Chapter 3

Review of the Field of Combustion Instabilities

This chapter attempts to provide the history, nature and the physics of the thermo-acoustic instabilities. Previous research in this area with emphasis on effects of fuel composition variation and models developed for flame dynamics are also discussed. Documentation of the research in thermo-acoustic instabilities extends back over a century in time, and the volume of available literature can be characterized as daunting. Various areas of engineering that incorporate combustion processes in their systems have looked at thermo-acoustic instabilities over time. With advancement of combustion technology and enhanced environmental awareness, the early 1950's saw a surge in research related to thermo-acoustic instabilities that were being experienced in liquid propellant rocket engines [16]. Problems related to these instabilities in propellant rocket engines were still being researched in the year 2000 [17]. In the 1970's the Heating Ventilation and Air-Conditioning, and furnace industries, also funded research to resolve the thermo-acoustic instabilities that they were experiencing. During the 1980's, the thermo-acoustic instabilities were encountered in Ram jets, while design of pulsed combustors, primarily for furnaces tried to take advantage of such instabilities in a controlled manner to enhance combustor and furnace efficiencies. In the decade of the 1990's, as the land based gas turbine industry modified their designs to cut out on NO_x pollution, they were limited in their efforts by the occurrence of the thermo-acoustic instabilities. In the coming years, the aviation industry is also expected to become increasingly active in this research because of their need to produce high thrust compact jet engines which will require a solution for the prevention of thermo-acoustic instabilities.

3.1 Thermo-acoustic Instabilities - a Historical Perspective

For more than a century, thermo-acoustic instabilities have been a concern for industries that involve combustion processes. These instabilities were first observed in 1777 by Higgins which were subsequently documented by Tyndall [2] in 1897 and scientifically explained in 1878 by Lord Rayleigh with his famous criterion that describes the mechanism by which heat release could excite acoustic waves [3].

> "If heat be periodically communicated to, and abstracted from, a mass of air vibrating (for example) in a cylinder bounded by a piston, the effect produced will depend upon the phase of the vibration at which the transfer of heat takes place. If the heat is given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged."

To this date, researchers have used Rayleigh's criterion to determine the tendency of any combustion process to go unstable due to thermo-acoustic instabilities. The verbal description of Rayleigh's criterion presented above can be mathematically written in many ways depending upon the nature of the specific problem. One of the more general mathematical forms of the Rayleigh's criterion pertaining to the direct transfer of the thermal energy to the mechanical energy of acoustical motions was presented in a short communication by Culick [18]. In this mathematical formulation, the author derived a relationship between the normal modes of a forced acoustic plant and the fluctuations of the thermal energy during a cycle.

The Rayleigh's criterion was also proven to be correct from a thermodynamic point of view by Putnam and Dennis [19]. Here the authors have detailed a thermodynamic analysis of the phase requirement for thermally driven oscillations, and have proven the basic assumption that an oscillating component of the rate of heat release must be in phase with the pressure variation. The same Rayleigh's criterion was expressed from the controls or the systems level perspective, and was directly related to the stable or unstable closed loop poles [20]. One of the most widely used form of the Rayleigh's criterion in literature is the integral form shown below:

$$R = \int_0^T p'(t)\, q'(t)\, dt \tag{3.1}$$

where T is the period of oscillation, p' is the fluctuation in pressure, q' is the fluctuation in heat release rate and R is the Rayleigh's index. A positive Rayleigh's index indicates an amplification of the pressure oscillation due to the fluctuating heat release rate while a negative Rayleigh's index denotes a dampening of the pressure oscillations.

This phenomenon described by Rayleigh has manifested itself as thermo-acoustic instabilities in many complex systems such as furnaces, gas turbines, and propulsion engines and at times has led to their structural failure. Yet the most widely investigated system, to study these thermo-acoustic instabilities is the Rijke tube, probably due to its simplicity and ease for conducting experiments under controlled laboratory conditions. Figure 3.1 shows a schematic of the Rijke tube, which is basically a self-excited acoustic oscillator that consists of a cylindrical duct (open at both ends), and a thermal energy source. Whenever the energy source is placed in the lower half of the Rijke tube, it results in self-excited acoustic oscillations while placing the energy source in its upper half attenuates any acoustic oscillations. This can be explained easily by evaluating the acoustic pressure and velocity modes in the tube. Since both its ends are open, for the 1^{st} acoustic mode the pressure nodes occur at the inlet and the exit, while the maximum pressure is at the center of the tube. The acoustic velocity, being ninety degrees out of phase with the acoustic pressure, has its

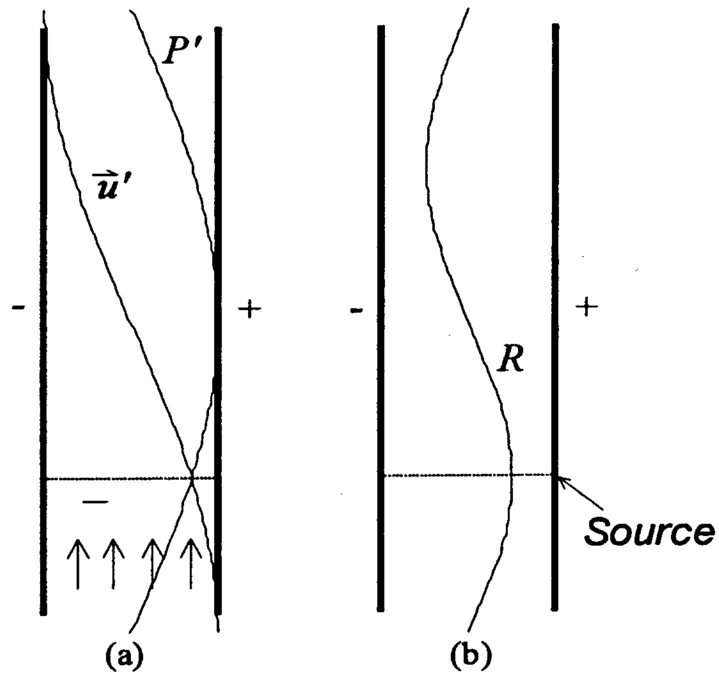

Figure 3.1: Schematic of a Rijke tube depicting the first mode instability.
(a) Pressure and velocity mode shape. (b) Rayleigh Index

node at the center of the tube and is positive in the lower half of the tube and negative in its upper half. It should be noted that for the first mode the pressure is positive throughout the length of the tube. Assuming the unsteady heat release from the thermal source varies in phase with the acoustic velocity, the Rayleigh's index given by equation 3.1 is positive in the lower half of the tube and negative in the upper half. Hence, the Rijke tube sustains self-excited thermo-acoustic oscillations when the thermal energy source is in the lower half of the tube only. A survey paper by Raun et al. [21], gives a detailed literature review of the work on the Rijke tubes, and discusses the physical mechanisms that are responsible for thermo-acoustic oscillations, for various energy sources such as wall temperature gradients, electrically heated wire gauze and combustion. Any heat source such as heated gauze, when placed within a vertical tube will transfer energy to the fluid within the tube and thus generate buoyancy driven upward flow. Presence of an acoustic field will then superimpose fluctuating acoustic velocities over the buoyancy driven steady velocity. The oscillations in the velocity field generate oscillations in the heat transfer from the heat source to the tube fluid and thus closes the thermo-acoustic loop. These are the basic underlining systems, which also generate thermo-acoustic oscillations in modern complex thermal systems.

3.2 Thermo-acoustic Instabilities in Complex Thermal Systems

Environmental pollution concerns drove the land based gas turbine manufacturers to device ways and means to reduce NO_x and other pollutant levels in the exhaust stream of these gas turbines. A number of techniques used to achieve the above goal are documented by Richards et al. [22]. These include exhaust stream cleanup using selective catalytic reduction (SCR), water injection into the reaction zone as a dilutant, lean premixed combustion, and catalytic combustion. In exhaust stream cleanup using the SCR, the exhaust stream is treated with ammonia in a catalytic reaction to generate molecular nitrogen. In lean premixed combustion, the equivalence ratio is maintained close to the lean flammability limit, thus ensuring large amount of excess air that acts as a dilutant and maintains lower flame and exhaust temperatures. In catalytic combustion, the fuel and air are premixed such that the equivalence ratios are below the lean flammability limit and a catalyst is used to convert the reactants to products. Although, catalytic combustion technology has shown promise, it is still in its nascent stage. Of the above techniques, the one most widely implemented is lean-premixed combustion, as it not only reduces pollutant formation, but also increases plant efficiency. But the advancement of this technology has been hampered by the presence of thermo-acoustic instabilities.

A great deal of research (both experimental and numerical) on the behavior of these thermal systems has been documented. All of this research has been directed towards understanding, predicting and controlling thermo-acoustic instabilities, yet there is no consensus on the most definitive solution to the problem. This is primarily because the complex nature of the dynamics of the physical processes involved and their interaction with each other, shrouds the solution in a veil of mystery. Thus, much of the recent work has been targeted towards providing reasonably simplified solutions to this complicated problem.

There has been much debate on the root causes of the unsteady heat release and its coupling to the acoustic plant in modern thermal systems. A number of combustion instability mechanisms including parametric flame instabilities, hydrodynamic instabilities, pulsating instabilities and periodic extinction are discussed by Candel [23]. Yet, literature shows that two main schools of thought have emerged with regard to the mechanisms driving the unsteady heat release. One of them believes that the heat release fluctuations are caused by the oscillations in reactant mixture strength or mass flux. The other school of thought is that flow instabilities such as vortex rollup are the only contributor to the heat release fluctuations. Regardless of the mechanism generating the heat release fluctuations, the coupling between the acoustics and the fore-mentioned mechanisms is through the fluctuation of the velocity field.

3.2.1 Instabilities Due to Mixture Strength Oscillations

In combustors, where mixture strength or mass flux pulsation, drive the thermo-acoustic instabilities, both fluctuations in equivalence ratio and in mass flux contribute to the heat release rate fluctuations. Under very lean conditions, Lieuwen et al. [24] have shown that small variations in equivalence ratio generate large changes in reaction rate, thus leading to large fluctuations in heat release rate relative to the heat release fluctuations generated by small variations in mass flux. Therefore, for lean premixed combustion processes it is generally assumed in the literature, that heat release rate oscillations are dominated by variations in equivalence ratios. In such cases it is common practice to assume the fuel flow to the mixing nozzle is choked and any acoustic oscillation present generates an oscillation in the mass flux of the air stream, thus generating an equivalence ratio fluctuation in the mixing nozzle. This fluctuation in the equivalence ratio is then convected downstream to the combustion zone at the rate of the mean flow, where it burns to generate fluctuation in heat release rate. This coupling mechanism is commonly referred in literature as 'air side coupling'. The above discussed argument hinges on the assumptions that acoustic pressure oscillations in the combustion chamber primarily generates velocity fluctuations in the system and does not significantly effect other flow variables such as density and temperature. This assumption has been shown to be correct for low mach number flows by Bloxsidge et al. [25].

Mongia et. al. [26] have developed a measurement technique to measure the fluctuations in equivalence ratio and have experimentally shown their existence, and their coupling to the pressure fluctuation in the combustion chamber. The presence of the equivalence ratio oscillations was indirectly confirmed by the successful match of the nonlinear heat release model developed by Peracchio et al. [27], that accounts for equivalence ratio oscillations to experimental data. Here the authors have modified the linear first order flame dynamic model discussed by Fleifil et al. [7] to simulate a turbulent flame with area variation and added to it effects of equivalence ratio fluctuations.

Richards et al. [28] have shown that the thermo-acoustic oscillations could be actively controlled by oscillating the fuel flow rate and hence the equivalence ratio between the two values which exhibit stable operation and thus effectively avoiding the equivalence ratio which is unstable. Thus, the process generates oscillations around a mean value of equivalence ratio that effectively nullifies the oscillations produced by thermo-acoustic instabilities. The success of this active control technique is another strong indicator of the presence of equivalence ratio fluctuations. The literature is rich in similar works that support this phenomenon such as reported by Lieuwen et al. [29], Murray et al. [30], and Richards et al. [31].

3.2.2 Instabilities Due to Fluid Mechanical Interaction

Apart from influencing the incoming mass flux and mixture strengths, the velocity fluctuations can also effect the shear layers present in the flow field, and thus coupling with the vortex shedding at the lip of the flame stabilizer. Such fluid mechanical instabilities are often known as vortex rollup. The combustion process normally has reaction rates that are much faster than the vortex shedding frequency. Thus the combustion rides on this unstable fluid flow as it convects downstream generating fluctuations in heat release. The resulting acoustic field feeds back on to these flow oscillations at the point of boundary layer separation, thus closing the loop. This mechanism for generating thermo-acoustic instabilities has been researched and reported by Keller [32]. Here the author has presented an overview of forced and self excited oscillations in gas turbine combustion chambers and has concluded that the leading cause of combustion driven oscillations in Dry Low NO_x combustors is the flow instabilities that produce fluctuations in reaction rate. He has also presented experimental data to support his analysis.

Bloxsidge et al. [25] have experimentally studied the low frequency thermo-acoustic instabilities in after burners, called Reheat Buzz and have developed a theory to predict them. The theory is valid assuming that the dynamic heat release is dependent on the flow structures downstream of the gutter, on which the flame is stabilized. Based on this theory, a semi-empirical flame dynamic model was developed, which was coupled to the theoretical acoustic model to predict the instabilities. The results of the simulation compared fairly well with the experimental data. This theoretical model was also applied by Macquisten and Dowling [33] to experiments conducted in an after burner at mach numbers of 0.15 to 0.27, with inlet conditions representative of an engine after burner. The flame was stabilized in the wake of a conical gutter. The predictions of the model compared well with the experimental data.

Paschereit et al. [34, 35] have studied control of thermo-acoustic instabilities in a swirl stabilized combustor that could be operated with either premixed charge or a diffusion flame. By changing the acoustic boundary condition, they were able to obtain three different thermo-acoustic modes in their rig. The authors noted that all the three instability modes were related to combustion within large scale structures that were excited in the combustion chamber due to interaction between the various flow instabilities and possible interaction with the acoustic resonant modes of the combustor. Research work reported by Dowling [36], and Fliefil et al. [7] are also based on the theory that thermo-acoustic instabilities are predominantly influenced by hydrodynamic instabilities.

3.3 Models for Flame Dynamics

For the past five decades, research in understanding and predicting thermo-acoustic instabilities has progressed at the pace at which the dynamics of the combustion process has been studied and understood. Due to the inherent nonlinear characteristics and the complexities involved with the combustion process itself, most of the research has relied on experimentally produced empirical models to predict the flame dynamics. The models generated theoretically from first principles are sparse and normally describe the behavior of the simplest of flames and are usually accompanied with sweeping assumptions.

One of the earlier works on flame dynamics was presented by Merk [37]. The author has presented a linear stability analysis of a combustion system and has derived a transfer function for burner stabilized laminar conical flames under very simplified conditions. The results presented showed that the flame transfer function, describing the fluctuating heat release rate as a function of velocity fluctuation was first order in nature. This model was later applied by Mugridge [38] to model his experiments. But Mugridge observed instabilities in regions not predicted by Merk's model and concluded that the Merk's transfer function was inadequate. Conical flames have also been studied experimentally by several other authors. Blackshear [39] studied propane air premixed conical flames within a Rijke tube like apparatus. The author noted that the heat transfer from the flame to the flame holder was significantly heating the incoming reactant mixture. The experimental results indicated that the phase lag of the flame area change with respect to the velocity perturbation, had a strong dependence on flame speed. Hence, the damping characteristics of the flame dynamics were flame speed dependent. The results also indicated that the magnitude of damping increased directly with increase in average inlet velocity. Putnam and Dennis [19] studied the combustion oscillation in three different burner-combustion chamber configurations and have tried to explain the results based on the changes in time delay and the location of the flame in the combustion chamber.

Goldshmidt, et al. [40, 41, 42] experimentally studied conical flames on a meeker burner.

The fuel burnt was liquidized petroleum gas. The authors obtained a flame transfer function that described the volumetric amplification of the flow due to the presence of a flame. The experimental data was best fitted with a model that was second order in nature and incorporated a time delay. The time delay was shown to be well approximated as

$$\tau = \frac{h}{3\,V_o} \tag{3.2}$$

where h was the cone height and V_o was the convective velocity of the reactant mixture at the base of the conical flame. This model was later applied by Antman et al. [43] to a Rijke tube consisting of a meeker burner placed within a cylindrical pipe, with an aim to simulate the entire process and predict the instabilities based on linear stability analysis.

Premixed mixture of air and city gas was burnt to evaluate the flame transfer function between the burnt and the injected volumetric flow rate by Becker and Gunther [44]. The authors showed that for premixed conical flames the time delay varied radially, and evaluated an effective time lag that was frequency dependent. The flame transfer function that best approximated the experimental data consisted of this effective time lag and a first order response.

Matsui [45] studied burner stabilized laminar conical flames. Air and methane were premixed and used as the reactant mixture. The author developed a flame transfer function describing the volumetric flow rate of the products as a function of the incoming reactant flow rate. A second order transfer function with two time delays was found to best fit the experimental frequency response.

One of the more modern mathematical models of flame dynamics discussed by Fleifil et al. [7] was also based on laminar conical flames. Here the steady field was modeled as a Poiseulle flow and the flame dynamics was derived by linearizing about the mean flame shape. The solution of the linearization gave the temporal and the spatial behavior of the flame front displacement from the mean position, when subjected to an acoustic wave at a given frequency. An infinite reaction rate approximation was used while developing the model. The solution was then related to fluctuating heat release rate, assuming that any velocity perturbations applied to the incoming reactants resulted only in area variation of the flame sheet while the flame speed remained constant. This analysis showed that the flame responded as a first order low pass filter. Based on this model, linear control methodologies have been developed by Annaswamy and Ghoniem [46]. The above model was used by Peracchio and Proscia [27] along with their own model for equivalence ratio fluctuations to predict stability of their test combustor. However, the analysis was only conducted for conditions where the heat release dynamics were dominated by fluctuations in equivalence ratio as compared to flame front oscillations. The limit cycle frequencies predicted by the analysis were about twenty percent higher than the measured value for equivalence ratio of 0.46 to 0.56.

The kinetic model [7] was later expanded to incorporate reacting mixture inhomogeneity by Fleifil et al. [47]. Here the authors have obtained a reduced order model for heat release dynamics that combines the effects of both the flame area fluctuations and equivalence ratio perturbation using a lumped parameter approach. From the results of the modeling, the authors show that both of the above discussed dynamic heat release mechanisms can couple with the rig acoustics and can lead to combustion instability. It was also noted that the choice of the mechanism that dominated the coupling with the rig acoustics was dependent, among other things, on the acoustic mode. For example, the bulk mode is primarily impacted by the equivalence ratio perturbations.

Apart from conical flames, the literature is very rich in analytical studies conducted on flat flames. Perhaps the most comprehensive analytical study of flame stability was done by Markstein [48]. This early work is based on perturbation analysis, starting with the fundamental conservation equations. One of the models discussed was that of parametric flame instability. Here the acceleration of the column of fluid surrounding the wrinkled flame was modeled as a second-order oscillator, that could force the flame to respond at a sub-harmonic frequency. This parametric instability was described using the Mathieu equation [49] and was subsequently studied by Searby and Rochwergeer [50]. Such a sub-harmonic resonance was observed in the unstable thermo-acoustic signature of the Rijke tube combustor discussed by Saunders et al. [51].

One Dimensional flat flames were also analyzed by Margolis [52]. The author has shown that under non-adiabatic conditions, one-dimensional flat flames, actually pulsate about their mean spatial position and that there is no time independent steady solution to its spatial location.

Much of the flame stability analysis has been centered around the two dimensional cellular structure of laminar flat flames as discussed by McIntosh [53], and Markstein [54]. In these analysis it has been assumed that it is impossible to realize a truly flat flame sheet because of non-uniformity in the in mean flow stream. The flame sheet always bubbles with cells, which may sometimes be very small in magnitude. Thus, an oscillation in the velocity field in which the flame is anchored would fluctuate the flame surface. The stretching and contorting of the flame sheet changes its characteristic propagation speed, which is directly related to the rate of combustion and therefore, the heat release. Such surface area variations due to local velocity perturbations can provide an excellent mechanism for self-excited thermo-acoustic oscillations.

Although, most of the work reported in literature in the area of flame dynamics pertains to simple conical or flat flames, attempts have also been made to analyze more complex flames seen in industrial settings, for their dynamic characteristics. One of the earlier works was done by Hurle et al. [55]. The authors studied premixed ethylene-air turbulent flames that were stabilized on open burners having a hydrogen-air pilot flame. They studied three burners with different cross-section diameters, and concluded that the flame could be modeled as a collection of monopole sound sources in the combustion zone. The authors were one of the first to correlate C_2^* and CH^* chemiluminescence to volumetric flow rate of the products of combustion for both laminar and turbulent flames.

The problem of oscillating combustion in industrial oil-gas fired boiler system was studied by Hadvig in the early seventies of the last century [56, 57]. The author evaluated from the experiments the transfer function of the combustion process, relating the volumetric flow rate of the products as a function of the volumetric flow rate of incoming reactant mixture. The term combustion process mentioned above included physical, chemical processes of combustion, fluid dynamics, atomization of liquid fuel, and droplet vaporization. The experimental data of the dynamic behavior of the combustion process was best described with a time delay and a seventh order and a fifth order system. The change in the order of the dynamic behavior was due to changes in burner geometry. The author noted that the type of lining and the dimensions of the combustion chamber, especially near the flame strongly influenced the flame transfer function.

Flame dynamics of afterburners was studied by Bloxsidge and Dowling [25], where the combustion zone length was a significant fraction of the acoustic wavelength. Therefore, the authors analyzed the combustion process as a distributed source and have related the low frequency instability (20 to 90 Hz) observed in afterburners to flow instabilities. They also developed a flame transfer function that relates the fluctuation in local heat release rate per unit length of the flame, to the mean heat release rate at that location, the Strouhal number, and a time delay. The time delay was defined as the time required to convect, at the mean flow velocity, the premixed charge from the start of the combustion zone to the plane under consideration. Based on the above model, a new analytical time lag flame model was developed by Ohtsuka et al. [58]. The new improved model took into account the heat release ratio distribution and the flame speed and was dependent on pressure, temperature, equivalence ratio and velocity. The model predictions were compared against experimental results from studying methane-air premixed swirl stabilized flames at elevated pressures of 0.6 to 0.9 MPa.

Very recently, Paschereit et al. [59] have evaluated the acoustic source matrices for turbulent swirling flows Here the authors have represented the entire thermo-acoustic system with a network of acoustic elements and have developed a methodology to study swirl stabilized flames as an acoustic source. The burner was experimentally analyzed as an acoustical two port, and its transfer matrix consisting of four elements was determined under conditions when there was no combustion. The flame was considered to be a source term that was determined by co-relating the results of the experiments with combustion, to the transfer matrix of the burner. The experiments were conducted with natural gas as fuel and air as the oxidizer. The authors concluded that the flame responded as an acoustic source in the frequency range of 40 to 160 Hz. Beyond 160 Hz, the source term representing the flame was very small. Unfortunately the authors have failed to report any of the test conditions such as equivalence ratio, swirl numbers, flow rate etc, thus making the results rather difficult to interpret.

Schuermans et al. [60] have developed an analytical model for the transfer matrix of a burner with premixed swirl stabilized flame. The model is based on Bernoulli's equation derived for incompressible isentropic flow of an ideal gas through the burner. The flame is modeled by using the Rankine-Hugoniot relations for pressure and velocity across a flame front of negligible thickness. The flame front itself is considered to be a discontinuity. The model developed was based on the assumption that the acoustic fluctuations generate equivalence ratio oscillations at the injector, which then get convected downstream to the flame, thus generating a time lag. The oscillating heat release generated due to the equivalence ratio fluctuations coupled to the acoustics, generate pressure oscillations, and thus close the loop. The transfer matrix for the burner was compared to the experimental results from an atmospheric combustion test facility. Studying the presented results, it may be concluded that the model and the experimental behavior are qualitatively similar, but no inferences can be drawn from them as the authors have failed to provide physical parameters such as equivalence ratio, flow rates etc that were used for this analysis.

Bohn et al. [61] developed a model to predict the dynamics of turbulent diffusion flames by simulating the entire combustion process using the full Navier-Stokes simulations. The authors first obtained a steady state solution, followed by a transient solution to a step change in the mass flow rate at the inlet of the burner. The results of the transient response were transformed into the frequency domain using the Laplase transformation. The turbulence was modeled using $K - \epsilon$ model, while the combustion was modeled with a 'mixed is burnt' model that neglects chemical kinetics. A beta-Pdf was used to account for the effects of turbulence on the combustion process. This was found to predict the heat release rather accurately. The steady state and the transient results of the simulations were compared to experimental data. While the steady state results matched the experimental data quite accurately, the transient results matched the experimental data only qualitatively.

Bohn et al. [62] also extended the above methodology to simulate premixed conical laminar flames Here a premixed methane-air mixture was modeled using a reduced 6 step reaction which took into account a set of 25 elementary reactions. The results were compared with the experimental results and with the existing analytical models. The steady state results compared well with the experimental data over a wide range of equivalence ratios. The dynamic results were only in qualitative agreement with experimental data, but the numerical simulations did a much better job of predicting the flame dynamics when compared to existing analytical models. The authors noted that the chemical delay time was an important factor that affected the dynamics and was not accounted in analytical models. Further, it was concluded that the interaction between the flow pattern of the burner nozzle and the chemical kinetics, greatly influenced the dynamic behavior of the flame. It was also reported that the common assumption of constant flame speeds used in analytical models is not valid.

3.4 Effects of Variation in Fuel Composition

Combustion systems related to power generation have improved considerably over the past five decades. In the process the systems have become more efficient and comply with very stringent emission standards. Considerable research, both fundamental and applied has been done to achieve todays standards. In the process, however, the systems have been fine tuned to a single fuel. Since natural gas gained popularity with land based power generation systems due to its easy availability and clean burning characteristics, most of the combustion research in this area concentrated on methane, a major constituent of natural gas, as a fuel. Yet, problems like thermo-acoustic instabilities have been experienced by the commercial systems purely due to their geographical location, a factor that effects the composition of natural gas. Such occurrences indicated that other constituents of natural gas may play a significant role in defining the optimized operating conditions. This brought the need to study the effects of fuel composition on the combustion dynamics into limelight. Further, the growing need of energy and economics have given rise to the need of using other gaseous fuels such as synthetic gas, marsh gas, biogas and also has led to the development of systems with dual fuel capabilities. Therefore, the researchers have dealt with these issues in the recent years.

Keller and Westbrook [63] studied the effects of changes in fuel composition on the performance of a Helmholtz-type pulse combustor. The fuels studied were pure methane and a mixture of methane and ethane in the ratio of 85:15. The choice of the fuels was such that only the chemical ignition delay time was significantly effected, while all the other physical properties essentially remained the same. Experiments were conducted to determine the lean stable operating limits of the combustor for the two fuels. Spatially integrated and ensemble averaged OH^* chemiluminescence was recorded as a measure of heat release rate and ensemble averaged pressure measurements in the injector were used to calculate the mass flow rate. Characteristic chemical kinetic time scales were estimated using the HCT code with detailed reaction mechanism. Experiments conducted for a total mass flux of $0.8\,Kg/sec - m^2$ showed that pure methane had a lean stability limit of $\Phi = 0.473$, while the methane-ethane mixture had a lean stability limit of $\Phi = 0.522$. The authors have also reported results for experiments conducted at $\Phi = 0.8$. For all the conditions studied, it was concluded that the difference in chemical kinetic mechanism between the two fuels caused changes in the chemical ignition delay timing, resulting in the modification of the phase relationship between the resonant pressure wave and the heat release rate due to combustion.

On a similar note Keller et al. [64] have examined the effects of various characteristic time scales on the performance of a Helmholtz-type pulse combustor. They defined the total ignition delay time for release of energy τ_{total}, to be a function of $\tau_{species}$, τ_{mixing}, and $\tau_{kinetic}$, where $\tau_{species}$ is defined as the time required to mix the fuel with the oxidizer, τ_{mixing} is the characteristic time required to mix the reactants with the hot products and raising the temperature of the reactants to ignition temperature, and $\tau_{kinetic}$ is the characteristic time for reactions to occur. The authors noted that the changes in $\tau_{kinetic}$ significantly changed the phasing between the oscillatory combustor pressure and the oscillations in the heat release rate, and thus effecting the performance of the pulse combustor.

Vandsburger et al. [65] have investigated the effect of the evaporation of liquid fuel spray on the heat release pattern and stability characteristics of a dump combustor. The experiments were conducted, by varying the liquid to gas fuel ratio from conditions of all gaseous fuel to half liquid and half gas. While varying the fuel composition, care was taken to maintain the same overall fuel/air equivalence ratio, and the same total fuel mass flow rate. The gaseous fuel used was ethylene and the liquid fuel was n-heptane and n-decane. Burning only gaseous fuel in premixed mode resulted in low frequency instabilities in the band around 50 Hz. (this was the fundamental mode of the combustor). This low frequency oscillation accounted for about 90% of the dynamic energy represented by the pressure spectrum. Upon co-burning liquid and gaseous fuels the energy level in the low frequency band reduced to 50-60% of its previous value, while there was increase in the dynamic energy concentration in a band around 250 Hz. For premixed gaseous fuel combustion, the reaction zone was narrow and resided on the large vortical structure, while the heat release had a broad distribution along the entire combustor. Introduction of liquid fuel changed the flame structure to become a compact distributed region encompassing less than $\frac{1}{2}$ of the combustor length, while most of the heat release took place in a small compact region near the dump.

Mehta et al. [66] have studied the effects of four different fuels on the thermo-acoustic instabilities within a 90 degree sector of an advance gas turbine engine combustor. The fuels used in the experiments were JP-4, JP-5, 50% blend of JP-5 and Diesel-2, and Diesel-2. The experimental results indicated that the most volatile of the tested fuels (JP-4), exhibited pressure oscillations at a much lower fuel-air ratio than the least volatile fuel. The authors noted that for every fuel there was a critical fuel to air ratio at which the pressure oscillations were maximum. On either side of this fuel air ratio the magnitude of the pressure oscillations dropped. Further it was noted that as the volatility of the fuel increased, the critical fuel to air ratio decreased. A similar variation was observed with changes in the core flow. Based on the experimental results, the authors concluded that the fuel spray vaporization process had a measurable effect on the operating characteristics of the combustor.

Janus et al. [67] have studied the effects of ambient conditions and fuel composition on combustion instability. The tests were conducted on a sub-scale combustor burning natural gas, propane, and some hydrogen/hydrocarbon mixtures. A premixed swirl stabilized nozzle, typical of industrial gas turbine was used. The results showed that increasing the inlet air temperature causes the unstable region to move to lower flow rates and at high inlet temperatures, a new unstable region also appeared in the high flow rate/low equivalence ratio region. It was concluded that inlet air temperatures changed the transport time by changing the Arrhenius kinetic ratio and also effecting the advection portion of the transport time. However, changes in the advection portion of the transport time were minor compared to changes in the reaction rate. Effect of humidity increase was found to be opposite to that of increase in inlet air temperature, but limited data prevented the drawing of precise conclusions. Changes in the fuel burnt generated changes in the reaction time. Since reaction time was found to dominate the total transport time in the experimental rig, burning different fuels significantly affected the stability maps. Finally, the authors have concluded that any parameter that effects the reaction time shall have a measurable influence on the thermo-acoustic instability.

Flores et al. [68] have studied the effects of fuel composition on the stability characteristics and emission levels from combustion in a test rig that mimics the key features of a full scale gas turbine. Tests were conducted at 1 atmosphere with inlet temperatures of 800K. The fuel blends used were natural gas, 85% natural gas and 15% ethane, 80% natural gas and 20% propane, and propane. The combustor performance was based on lean blowoff limits and the emission of CO and NO_x, both of which were corrected to a fixed dilution of 15% O_2. The authors concluded that lean blowoff limits co-relate with reaction rate, suggesting that the kinetic mechanism is responsible for stabilizing the flame. Further, higher hydrocarbons produced more NO_x when compared at the same firing temperature.

Habik [69] studied the effects of adding low concentration of hydrogen and ethane to propane-air flames. A chemical kinetic model consisting of 72 reactions among 29 species was used to evaluate the effect of the fuel composition variation on the burning velocity and the concentration of NO_x and CO. The predicted burning velocities compared well with the experimental data. Adding small amounts of hydrogen increased the burning velocity significantly. NO_x levels decrease with addition of hydrogen, while the CO levels increase substantially with its addition.

3.5 Summary

Table 3.1: Summary table of the literature available on Flame Dynamics

YEAR	AUTHOR	DESCRIPTION
1953	Blackshear, Jr., P.L.	Studied propane-air premixed conical flame within a Rijke tube like apparatus.
1953-1956	Putnam, A. A and Dennis, W. R.	Combustion oscillation in three different burner-combustion chamber configurations using premixed H_2-air, and H_2 diffusion flames
1956	Merk, H. J.	Transfer function for burner stabilized conical flames - laminar
1952-1964	Markstein, G.H.	Perturbation analysis of the parametric flame instability and two dimensional cellular structure of laminar flat flames
1968	Hurle, I. R. et al	Studied premixed ethylene-air turbulent flames. Flame modeled as a collection of monopole sound sources

Table 3.1: (continued)

Year	Author	Description
1970	Becker, R and Gunther, R.	Burned premixed mixture of air and city gas to study conical flames
1971-1973	Hadvig, S.	Oscillating combustion in industrial oil-gas fired boiler system
1974-1978	Goldschmidt, V.W. et al.	Conical flames on meeker burner Fuel - LPG
1980	Margolis, S. B.	Analytical study of one-dimensional flat flames under non-adiabatic conditions - pulsating flames
1981	Matsui, Y.	Studied laminar premixed conical flames of air and methane
1985	McIntosh, A. C.	Flame stability analysis - two dimensional cellular structure
1988	Bloxsidge, G.J. et al.	Flame dynamics of afterburners assuming distributed heat release
1992	Searby, G. and Rochwerger, D.	Studied parametric flame instability using the Mathieu equation
1996-2000	Fleifil, M. et al.	Analytical solution for dynamics of laminar conical flames assuming constant flame speed and later incorporating reacting mixture inhomogeneity.
1997-1998	Bohn, D.	Developed numerical models to predict the dynamics of turbulent diffusion flames and premixed conical laminar flames in a matrix burner configuration
1998	Peracchio, A. A. and Proscia, W.M.	Used the model of Fleifil et al. and added their own model for equivalence ratio variation

Table 3.1: (continued)

YEAR	AUTHOR	DESCRIPTION
1998	Ohtsuka, M et al.	Improved on the model of Bloxsidge et al. to account for the dependence of the dynamics on temperature, pressure, equivalence ration and velocity
1999	Paschereit, C. O. et al.	Evaluated acoustic source matrices for swirl stabilized flames.
1999	Schuermans, B. B. H	Developed an analytical model for the transfer matrix of a swirl stabilized premixed flame

Table 3.2: Summary table of the literature available on Rijke Tube Burner

YEAR	AUTHOR	DESCRIPTION
1953-1956	Putnam, A. A. and Dennis,R. R.	Studied stoichiometric Premixed H_2/air, H_2 diffusion flame, premixed natural gas-air on wire gauze, and premixed ethane, methane and propane-air flames on a hexagonal tube array
1957	Bailey, J.J.	Conducted experiments on premixed air-propane flames on brass screen
1957-1958	Merk, H. J.	Conducted experiments on hot wire gauze and studied premixed flames on a multiport burner
1963	Diederichsen, J.	Studied lean Calor gas-air on wire gauze
1965	Tsuji, H. and Takeno, T.	Carried out experiments with 'city gas'-air flames stabilized on a injector plate, analogous of a liquid-rocket motor
1971	Sipowicz, W. W. et al.	Experimented with premixed methane-O_2-N_2 flames

Table 3.2: (continued)

YEAR	AUTHOR	DESCRIPTION
1977	Schimmer, H. and Vortmeyer, D.	Studied premixed propane-air flames on Copper tube matrix
1980	Mugridge, B. D.	Conducted experiments on premixed natural gas-air flames on a multiport burner
1984-1985	Braithewaite, P. C. et al. and Beckstead, M. W. et al.	Used premixed propane-O_2-N_2 to stabilize flames on a wire gauze burner for their experiments
1985-1993	Raun, R. L. and Beckstead, M. W.	Developed numerical model for a Rijke tube burner having a premixed flame stabilized on a wire gauze and wrote a review article on Rijke tube burners
1986	Joos, F. and Vortmeyer, D.	Experimented with premixed propane-air flames on burner matrix
1986-1987	Poinsot, T. et al.	Experimented with premixed propane-air flames stabilized on slot burner
1986	Sankar, S. V. et al.	Experimented with premixed propane-air flames stabilized on a ceramic matrix
1986-1990	McIntosh, A. C.	Conducted analysis of a premixed flame on porous flame holder
1987	Sivasegram, S. and Whitelaw, J. H.	Conducted experiments with premixed natural gas-air flames stabilized on bluff body
1987-1991	Finlinson, J. C. et al.	Conducted experiments with premixed propane-O_2-N_2 flames on wire gauze
1988-1989	Brinckman, G. et al.	Conducted experiments with methane injected near $\frac{L}{4}$ position of the Rijke tube

Table 3.2: (continued)

Year	Author	Description
1988	Hegde, U. G. et al.	Studied V-shaped premixed propane-air flame stabilized on single wires
1991	Bai, T. et al.	Conducted experiments with propane-air premixed and diffusion flames
1992	Gutmark, E. P. et al.	Studied conical premixed propane-air flames anchored on a circular orifice plate
1999	Saunders, W. R. et al.	Studied laminar premixed flames stabilized on a ceramic matrix

Table 3.3: Summary table of the literature available on Thermo-Acoustic Instabilities

Year	Author	Description
1953-1956	Putnam, A. A.	Studied the instabilities on simple combustors and theoretical investigation of the Rayleigh's criterion
1963-2000	Zinn, B. T. et al.	Has investigated thermo-acoustic instability in combustors using liquid, gaseous and solid propellant rocket fuels and have developed control methodologies to suppress their occurrence. Also worked on utilizing these thermo-acoustic instabilities to enhance the efficiencies of pulsed combustors
1969	Barrère, M. and Williams, F. A.	Have described the various combustion instability mechanisms that are observed in various combustors
1971-1973	Hadvig, S.	Studied the problem of oscillating combustion in industrial oil-gas fired boiler system

Table 3.3: (continued)

Year	Author	Description
1974-1978	Goldshmidt, V. W. et al.	Attempted to predict thermo-acoustic instability by applying the systems level approach to simple burners
1977-2000	Culick, F. E. C. et al.	Concentrated on understanding the nonlinear aspects involved in thermo-acoustic instability with respect to their occurrence in propulsion systems
1981-2000	Yang, V. et al.	Studied the occurrence of thermo-acoustic instability primarily in rocket engines and developed control algorithms for their active control
1983-2000	Candel, S. M. et al.	Studied dynamics of flames and their interaction with vortices present in the flow. Also dealt with validation of the OH^* signal as a measure of heat release rate and active combustion control
1987-2000	Whitelaw, J. H.	Primarily studied thermo-acoustic instability occurring in premixed turbulent flow environment and concentrated on the various fluid mechanical aspects involved in these instabilities
1988-1999	Dowling, A. P. et al.	Experimentally studied thermo-acoustic instability on an after burner geometry and developed models for their prediction based on the effects of vortex shedding on the flame dynamics
1988	Bloxside, G. J. et al.	Studied causes of Φ oscillations at low Mach number flows and their impact in thermo-acoustic instability. Most of the authors work is done on After burner geometries

Table 3.3: (continued)

YEAR	AUTHOR	DESCRIPTION
1989-2000	Gutmark, E. P. et al.	Studied the interaction of the combustion process with fluid mechanical instabilities and their effects on the occurrence of thermo-acoustic instability
1989-1995	Keller, J. O. et al.	Studied various mechanisms responsible for thermo-acoustic instability and the role of chemical kinetics on their behavior. They were also involved in the research of pulse combustion where these thermo-acoustic instabilities are utilized to augment heat transfer and efficiency
1989	Vandsburger, U. et al.	Studied the effects of fuel composition on the occurrence of thermo-acoustic instability and algorithms for their active control
1990-2000	Richards, G. A. et al.	The authors have experimentally studied thermo-acoustic instabilities and their control. They have also attempted to correlate the occurrence of these instabilities to the effects of ambient conditions and composition of the fuel. They have developed a number of models to predict these instabilities including the $\tau - f$ model.
1995-2000	Ghoniem, A. F. et al.	Developed analytical and numerical models to predict thermo-acoustic instability and algorithms for their active control
1996-2000	Samuelson, S. C. et al.	Studied effects of fuel composition and unmixedness on the occurrence of thermo-acoustic instability and emissions

Table 3.3: (continued)

YEAR	AUTHOR	DESCRIPTION
1998-1999	Paschereit, C. O. et al.	The authors have concentrated on the effects of coherent structures present in swirling turbulent flows on thermo-acoustic instability
1998	Mongia, R., Dibble, R. and Lovett, J.	Developed sensors to capture the Φ oscillations caused by the coupling of the heat release rate to the acoustic pressure
1998	Perrachio, A. A. et al.	Developed models for predicting thermo-acoustic instability and compared with their experimental results. In the process, have indirectly shown the existence of thermo-acoustic instability
1999-2000	Lieuwen, T. et al.	Discussed the effects of Φ oscillation on the dynamic heat release, especially under very lean operating conditions and studies the influence of near field effects on thermo-acoustic instabilities