Lean Premixed Flame Stability Investigations

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Fellowship Experience

Throughout my twelve-week fellowship at Pratt & Whitney I had the opportunity to interact with numerous engineers and managers as well as to be exposed to a variety of disciplines and areas of engineering. My mentor, Bill Proscia, is an expert in the field of combustion instability analysis and modeling. I gained valuable experience working on a combustion project under his guidance. The project involved studying combustor aerodynamics and static stability of lean-premixed flames for two combustor geometries as a function of swirl number and fuel type. Having an almost non-existent background in the field of combustion, this was a challenging, but very rewarding project to work on.

The first few weeks consisted of meeting with engineers and managers to decide on what kind of study I could conduct that would be useful to Pratt & Whitney. During this time I also was able to learn about the business side of engineering and gain a small insight into the overall infrastructure of Pratt & Whitney. In addition to these meetings much of my time was spent reading published literature as well as textbooks on combustion, methods used for modeling combustion, combustion stability, and other related topics. These resources were a tremendous aid in understanding the challenges involved in flame stability, particularly in dry low NO_x applications. While my understanding of combustion principles is still far from that needed to work in this area of engineering, I have learned a tremendous amount since my first day thanks to the patience and help of my mentor.

Throughout the fellowship I was able to make multiple visits to Pratt & Whitney's manufacturing and testing facility. These trips allowed me the opportunity to see parts of the engine that I was working with as well as many other parts that I was familiar with from my university studies, but had never seen. I also was given the opportunity to watch an aero-engine test and see the challenges involved in testing a complex machine such as a gas turbine engine. These trips gave me a small insight into the important role of manufacturing and testing as well as their crucial interaction with engineering.

My overall experience at Pratt & Whitney was exceptional. The opportunity to experience engineering outside of the university environment was very valuable. I was also pleased with my project and the opportunity it gave me not only to learn, but also to use some of the skills I've acquired in obtaining my bachelor's degree. This experience also has given me some new ideas of the direction I might like to take in my postgraduate studies and professional endeavors. I'm hopeful that many of the associations I've been able to make during my fellowship will continue and be of great benefit in my future studies and career.

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Introduction

Lean premixed gas turbine engines are an area of continued development because of their capability to produce low NO_x emissions to meet government regulations. This project focuses on lean premixed flame stability in two combustors of differing geometries as predicted by 2-D, axisymmetric, steady, RANS computational fluid dynamics (CFD) calculations performed using FLUENT software. Swirl number was varied to look at its effect on flame stability. Two fuel types were used to investigate the effect of "H_2/CH_4" mixtures on flame stability. Methane was used to represent the standard fuel used today. Because sufficient details of true H_2/CH_4 mixtures were unavailable, the actual effect of these mixtures on flame stability is not part of this study. A change was made in the FLUENT combustion model that represents a limit case in which the effects of flame stretching are essentially eliminated. This simulated environment, termed "H_2/CH_4", may be achieved if the H_2/CH_4 mixture has a low sensitivity to flame stretch, however the properties of the actual mixture must be used in the FLUENT model before this can be substantiated.

FLUENT Preparation

Before CFD calculations could be performed a number of other processes had to be completed. My first task was to use the operating conditions of a current engine, together with the desired equivalence ratio of approximately 0.5, to determine the dimensions of the injector needed to maintain an exit velocity appropriate to prevent flashback. Additional calculations were performed throughout the project as new equivalence ratios and swirl numbers were incorporated into the study.

After some tutorial sessions with an experienced CAD user, I was able to incorporate these calculated dimensions, current drawings, and some approximations to create solid models for each of the combustor geometries using Unigraphics. Additional training took place with qualified ICEM users. ICEM is the program used at Pratt & Whitney to make the grid needed to perform CFD calculations. Following this training I was successful in making grids for my solid models. The grids were made using tetrahedral elements because they were the simplest to generate and considered adequate for this project.

FLUENT Modeling and Turbulence Model Validation

Having previously never used FLUENT, substantial time was spent learning as much as possible about how to use it including: examining the user's manual, completing a variety of tutorials that come with FLUENT, as well as considerable trial and error in running the first cases. However, the help of an expert in the field of CFD analysis at UTRC during the last few weeks of case studies greatly benefited the project and its results.

The 2-D axisymmetric models were solved initially with using the standard k-ε turbulence model, however the results failed to show the central recirculation zone expected from theory. The RNG turbulence model was used with slightly better results. LDV data from a previous UTRC study was used to assess and choose the appropriate turbulence model for use in this study. Three turbulence models were compared: std k-ε, RNG k-ε, and Reynolds Stress Model (RSM). Axial velocity plots from data taken at four axial locations were compared to CFD predictions and the results are shown in Figure 1.

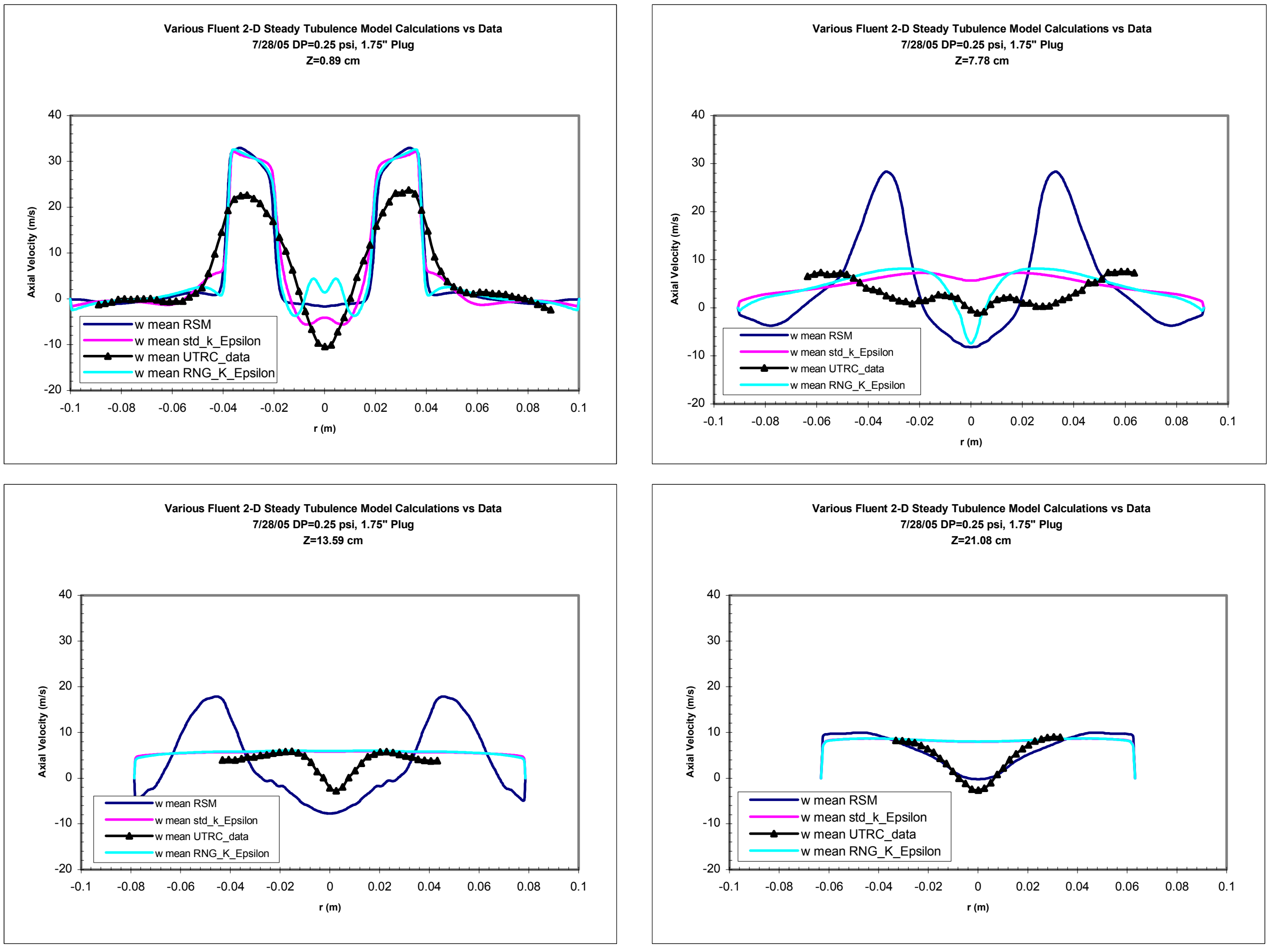

Figure 1: Axial velocity plots at four axial locations in the combustor tested

Based on these results the RSM turbulence model was selected for use in this study. This selection was made mainly because of the failure of both the std and RNG k-ε models to predict the large central recirculation zone, which is an important feature of the combustor tested, and not because it is considered to be an ideal match for the data.

The perfectly premixed combustion model in FLUENT was used to model two fuels: methane and "H_2/CH_4". The perfectly premixed model predicts flame front propagation by solving for the scalar quantity c, the reaction progress variable, in the following transport equation (see FLUENT user's manual [3] for a complete treatment of the perfectly premixed combustion theory):

$$\frac{\partial \rho}{\partial t}(\rho c) + \nabla \cdot (\rho \vec{v} c) = \nabla \cdot \left(\frac{\mu_t}{S_{c\,t}} \nabla c \right) + \rho S_c \qquad (1)$$

In order to account for the effect of flame stretching the source term in (1) (ρS_c) is multiplied by a stretch factor, G . This stretch factor represents the probability that the stretching will not quench the flame, i.e. if G =1, flame stretching will not occur. The variable G is obtained from the following equation:

$$G = \frac{1}{2} erfc \left\{ - \sqrt{\frac{1}{2\sigma}} \left[\ln\left(\frac{\varepsilon_{cr}}{\varepsilon} \right) + \frac{\sigma}{2} \right] \right\} \tag{2}$$

Through equation (2) and an additional equation not shown, the stretch factor is directly related to a variable termed the critical rate of strain (g_{cr}), which is a function of laminar flame speed. For this study the laminar flame speed of methane was known and used to find g_{cr} . However to simulate the possible benefits of "H_2/CH_4" mixtures, a limit case was used in which g_{cr} was set to 1e8 making G =1 and thus eliminating the effects of flame stretching. At the equivalence ratio of interest for low NO_x emissions this limit case represents the best possible conditions for which a flame could be stabilized.

Cases Studied

The various parameters used in comparing the two combustor geometries are shown in Table 1.

Config-1	Config-2
ϕ = 0.5, 0.6, 0.7	ϕ = 0.5, 0.6
U_l for each ϕ	U_l for each ϕ
Adiabatic Flame Temp for each ϕ	Adiabatic Flame Temp for each ϕ
g_{cr} for each ϕ for Methane	g_{cr} for each ϕ for Methane
(2800, 11201, 25031)	(2800, 11201)
g_{cr} of 1e8 at each ϕ to simulate possible "H_2/CH_4" mixture	g_{cr} of 1e8 at each ϕ to simulate possible "H_2/CH_4" mixture
Swirl Level	Swirl Level
(10, 20, 40, 80, 100%)	(10, 20, 40, 80, 100%)

Table 1: Parameters used for flame stability investigation of Config-1 and Config-2

Swirl levels used by FLUENT were converted to swirl numbers using the following equation:

$$S = \frac{2}{3} \tan\alpha \frac{1 - R^3}{1 - R^2 + m^2 \left(\frac{1}{R^2} - 1 \right)^2 R^2} \tag{3}$$

In equation (3) α represents the swirl angle, R is the ratio of center body radius over the injector radius, and m is the mass flow ratio of the unswirled mass flow over the swirled mass flow (which in this study was zero). Swirl level conversions to swirl number are shown in Table 2.

Swirl Level	Swirl Number Config-1	Swirl Number Config-2
10%	0.07	0.08
20%	0.15	0.15
40%	0.29	0.31
80%	0.58	0.61
100%	0.73	0.77

Table 2: Swirl levels converted to swirl number using Equation (3)

Results

Numerous cases were run varying the different parameters of interest. A complete treatment of each of the cases run is not provided in this report however; a summary of the results for all of the cases run is shown in Table 3.

Config-1							Config-2				
	$\phi = 0.5$		$\phi = 0.6$		$\phi = 0.7$			$\phi = 0.5$		$\phi = 0.6$	
Swirl	**Methane** $g_{cr} = 2800$	**H2/CH4** $g_{cr} = 1e8$	**Methane** $g_{cr} = 11201$	**H2/CH4** $g_{cr} = 1e8$	**Methane** $g_{cr} = 25031$	**H2/CH4** $g_{cr} = 1e8$	Swirl	**Methane** $g_{cr} = 2800$	**H2/CH4** $g_{cr} = 1e8$	**Methane** $g_{cr} = 11201$	**H2/CH4** $g_{cr} = 1e8$
No	No Flame	Partial Flame	No Flame	Tulip Flame	No Flame	Tulip Flame	No	Mushroom Flame	Tulip Flame	Mushroom Flame	Tulip Flame
10%	No Flame	Partial Flame	No Flame	Tulip Flame	No Flame	Tulip Flame	10%	Mushroom Flame	Tulip Flame	Mushroom Flame	Tulip Flame
20%	No Flame						20%	Mushroom Flame			
40%	No Flame	Partial Flame	No Flame	Tulip Flame	No Flame	Tulip Flame	40%	Mushroom Flame	Tulip Flame	Mushroom Flame	Tulip Flame
80%	No Flame	Partial Flame	No Flame	Tulip Flame	Lifted Flame	Tulip Flame	80%	Mushroom Flame	Tulip Flame	Mushroom Flame	Tulip Flame
100%	No Flame	Partial Flame	No Flame	Tulip Flame	Lifted Flame	Tulip Flame	100%	Mushroom Flame	Tulip Flame	Mushroom Flame	Tulip Flame

Table 3: Summary of results for cases run using both geometries.

Results show that for $\phi = 0.5$ the Config-1 geometry had no flame using methane and a partial flame using “H_2/CH_4”. The partial flame was not suitable for an operable combustor, but did illustrate the strong factor flame stretch effects have on the premixed combustion model. When the parameters were adjusted for $\phi = 0.6$, the Config-1 geometry still exhibited no flame at any swirl level using methane. However, when g_{cr} was increased to the limit case to simulate possible “H_2/CH_4” mixtures, a tulip shaped flame formed as shown in Figure 2. While this figure depicts the 100% swirl case it is representative of the flame at all swirl levels.

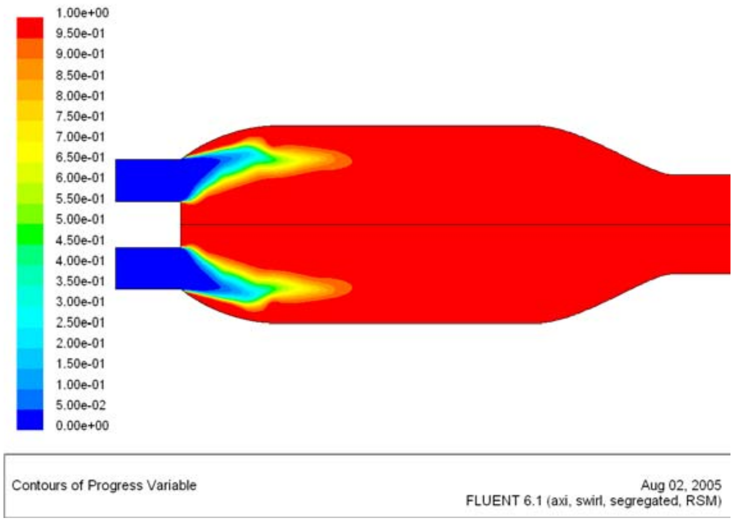

Figure 2: Progress variable contours showing tulip flame of Config-1 combustor burning "H_2/CH_4" at $\phi = 0.6$

The parameters were adjusted for $\phi = 0.7$ and the Config-1 geometry still failed to stabilize a flame using methane at low swirl levels. At 80 and 100% swirl levels a lifted flame began to form. These flames were not completely burned nor attached to the center body, however the 100% swirl case had a slightly higher amount of burned products and was closer to being attached to the center body. The lifted flame for the 100% swirl case is shown in Figure 3. In the limit case at this equivalence ratio using possible "H_2/CH_4" a stable tulip flame formed at all swirl levels almost identical to the cases with $\phi = 0.6$.

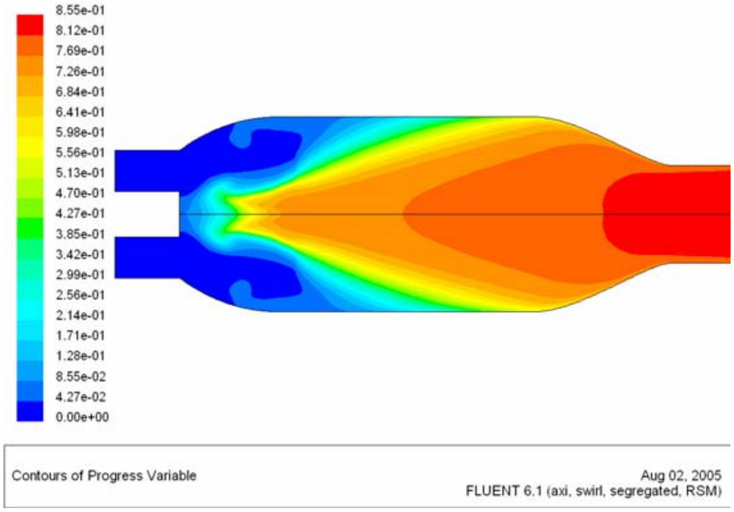

Figure 3: Progress variable contours showing lifted flame in Config-1 combustor burning methane at $\phi = 0.7$

Results for the Config-2 geometry were significantly different. At both equivalence ratios studied for this geometry (0.5, 0.6) using methane, a mushroom shaped flame formed at all swirl levels with the flame approaching stabilization on the center body as the swirl level increased. The $\phi = 0.5$, 100% swirl level case is shown in Figure 4 which is representative of the results for all swirl levels at both $\phi = 0.5$ and 0.6.

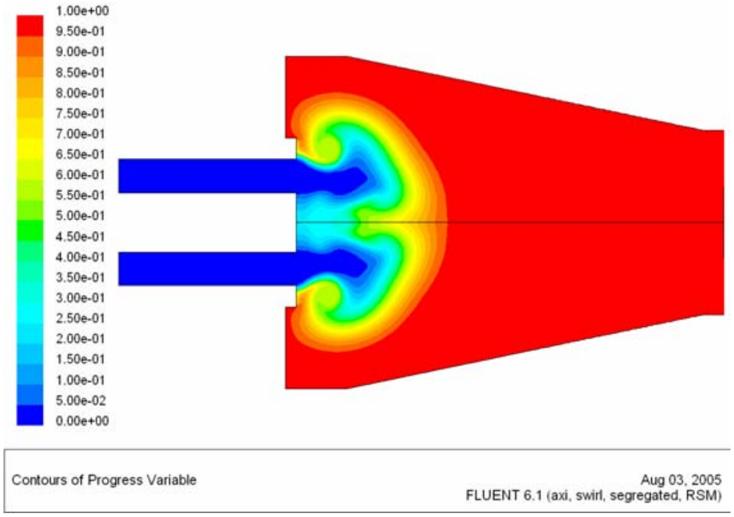

Figure 4: Progress variable contours showing mushroom flame in Config-2 combustor burning methane at $\phi = 0.5$

When g_{cr} was increased to the limit case to simulate the possible “H_2/CH_4” a tulip shaped flame formed for all swirl levels at both equivalence ratios studied for this geometry. The $\phi = 0.5$, 100% swirl level case is shown in Figure 5 which is representative of the results for all swirl levels at both $\phi = 0.5$ and 0.6.

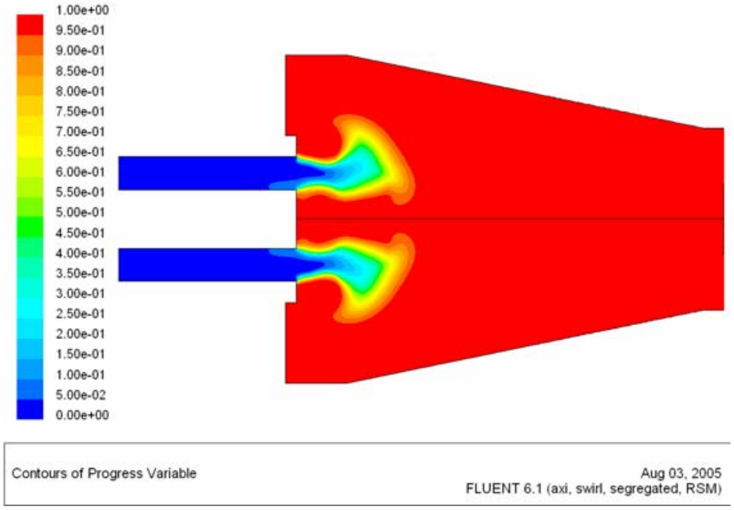

Figure 5: Progress variable contours showing tulip flame in Config-2 combustor burning “H_2/CH_4” at $\phi = 0.5$

Conclusions & Recommendations

Based on these preliminary results, lean premixed flame stability can be achieved in the Config-1 geometry, but only by increasing the equivalence ratio to 0.6 and using a fuel that has a high critical strain rate to mitigate flame stretch effects. However, because low NO_x emissions are necessary, a stable flame at the desirable equivalence ratio of 0.5 in the Config-1 would require a fuel that has a high critical strain and a modification to the geometry. The modification would need to be made in the direction of the Config-2 geometry since the outside recirculation zones present in the Config-2 geometry provide increased flame stability based on the results obtained. Flame stability can be achieved in the Config-2 geometry with the use of a fuel with a high critical strain rate, which could possibly be found in H_2/CH_4 mixtures.

Additional CFD analysis should be conducted and could include the following:

- Including chemical properties (U_l, T_{ad}, g_{cr}) of actual H_2/CH_4 mixtures
- Use of the partially premixed combustion model in FLUENT to study the effects of pilot flow in addition to the main premixer flow
- Modeling dilution and cooling air (using partially premixed combustion model)
- Investigate effects of mesh size on results as well as changing from tetrahedrals to hexahedrals or other preferred shapes
- Changing from 2-D steady RANS to 3-D unsteady LES modeling

References

[1] FLUENT Inc, “Modeling Premixed Combustion”, User’s Manual. (2003) Section 15.2.