Part IV

Conclusions

Chapter 9

Conclusions and Future Work

CFD studies of premixed laminar and turbulent combustion dynamics have been conducted. These studies were aimed at explaining physical phenomena present in the combustion dynamics of premixed flames. Instead of using analytical methods which often times fail for complex combustion systems, CFD has been applied to capture the physical phenomena by solving the reacting unsteady conservation equations. The frequency response function (FRF) between unsteady oscillations in incoming mass flow rate and the unsteady heat release rate of the flame has been applied to understand the coupling between acoustics and flame dynamics. Using the FRF calculated, part of the combustion control loop can be completed. The direct implementation of the FRF has also been to understand the phenomena of thermoacoustic instabilities and investigate the factors affecting its occurrence. Factors like heat transfer to the burner and vortex shedding have been investigated.

9.1 Summary of Results and Conclusions

The present research goals have been influenced by the need to understand the thermoacoustic instability mechanism. The CFD research conducted has been strongly coupled with

experimental studies undertaken at VACCG to understand the role of acoustics on premixed flame dynamics. CFD studies have been performed to improve the understanding of laminar and turbulent premixed flame dynamics. Only one part of the combustion control loop (the flame dynamics part) has been investigated. Other parts of the loop, like the acoustics, are being investigated at VACCG by other researchers. These investigations involve experimental measurements, finite element modeling (FEM) and analytical modeling of controllers. This section includes summaries of two parts of the research – the laminar flame dynamics part and the turbulent flame dynamics part. In the laminar flame dynamics part, the self-excited Rijke tube combustor work is summarized followed by the summary of linear stability analysis of the flat flame. The turbulent flame dynamics work is summarized by first describing the cold-flow simulations and then the reacting-flow simulations.

9.1.1   Laminar Flame Dynamics

Two case studies have been performed using CFD analysis to understand the physics behind thermoacoustic instabilities occurring in laminar flames. A self-excited combustor – the Rijke tube combustor, has been first analyzed to validate experimental evidence gathered earlier at VACCG. The study focused on capturing the hot acoustics of the Rijke tube and also on investigating the nonlinear coupling mechanism between heat release rate and acoustics of the combustor. This study has been followed up by isolating the Rijke tube flat flame in a simpler burner system and by performing linear stability analysis of the flame to incoming velocity perturbations. The linear stability analysis performed increased the understanding of the flat flame dynamics and created a Frequency Response Function (FRF) of the flame that can be used in controls algorithms.

Self-excited Rijke Tube Combustor

Numerical simulation of reacting flow in the Rijke tube combustor was successfully carried out for $\phi = 1.0$ and $Q = 120\,cc/s$. The objective of capturing the thermoacoustic instability in the combustor was achieved and the acoustic signature obtained from the experimental investigation was validated by the computed results. Unsteady growth of pressure oscillation was observed in the solution and is indicative of the fact that the numerical model was able to simulate the limit-cycle phenomena which occurs in the experimental Rijke tube combustor. The key achievement was the successful modeling of the self-excited system. The following remarks summarize the observations from the study:

1. The temperatures predicted inside the flame region compare well with the observed temperature although the temperature distribution downstream of the flame do not agree well with experimentally measured temperatures. The absence of radiation modeling and accurate convective boundary condition on the combustor wall affects the capability of the model to predict temperatures with a high degree of accuracy. The predicted temperature field does not affect the resulting prediction of the fundamental frequency and therefore is not of a great concern to the study.

2. Flame anchoring on top of the honeycomb was successfully achieved. The ability of the model to predict flame anchoring is a major improvement over the failure of previously conducted studies to model flame heat sources in Rijke tube combustors. The flame shape has also been computed accurately and shows curling behavior near the wall. The predicted temperature field inside the honeycomb channel confirm the anchoring process of the flame and shows the ability of the numerical model to capture the heat transfer mechanism between the flame and the honeycomb.

3. The fundamental frequency is predicted close to the second mode of the acoustic system and matches well with the experimentally obtained value.

4. Other features of the pressure power spectrum have been captured accurately. The first

four harmonics of the fundamental frequency $(187\,Hz)$ show up at $374\,Hz$, $561\,Hz$, $748\,Hz$ and $935\,Hz$.

5. The pulsating subsonic instability which was seen to occur in the experiments has been captured. The effect of this instability is observed on the fundamental frequency as well as the harmonics in the form of sidebands (amplitude modulation at $\pm 24\,Hz$).

Having successfully computed the unsteady pressure field inside the Rijke tube combustor, the second step of understanding the flame dynamics was to investigate the flat flame's behavior to velocity perturbations. Also, it was important to understand the role of other instabilities on flame dynamics. Therefore, the role of the pulsating instability has also been investigated in the second part of the laminar studies. The Fluent CFD solver was used for the Rijke tube simulation and has been also used for the flat flame study.

Flat Flame Burner: Flow Forcing of Laminar Flat Flame

Decoupling the nonlinear feedback from the acoustics of the chamber by insuring that the resonant modes of the flat flame burner lie in the kilohertz region, the flat flame has been perturbed with incoming velocity oscillations. Numerical simulation of the flat flame has been performed for $\phi = 0.75$ and $Q = 200\,cc/s$ with premixed methane-air mixture. A range of frequencies, $20\,Hz$ to $500\,Hz$, have been imposed and the FRF between velocity fluctuation and unsteady heat release rate has been computed. The following is a list of observed phenomena from the reacting flow study:

1. Full two-dimensional simulation of reacting flow has been performed and the resulting computed FRF has been compared with the experimentally obtained FRF. The computed FRF showed agreement with the order of the dynamics of the experimental FRF, but failed to capture the phase accurately. Also, the low frequency resonance phenomena observed in experiments was not captured.

2. To improve the accuracy of the solution, single channel simulation of the flat flame has been performed. The resulting FRF compared well with the experimentally obtained FRF. The pulsating instability is observed to occur at $30\,Hz$ as compared to $32.5\,Hz$ observed in the experiments. The computed FRF magnitude matches the experimental values between $15\,Hz$ and $35\,Hz$. The slope of the computed FRF magnitude differs slightly from the experimental values for higher frequencies. The roll-off at higher frequencies is of the order of $45\,dB$ per decade for the CFD result as compared to around $40\,dB$ per decade for the experiment.

To investigate the pulsating instability further and to explain the phenomena physically, a heat transfer study was performed. In the heat transfer study, the flat flame was replaced by a heat source downstream of the honeycomb. The following observations summarize the results obtained from the study:

1. A constant heat source invariant in time did not contribute toward the development of the pulsating instability. The FRF obtained between unsteady velocity fluctuations and temperature at the exit of the honeycomb did not show any resonance.

2. A second-order system can create a resonance, therefore apart from the oscillating velocity, first source of forcing, an oscillating heat source (second source of forcing) was imposed. The heat source was oscillating out of phase with the incoming velocity oscillations. The phase between the heat source and incoming velocity was obtained from the reacting flow FRF phase plot. Because of the second source of forcing, a resonance behavior was observed at $30\,Hz$ that matched the $30\,Hz$ resonance observed in the reacting flow FRF.

3. It can be concluded that the heat transfer between the flame and subsequent preheating of the incoming air-fuel mixture was the phenomena responsible for the resonance and that the resonance was not chemistry related.

A further study of the effect of fuel variability was conducted with premixed propane-air as the mixture. The FRF obtained from the simulation has good agreement with the methane-air case FRF. The study showed that the $30\,Hz$ resonance occurred for both the propane-air case and the methane-air case, making the hypothesis of the heat transfer resonance phenomena stronger. The phase predicted in the propane-air study was similar to the phase predicted in the methane-air study.

The effect of incoming velocity fluctuations on a laminar premixed flat flame has been investigated and a FRF between the unsteady velocity and the unsteady heat release rate from the flame has been created. Flame–acoustic wave interactions in real gas turbine combustors occur in noisy surroundings, where the flame is a highly perturbed front, even in the absence of coherent acoustic oscillations, and executes large oscillations about its mean position. Any model of the response of laminar flames to incoming velocity perturbations needs to be generalized to include the fact that real flames are highly unsteady. Therefore, the successful work performed on laminar flat flame should be extended to turbulent flow situations.

9.1.2   Swirl Stabilized Turbulent Flame Dynamics

Turbulent combustion modeling of a gaseous swirl stabilized combustor has been performed. Both unsteady RANS and Large Eddy Simulation (LES) of reacting flow have been performed. Full 3-D cold flow simulations were performed to generate the inlet velocity boundary condition for the 2-D axisymmetric unsteady RANS (URANS) reacting flow simulation of the combustor. Since the velocity boundary condition used in the URANS calculations was not perfectly accurate, hot-wire anemometry data was used to generate the boundary condition for the LES of unsteady combustion in the 2-D axisymmetric combustor geometry.

Turbulent Flame Modeling

By applying inlet boundary conditions obtained from the 3-D cold flow calculations, 2-D axisymmetric solution of the unsteady Navier-Stokes equations was obtained using a mixture fraction-PDF turbulence-chemistry interaction model. The reacting flow solution was achieved for $Q = 20\,SCFM$, $\phi = 0.75$ and a geometric swirl number of $S_g = 1.19$. Two important conclusions can be drawn from the simulations:

1. The Damkohler number for the combustion region suggested that the flame is made up of well stirred reactors and distributed reaction zones. This important observation necessitated accurate modeling of the effect of turbulence-chemistry interactions. Further studies with LES, therefore, were required for capturing the effect of turbulence on chemistry.

2. The flame in the URANS calculations was perturbed with an incoming velocity fluctuation and the FRF between unsteady velocity and unsteady heat release rate was obtained. The FRF magnitude and phase showed zeroth order dynamics. Thus, the need for using LES of the turbulent flame was necessitated.

Further studies of the swirl stabilized turbulent flame was performed by LES. A 2-D axisymmetric LES of reacting flow in the combustor geometry was performed. Time accurate reacting flow Navier-Stokes equations were solved with dynamic subgrid scale modeling, by applying the Linear Eddy Model (LEM) for turbulence-chemistry interactions and using a nineteen step reduced reaction mechanism for premixed methane-air combustion. The reacting flow solution obtained showed important characteristics of the turbulent flame. One important discovery was the $255\,Hz$ vortex shedding phenomena that was captured to occur at the quarl (diverging section) because of shear layer breakdown. The vortex shed from the shear layer was interacting with the flame shape which resulted in a periodic flapping motion of the flame. This phenomena was also observed in the experiments (heat release rate measurements) and closely matches the $275\,Hz$ frequency that was observed in the experiments.

A possible explanation of the $275\,Hz$ peak seen in the experimental FRF was proposed with the explanation of flame-vortex interaction.

Frequency Response Function

The unexcited turbulent flame was subsequently excited with incoming velocity perturbations to obtain a FRF between the imposed velocity oscillations and the resulting heat release rate fluctuations. Heat release rate from the flame was computed by integrating the product of H_2CO and OH mass fractions inside the combustor. To force the flame with incoming velocity oscillations, it was assumed that the wave entering the computation domain was planar. Therefore, only the axial component of velocity was perturbed, the radial and tangential velocity distribution were held stationary in time. A summation of sines (between $25\,Hz$ and $750\,Hz$) was imposed as the time varying boundary condition. The resulting FRF from exciting the flame showed good agreement with the experimentally obtained FRF. The following observations summarizes the study:

1. The computed FRF magnitude increased between $40\,Hz$ and $100\,Hz$ and then decreased till $750\,Hz$. The magnitude curve was noisy and distinct peaks were visible at $175\,Hz$, $255\,Hz$ and $500\,Hz$. These peaks were observed to occur close to the peaks seen in the experimental FRF magnitude. The $255\,Hz$ peak was identified to occur because of the vortex shedding phenomena.

2. The computed FRF phase showed a close match with the experimentally obtained phase between velocity and heat release rate. Overall, a drop of $700°$ in phase occurred between $40\,Hz$ and $500\,Hz$.

In summary, both laminar and turbulent premixed flames were studied using unsteady CFD analysis. The laminar flame dynamics study of the flat flame helped in the understanding of the role heat transfer plays in burner stabilized flames. The turbulent flame dynamics study was successful in predicting the flapping motion of the swirl stabilized flame observed in

experiments. The FRF obtained in the turbulent study closely matched the experimentally obtained FRF in both magnitude and phase.

9.2   Suggestions for Future Work and Recommendations

Continued work in applying unsteady CFD analysis to study flame dynamics is needed. Both laminar and turbulent flame dynamics that are affected by fluctuations of equivalence ratio and oscillations in velocity can be understood in depth if successful CFD modeling of the flames can be performed. The following recommendations for all three parts of the study – the self-excited Rijke tube, the flat flame burner and the turbulent combustor – are being made for future studies:

Rijke Tube Combustor – Self-excited combustion

- The unsteady reacting flow in the Rijke tube self excited combustor should be investigated for different equivalence ratios. Further understanding of the coupling mechanism between the pressure waves and heat release rate is needed.

- An attempt to include controls algorithm into the CFD solver (via user subroutines) should be attempted. Successful control of the thermoacoustic instability by the controller can help in the creation of robust controllers that are based on the physics of the combustion system.

Flat Flame Burner – Forced Response of Laminar Flame

- The FRF obtained from the flat flame simulation was obtained by using two-step curve fitting chemistry mechanisms. A much more rigorous investigation of flame dynamics by applying detailed chemistry modeling should be attempted.

- Different equivalence ratio and flow rate combinations should be simulated to further understand the flame dynamics process. Flame dynamics studies with different fuels including combination of fuels (Syngas, natural gas) need to be pursued to extend the understanding of flame dynamics of methane and propane to other industrial gases.

Turbulent Swirl Combustor – Forced Response of Turbulent Flame

- The swirl stabilized combustor offers several modeling challenges to the researcher. One study that needs to be pursued is the modeling of the effect of equivalence-ratio fluctuations on the unsteady heat release from the flame. Also, the effect of partially premixed combustion needs accurate modeling. Recent developments in reacting flow CFD are promising and future implementations of CFD modeling of turbulent reacting flows will yield useful information of flame dynamics.

- Vortex-flame interactions can be studied closely by investigating a vortex passing through a laminar flat flame. This study is important to fully understand the high frequency instabilities that occur in gas turbine combustors because of vortex shedding.

- An extension of gaseous premixed flame dynamics study to CFD studies of lean direct injection (LDI) combustion systems must be carried out to stay on par with the combustion community's interest in this future technology.