# 6 Conclusions and Recommendations

## 6.1 Conclusions

Even with unprecedented interest in renewable energy sources such as fuel cells, wind energy, and solar energy; combustion remains, and will remain for the foreseeable future, vastly important for energy production, process heating, and reforming. As we strive to make combustion processes cleaner and more efficient, we butt against the walls of stability. A complete understanding of flame dynamics is critical to making further reductions in pollutants and gains in efficiency. Combustion engineers currently have no adequate means of predicting instabilities for a given combustor design. Instabilities must be combated through design iterations and passive means when they arise. Due to instabilities, operating conditions are often restricted. Combustion instabilities prohibit operating at increasingly lean conditions, making further reductions in pollutants impossible. This study focused on gaining an understanding of flame dynamics to be applied in predictive tools and active control strategies.

Through investigating the effect of velocity perturbations on heat release rate, further knowledge of flame dynamics was acquired. Previous experimental studies of flame dynamics used chemiluminescence as an indicator of heat release rate, and therefore as a driver of thermoacoustic instabilities. Analytical and numerical work within the VACCG [1] shows that the energy that feeds back into the acoustics to cause thermoacoustic instabilities, or the acoustic forcing function, is more accurately measured through gas temperature fluctuations. Tunable Diode Laser Absorption Spectroscopy was used to measure fluctuations in product gas temperature through water absorption. To the author's knowledge, this study represents the first time TDLAS has been used to measure frequency response functions of flame dynamics. A methodology was developed to measure flame dynamics using TDLAS. Low-order dynamic models are based on the flame dynamics measurements. This methodology was applied to a laminar, flat-flame burner and a turbulent, swirl-stabilized combustor.

Frequency response functions of flame dynamics were measured using OH* chemiluminescence as an indicator of chemical heat release rate (reaction rate) and product gas temperature as a measure of the acoustic forcing function. In this manner, the difference between reaction rate dynamics and acoustic forcing function dynamics was observed. It was found that for both laminar and turbulent flames, the reaction rate dynamics and acoustic forcing function dynamics coincided at frequencies below approximately 200 Hz, where the dynamics began to diverge. This supports the theory that chemical heat release rate dominates the acoustic forcing function at low frequencies. At high frequencies, heat transfer and thermal diffusion dominate the acoustic forcing function. The role of heat transfer has been known to be dominant in Rijke-tube instabilities, but the role of thermal diffusion was never thought important in turbulent flames without a flame holder. The data from this study suggests heat transfer and thermal diffusion dominate the acoustic forcing function at high frequencies for both laminar and turbulent flames.

The effect of fuel composition on flame dynamics was investigated. Through measurements of flame dynamics for methane, ethane, and propane; it was shown that the mean energy content of the fuel controls the gain of flame dynamics. The flame speed affects the bandwidth of the response. Thus, propane has a much higher dynamic gain than methane, and would be more susceptible to thermoacoustic instabilities.

Through a dimensional analysis, the dominant parameters affecting flame dynamics were defined. Compact, low-order transfer functions were and fit to the frequency response data. Laminar flame dynamics, for both reaction rate and acoustic forcing function, were modeled using a 2nd order system with time delay. The turbulent reaction rate dynamics exhibited three resonances, requiring a 6th order system with time delay. The acoustic forcing function dynamics for the turbulent flame were adequately modeled with two zeros and two poles, resulting in a 4th order system. The models indicate that flame dynamics, even in turbulent combustors, can be described with simple models. In general, natural frequency and damping of each resonance increased with equivalence ratio and flow rate. Increased swirl and turbulence resulted in increased dynamic gain in the models.

The resulting models of flame dynamics can be applied to predicting instabilities and to develop control algorithms. When coupled with a model of combustor acoustics, the frequency and amplitude of thermoacoustic instabilities can be predicted. Model-based controllers can be developed for active combustion control. Alternatively, adaptive controllers can use the models to make better control decisions. More important than direct application, the study has provided insight into the physics important to flame dynamics. A methodology was developed to formulate empirical models of flame dynamics based on TDLAS measurements.

Due to the limited scope of this investigation, the results have certain limitations. Two types of flames were studied: a laminar, flat flame and a turbulent, swirl-stabilized flame. Although the conclusions drawn may be generally applicable, other flame configurations must be tested to insure generality. The nature of the line-of-sight TDLAS measurement resulted in lingering issues on how to interpret the frequency response data. Possible solutions to these limitations are discussed in the recommendations for future work.

In summary, the investigation into the dynamics of laminar and turbulent premixed flames provided needed insight into the physical processes of flame dynamics. A methodology to measure the acoustic forcing function dynamics was developed using Tunable Diode Laser Absorption Spectroscopy. The influences of chemical kinetics, heat transfer, and fluid mechanics on flame dynamics was quantified. Compact models, for application in the prediction and control of thermoacoustic instabilities, were developed. The lessons learned from this study can be used as a step for future experimental and theoretical work into characterizing flame dynamics.

## 6.2 Recommendations for Future Work

Although combustion processes have been studied for about 300 years, the study of flame dynamics is still in its infancy. The present investigation focused on relatively simple laminar and turbulent flames. First, ambiguities in the measurements must be resolved. The response of flame dynamics to other inputs, notably equivalence ratio fluctuations, must be investigated. More complicated combustors, along with a variety of fuels, should be studied. In order to implement active combustion control, sensors and algorithms must be developed for installation in real gas turbines.

**6.2.1 Laminar Flame Dynamics.** As stated in Chapter 4, some questions still remain on interpreting the temperature frequency response data. Although it is postulated that 2-D effects cause spurious peaks in the magnitude, measurements are needed to prove this theory. Tomography or PLIF could be used to resolve the flame surface and observe 2-D phenomena.

After these questions are answered, the models of flame dynamics can be coupled with models of combustor acoustics to predict thermoacoustic instabilities in self-excited systems. These predictions could be tested in a simple Rijke tube combustor. It may be instructive to repeat this exercise with a water-cooled burner to separate the effects of the chemical reaction and heat transfer on flame dynamics.

**6.2.2 Turbulent Flame Dynamics.** The same closed-loop analysis should then be completed with the measurements of turbulent flame dynamics. By adding a longer combustion chamber, the Raleigh Criterion would be satisfied and the system would become self-excited. In this manner, predictions of thermoacoustic instabilities in turbulent systems could be tested.

Combustors in real gas turbines are operated at high pressures and flow rates. The validity of the methodology used in this study must be tested on high-pressure combustors. High pressure presents difficulty with respect to spectroscopy, as increased collisions between molecules cause the transitions to broaden.

**6.2.3 Equivalence Ratio Fluctuations.** The study presented in this document focused on measuring the effect of velocity fluctuations on the unsteady heat release rate of the flame. As seen in Figure 6.1, equivalence ratio fluctuations can also force variations in heat release rate. Subsequent studies must measure the flame dynamics with respect to equivalence ratio variations. The current effort focuses on using fast solenoid valves with a bandwidth of 500 Hz, to pulse the fuel. The fuel pulse creates a fluctuation in equivalence ratio and velocity. The equivalence ratio fluctuations are measured via methane absorption of an IR-HeNe laser. Since the effect of velocity fluctuations on the flame dynamics is known (from this study), the effect of equivalence ratio fluctuations can be isolated. In this manner, a complete model of flame dynamics can be ascertained. Attempts at forcing equivalence ratio fluctuations, without forcing large velocity fluctuations, were unsuccessful in the laminar burner due to the dominance of diffusion. Forcing equivalence ratio in turbulent flames holds more promise, as diffusion is less dominant.

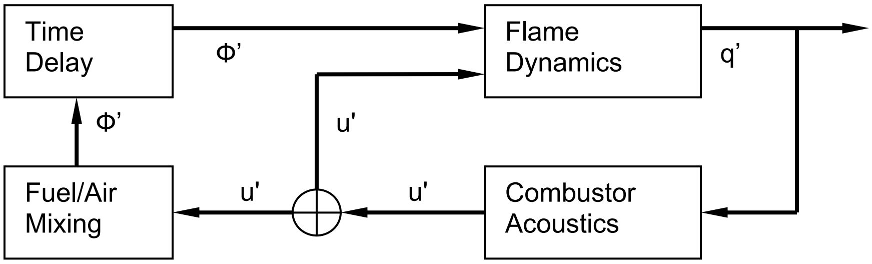

**Figure 6.1.** System diagram of self-excited thermo-acoustic instabilities.

**6.2.4 Fuel Variability.** The current study measured laminar flame dynamics using methane, ethane, and propane. Only methane was used in the measurements of turbulent flame dynamics. These measurements should be extended to ethane and propane. Natural gas composition varies depending on its source. Each field has its own composition. Also, natural gas from landfills or biomass differs from mined natural gas. By studying different fuels, the effect of fuel composition on flame dynamics can be determined.

The recent interest in coal-derivatives like syngas as well as hydrogen provides incentive for studying different fuels. Syngas primarily consists of hydrogen and carbon monoxide. Due to the increased flame speed of fuels containing hydrogen, much leaner mixtures can be burned. It is expected that the bandwidth of the flame dynamics will be increased due to the increased flame speed. Also, the damping will decrease due to leaner conditions.

**6.2.5. Active Combustion Control.** This study has many implications for active combustion control. First, the models of flame dynamics can be used to develop model-based control algorithms. Quasi-adaptive routines could also be tuned using these measurements.

In addition to developing control algorithms, TDLAS may be able to be used as a sensor for ACC. Diode lasers are inexpensive, lightweight, and compact. In addition, they are available in optical fiber-coupled packages. A fiber-based sensor could be developed to measure flame dynamics on-line. In this manner, the controller could adjust to varying combustion environments.

## Bibliography

1. Haber, L. and U. Vandsburger. *Combustion and heat transfer dynamics in a premixed laminar flat-flame burner*. in *Aerospace Sciences Meeting*. 2004.