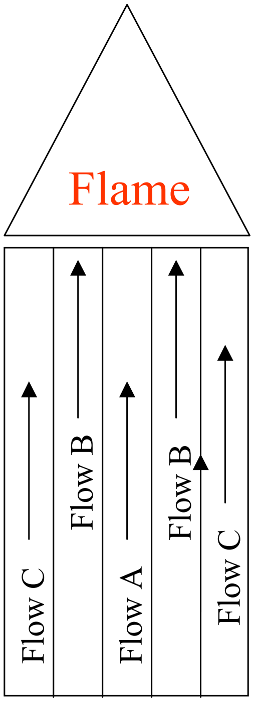

Figure 12.2: Schematic of the laminar conical flame burner with radial variations in species concentrations/mixture-equivalence ratio

resonant frequencies. Therefore, it is recommended that a detailed analysis (mainly computational) be performed to define the coupling between the longitudinal acoustic modes and the evanescent waves. Once this coupling is known, studies could then be performed to predict their presence, both in magnitude and phase, just by knowing the details of the plane wave acoustics. These studies will eventually help in increasing the accuracy of prediction of thermo-acoustic instabilities, based on systems level linear stability analysis.

12.5 Simpler Fundamental Studies Related to Flame Dynamics

The present research effort was unable to correlate the dynamics of turbulent flames to physical parameters, primarily due to the complex nature and high order of the dynamics involved. However, the author is of the opinion that the problem could be solved more efficiently by bridging the gap between the dynamics of laminar flat flames and turbulent swirl stabilized flames by studying the dynamic behavior of other simple combustors. The author proposes that similar dynamic studies be carried out on laminar premixed conical flames, to verify the dynamic results exhibited by laminar premixed flat flames and add to them the effects of area variation. The next step would then be to try to develop experiments with laminar conical flames having a controlled spatial variation of the equivalence ratios. A possible burner design concept for the same is shown in Figure 12.2. The conceptual burner consists of a number of co-axial tubes with the flow of the premixed reactants occurring in the core tube, and the various annuli. The equivalence ratio of each of these independent flows could be varied to generate a species distribution that varies in the radial direction at the base of the conical flame.