

RCL[®] Premixer Optimization

2007 UTSR Project

Aug 29, 2007

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Introduction

Pollution Emissions are of increasing concern in the United States as their hazardous effects have become better understood. Nitrogen Oxides (NO_x) are of particular interest and are known to increase ground level ozone, damage plant life, and contribute to acid rain. To deal with these health and environmental concerns, the U.S. government has imposed increasingly strict emissions regulations in the past 15 years. In 2005, The U.S. Environmental Protection Agency (EPA) issued the Clean Air Interstate Rule (CAIR), which requires a 70% reduction of NO_x for a large portion of the U.S. (28 states) by 2015. The proposed method of this pollution reduction is through the power generation industry, of which the gas turbine industry is a key player [1].

Three proven methods of reducing NO_x formation in gas turbine combustors listed in order of influence include: lowering the adiabatic flame temperature, eliminating local hot spots in the reaction, and minimizing the total NO_x formation time. NO_x formation is controlled largely by the adiabatic flame temperature and is significant at temperatures above 1575°C. NO_x formation increases exponentially with temperature making it by far the most influential factor affecting emissions. Local hot spots in the reaction are prevalent when combustion of a non-homogeneous fuel/air mixture occurs. Each local hot spot can have NO_x formation rates many times greater than the average, which make them large contributors to the total NO_x production. NO_x rate of formation is generally constant for a given flame temperature so twice the residence time means twice the NO_x [2].

Lean premixed combustion is the current leading low NO_x gas turbine technology and has been able to produce NO_x levels below 9 ppm. The guiding principle is to operate the combustor at the lowest temperatures possible, which is at lean conditions approaching the flame blowout limit. These combustors are typically operated at temperatures higher than 1525°C in order to achieve acceptable flame stability and margin from blowout. Catalytic combustion has the potential to take low emission gas turbines to new lows. A catalytic combustor has a much reduced flame blowout limit and can reduce thermal NO_x by maintaining far lower temperatures and sustain NO_x emissions below 3 ppm [3].

A catalyst is a substance that accelerates a chemical reaction and is not consumed in the process. Precious metals such as palladium are used as catalyst materials for catalytic combustion applications. The fuel and air react on contact with the catalytic material and fuel oxidation with heat release occurs. Catalytic combustion differs from regular gas phase premixed combustion in that it is a flameless process that is stable outside the normal flammability limits of fuel-air mixtures. This allows combustion to occur at leaner or richer conditions than is otherwise possible, which results in the possibility of operating at reduced adiabatic flame temperatures and NO_x levels [2].

Complete combustion is not currently feasible for catalytic combustors due to material limitations of the catalyst substrate. The substrate is the backbone onto which the catalyst is applied and must withstand huge thermal stresses. The most suitable substrate materials are limited to temperatures under 950C to ensure sufficient strength and longevity of life [4]. While complete catalytic combustion is not possible due to the inherent high temperatures involved, partial catalytic combustion is possible and produces substantial NO_x reductions.

Precision Combustion Inc. (PCI) has developed a catalytic combustor using a two stage Rich Catalytic Lean Burn RCL[®] cycle. A schematic of this cycle can be seen in Figure 1. At the inlet, air is split into two streams. One air stream is reacted with fuel in the catalyst bed while the other stream is used to cool the catalyst bed. This reaction occurs under fuel rich conditions and is the first stage. Operating fuel rich allows the extent of reaction and thus the temperature at the catalyst to be controlled by limiting the oxygen in the mixture. The relatively low temperatures maintained in the catalytic reactor are necessary to ensure stable long-term reactor operation.

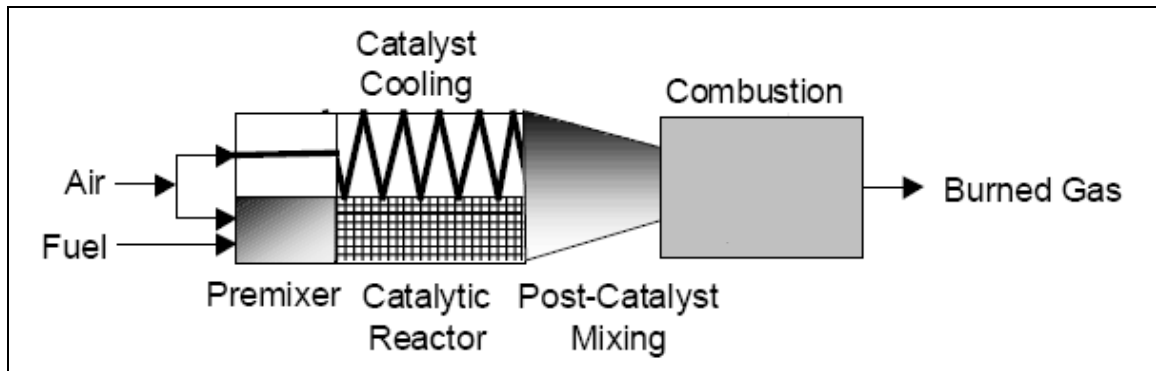


Figure 1. Schematic of PCI's two-stage RCL[®] catalytic combustor.

In the second stage, the cooling air that was used to cool the catalyst materials is mixed with the partially reacted fuel/air mixture to create a fuel lean mixture. After complete homogeneous mixing has occurred, the lean mixture is auto-ignited in regular gas phase combustion. This method produces complete combustion with low single digit NO_x levels which are far below levels currently possible with lean premixed combustion.

Project Description

The project consisted of optimizing the design of a RCL[®] Premixer in terms of the fuel/air mixing performance in order to reduce NO_x emissions. The premixer base geometry was to be maintained, although the inlet fuel hole location, angle, and size could be adjusted. The optimal design was to maximize the fuel/air mixing while maintain the manufacturability of the fuel injector. Both coaxial and cross flow injection were to be explored as well as full and part loading effects on performance.

Theory

Mixing performance has a large impact on NO_x formation in both catalytic and lean premixed combustion. Poorly mixed streams have large gradients in the fuel to air ratio across the mixture, which result in large temperature gradients once combustion has begun. These undesirable high temperature regions produce large amounts of thermal NO_x. The control strategy for this project is to reduce NO_x formation by optimizing mixing performance.

For this project a term called the “unmixedness” was used to quantify the mixing performance and was defined as the standard deviation of the fuel to air ratio divided by the average fuel to air ratio as shown in equation 1. A zero percent unmixedness corresponds to a perfectly mixed stream. It was desired to minimize this parameter at the exit of the RCL[®] premixer.

$$unmixedness = \frac{\text{standard deviation}(F/A)}{\text{average}(F/A)} \quad (1)$$

Overview of Studies Performed & Grid

Five studies involving 31 individual CFD cases were performed to optimize the mixing of air and methane in an external RCL[®] Premixer. These studies are shown in Figure 1 and include: Air Mass Flowrate Inlets vs. Pressure Inlets, Angled Fuel Holes, Horizontal Holes, Alternative Loading Performance, & Grid Refinement. The premixer was simulated using a 3-D axisymmetric model. The geometry was simplified to 6° of axial rotation and a k-epsilon model was used for turbulence modeling.

The meshes used for all but the Grid Refinement study had identical grid spacing. These meshes had a spacing of .02in downstream & .015in upstream of fuel injector nose, and each contained between 123,000 – 136,000 cells. The downstream contained hexagonal cells while the upstream contained tetrahedral cells. The Initial configuration mesh is shown in Figure 2. The equiangle & equivolume skewness of each grid was checked and found to be between 0.5 and 0.8, which satisfies Fluent's recommended equiskewness requirement of being less than .98 [5].

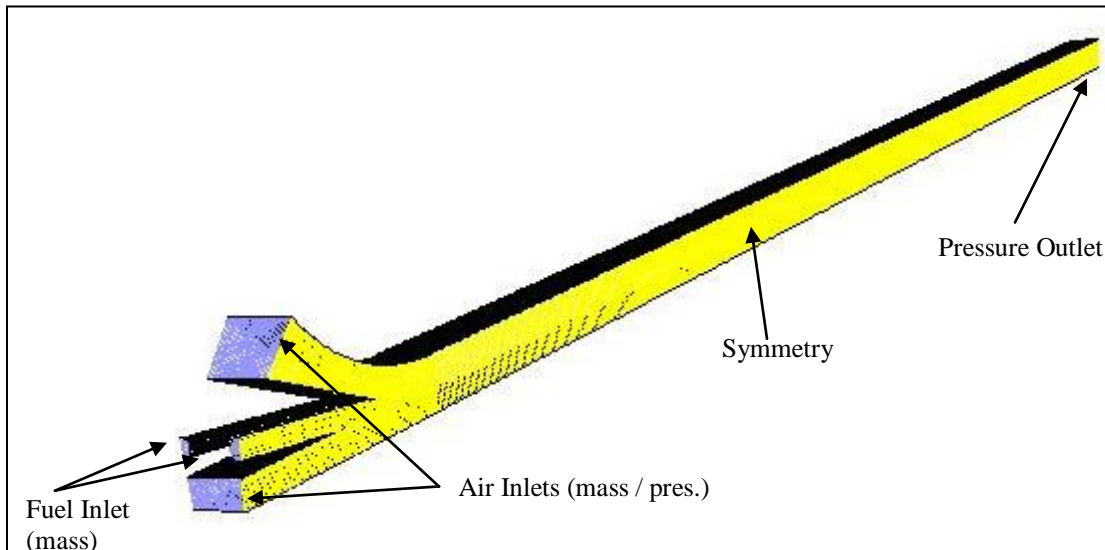


Figure 2. Diagram showing boundary types on the Initial configuration grid.

Air Mass Flowrate Inlet vs. Pressure Inlet Study 1

- 3 - Mass Flowrate Inlet Cases (50/50 split to top & bottom)
 - Initial Config.....(case 1)
 - Wide Alter. Holes(case 2)
 - Narrow Holes.....(case 3)
- 5 - Pressure Inlet Cases
 - No Fuel.....(case 4)
 - Initial Config.....(case 5)
 - Wide Alter. Holes.....(case 6)
 - Narrow Holes.....(case 7)
 - Wide Top Holes.....(case 8)

Angled Fuel Holes Study 2

- 4 - Wide Alternating Hole Cases at various angles (pres. inlet)
 - 90°.....(case 9)
 - 45°.....(case 10)
 - 30°.....(case 11)
 - 15°.....(case 12)
- 4 - Narrow Hole Cases at various angles (pres. inlet)
 - 90°.....(case 13)
 - 45°.....(case 14)
 - 30°.....(case 15)
 - 15°.....(case 16)

Horizontal Holes Study 3

- 5 - Wide Hole Cases at various positions (pres. inlet)
 - Horizontal High.....(case 17)
 - Horizontal Middle.....(case 18)
 - Horizontal Low.....(case 19)
 - Horizontal Alter. High & Low.....(case 20)
 - Alter. Horizontal Low/45°.....(case 21)
- 1 - Narrow Hole Case (pres. inlet)
 - Horizontal Low.....(case 22)

Alternative Loading Level Study 4

- 2 - No Fuel Cases at alternative loadings
 - 75% loading.....(case 23)
 - 50% loading.....(case 24)
- 2 - Initial Config. at alternative loadings (pres. inlet)
 - 75% loading.....(case 25)
 - 50% loading.....(case 26)
- 2 - Best Configuration Case at alternative loadings
 - 75% loading.....(case 27)
 - 50% loading.....(case 28)

Grid Refinement Study 5

- 1 - Initial Config. refined
 - 1.1 million cells.....(case 29)
- 2 - Best Case refined
 - 1.1 million cells.....(case 30)
 - 1.8 million cells.....(case 31)

Figure 3. Diagram of different studies performed along with each individual CFD case.

Hole Configurations Studied

The Air Mass Flowrate Inlet vs. Pressure Inlet study analyzed four different configurations. Sketches of the geometries can be seen in Figure 2. The first geometry is called “Initial” and consisted of a coaxial flow style mixer where the fuel inlet ports are set to inject fuel parallel to the bulk air flow. This was the geometry to which performance comparisons were made. The second geometry is “Wide Alternating Holes” and contains holes of the same area as the Initial configuration that alternate from top to bottom on the fuel injector axially every 6° . The third geometry is named “Narrow Upper & Lower Holes” and contains holes that each have half the area of the Initial holes and occur axially every 6° . The last geometry is called “Wide Top Holes” and has the same hole size and location as the Wide Alternating Holes case except that the holes are only on the top side of the fuel injector.

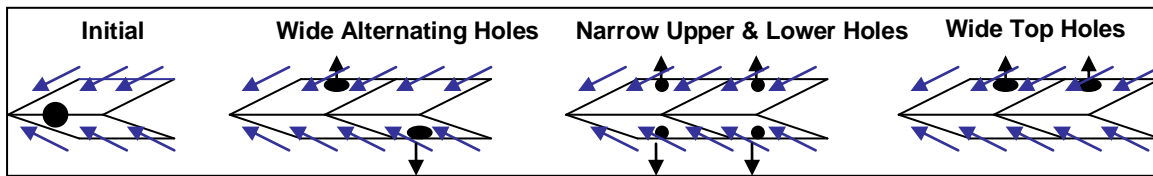


Figure 4. Sketches of fuel injection configuration for Air Mass Flowrate Inlet vs. Pressure Inlet study.

The Angled Fuel Holes study used different projected area configurations for four different angles. Both Wide and Narrow hole sizes were used at 90° , 45° , 30° , and 15° . These angles were measured from the downstream side of the upper and lower fuel injector faces and can be seen in Figure 3.

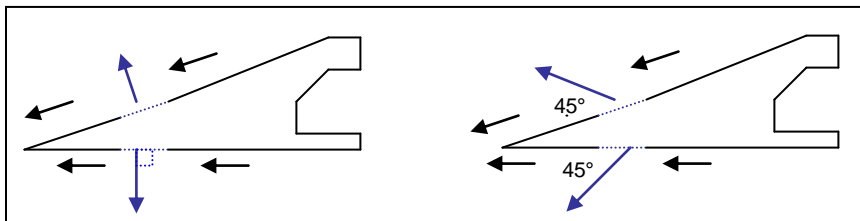


Figure 5. Sketches of fuel injector geometry at 90° and 45° fuel injection cases.

The Horizontal Holes study mostly explored variations of horizontal holes due to their ease of manufacture. Three cases were performed on wide holes at different vertical heights designated as Low, Center, & High as shown in Figure 4. A case was performed with narrow holes at the low vertical position and another was performed with a wide hole that was alternating between the horizontal low and 45° hole position.

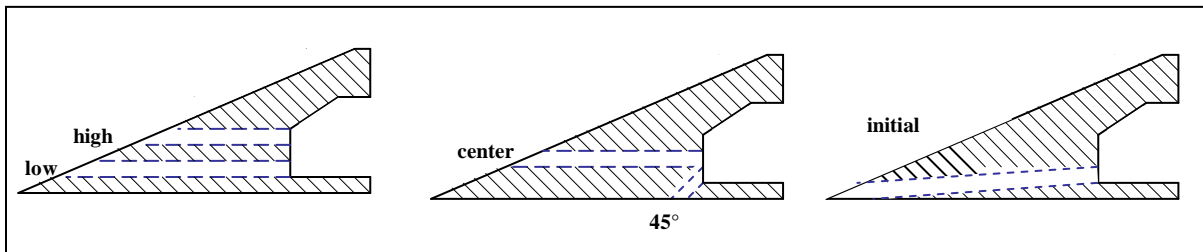


Figure 6. Sketches of fuel injector hole locations for Horizontal Holes Study.

Study 1: Air Mass Flowrate Inlets vs. Pressure Inlets

Objective: Study 1

The objective of the Air Mass Flowrate Inlet vs. Pressure Inlet study was to gain some intuition into the effects of introducing cross flow fuel injection into the RCL[®] premixer geometry and also to compare the unmixedness when using mass flowrate inlets to pressure inlets. The individual cases ran can be seen in Figure 5.

Air Mass Flowrate Inlet vs. Pressure Inlet Study 1	
3 - Mass Flowrate Inlet Cases (50/50 split to top & bottom)	
- Initial.....	(case 1)
- Wide Alter. Holes	(case 2)
- Narrow Holes.....	(case 3)
5 - Pressure Inlet Cases	
- No Fuel.....	(case 4)
- Initial.....	(case 5)
- Wide Alter. Holes.....	(case 6)
- Narrow Holes.....	(case 7)
- Wide Top Holes.....	(case 8)

Figure 7. Sketches of individual CFD cases ran for Study 1.

Results and Discussion: Study 1

The air mass flowrate inlet & pressure inlet cases showed considerable improvement in mixing performance for the cross flow cases. The unmixedness data is seen in Figures 7 and 8. The performance of the pressure inlet cases showed marginal similarity with the mass flowrate cases. It was observed that the fuel inlet hole configuration largely affected the total air inlet mass flowrate. The results can be seen in Table 2. It was highly undesirable for the inlet mass flowrate of air to undergo large changes from the no fuel case because these change the inherent combustion characteristics of the mixture. The inlet pressure also cannot be easily changed or adjusted on the hardware to compensate for the change in air mass flowrate.

Table 1. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for pressure inlet case. The sign denotes whether the air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff (%)	total air diff (%)
Initial	0.8	2.8	1.6
Wide Alternating Holes	-25.7	-31.7	-28.1
Narrow Holes	-24.8	-31.2	-27.4
Wide Top Holes	-51.8	7.9	-27.2

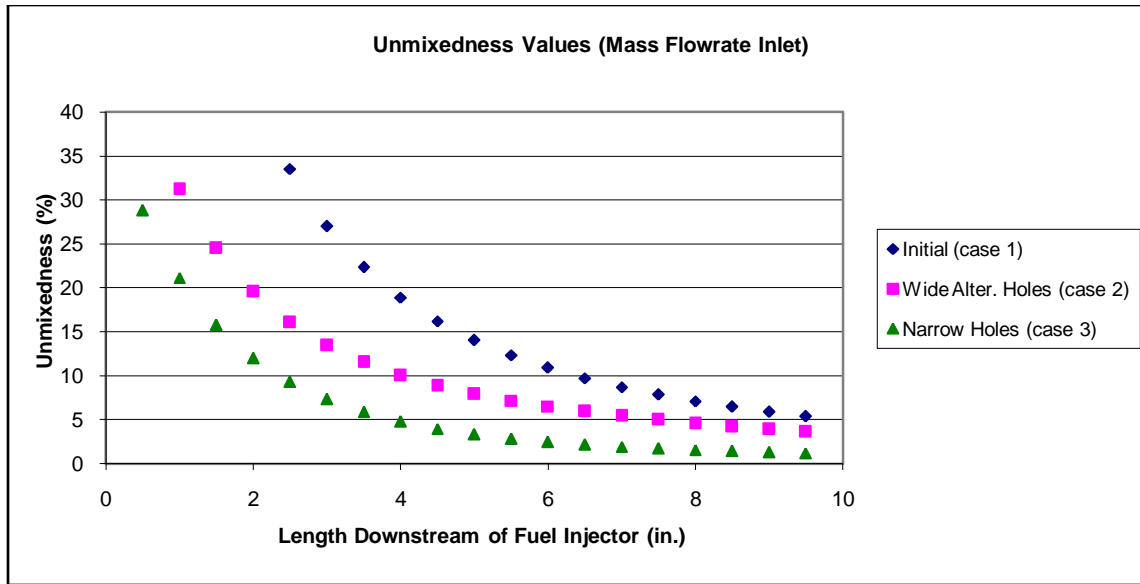


Figure 8. Unmixedness for air mass flowrate inlet cases of study 1.

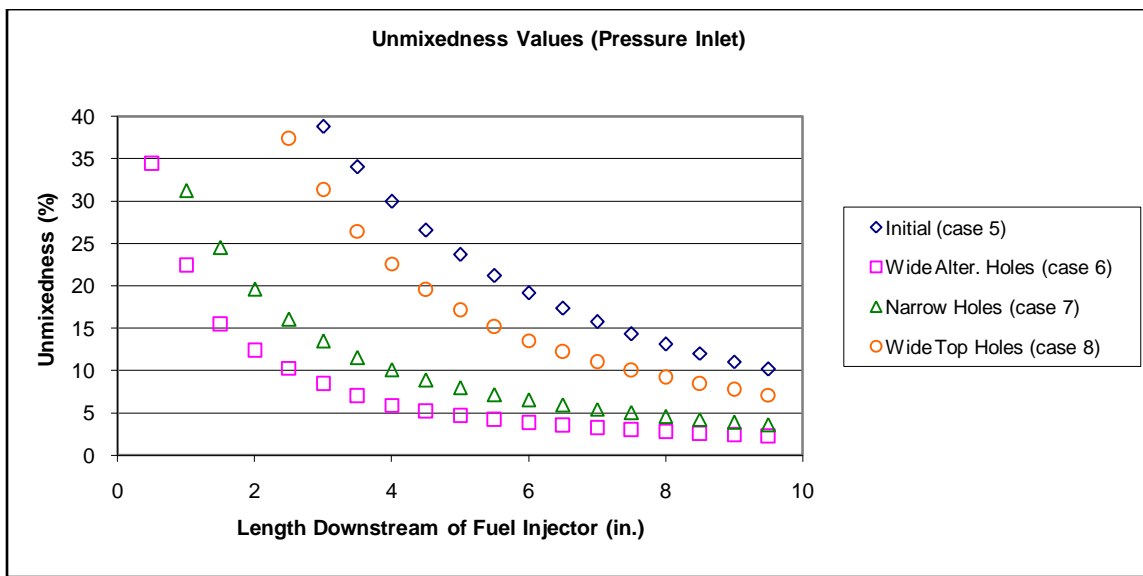


Figure 9. Unmixedness for pressure inlet cases of study 1.

Conclusions: Study 1

This study showed promising results by demonstrating that drastic mixing improvements are possible by altering the fuel inlet hole configuration. Conversely it was found that attempting to inject the fuel into the air in a cross flow manner with the given geometry carries with it the undesirable effect of changing the total inlet mass flowrate of air. This drawback is substantial and changes the combustion characteristics of the mixture. The inlet pressures also cannot be readily adjusted on the actual setup to compensate for the decrease in air mass flowrate.

Study 2: Angled Fuel Holes (Pressure Inlets)

Objective: Study 2

The objective of the Angled Fuel Holes study was to gain some intuition about the fuel injection model with regards to the influence of the fuel injection angle and number of holes on the mixing performance and the resultant mass flowrate of air. The individual cases ran can be seen in Figure 9. The angles are measured from the fuel injector face on the downstream side of the hole.

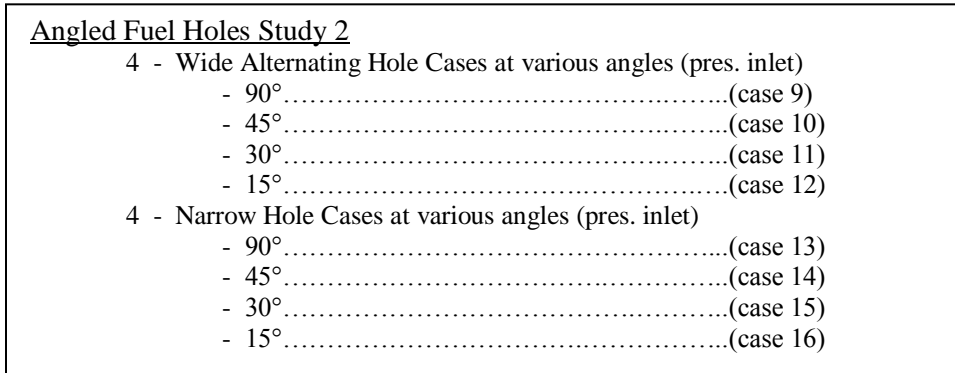


Figure 10. Diagram showing the individual CFD cases ran for study 2.

Results and Discussion: Study 2

The Angled Fuel Holes study showed very similar trends between the wide and narrow hole cases. The unmixedness and total inlet mass flowrate of air results can be seen in Figures 10 & 11, and Tables 3 & 4. In general, the narrow holed cases had better mixing performance than the wide holed cases although this was not true for all ranges of every case and especially not for the 90° case.

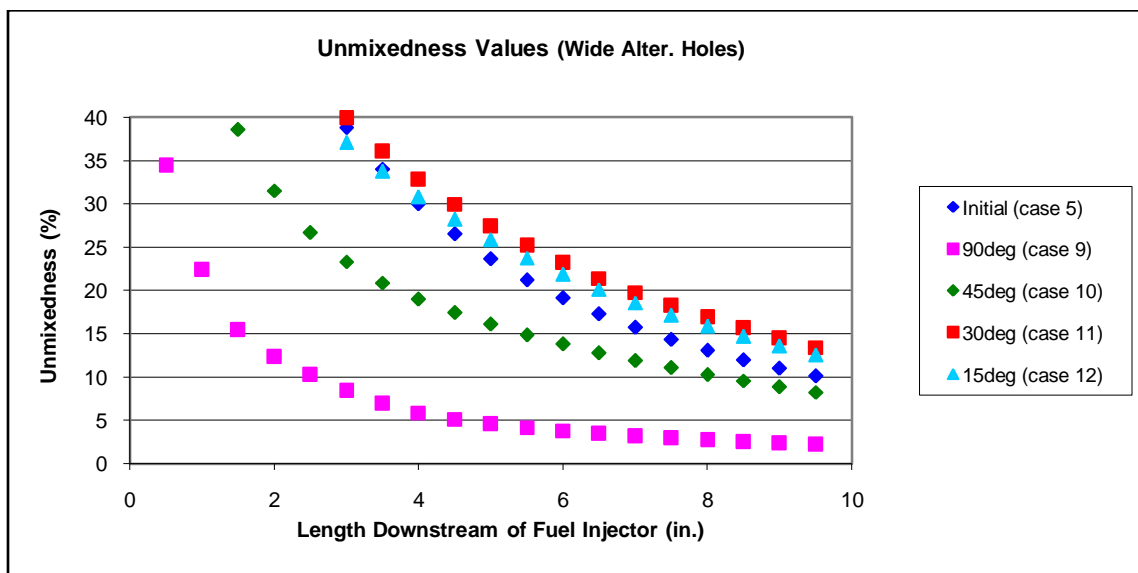


Figure 11. Unmixedness for Wide Alternating Hole cases at various angles for study 2.

Table 2. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff (%)	total air diff (%)
Initial	+ 0.8	+ 2.8	+ 1.6
Wide Alter. Holes 90 deg	-25.7	-31.7	-28.1
Wide Alter. Holes 45 deg	-7.5	-7.9	-7.6
Wide Alter. Holes 30 deg	-2.6	-3.8	-3.1
Wide Alter. Holes 15 deg	+ 1.0	-1.6	-0.1

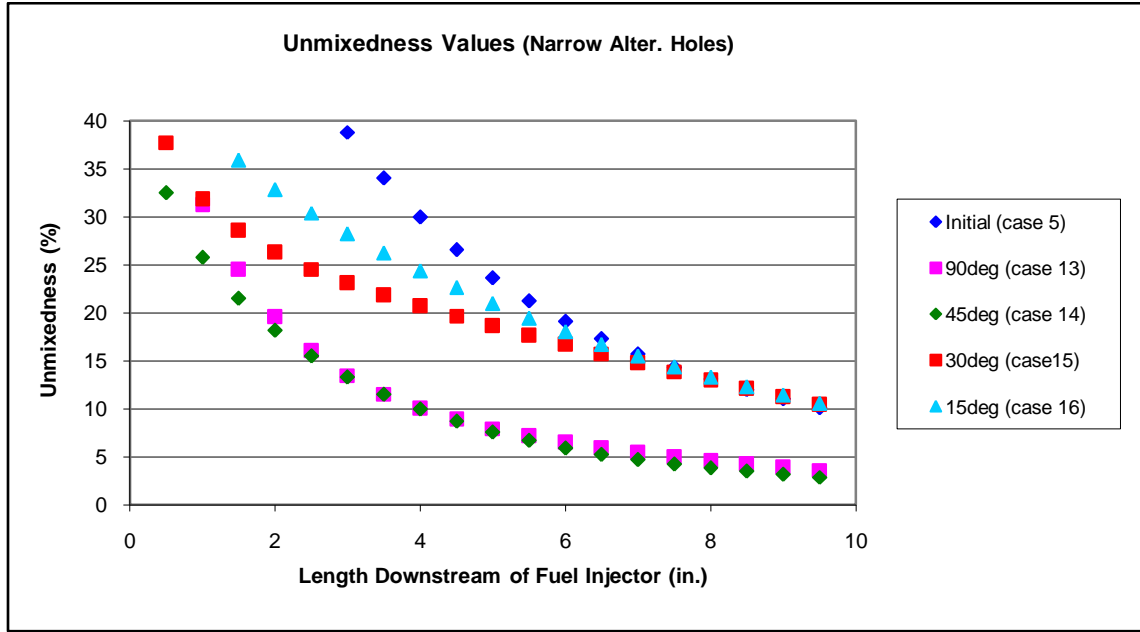


Figure 12. Unmixedness for narrow hole cases at various angles for study 2.

Table 3. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff (%)	total air diff (%)
Initial	+ 0.8	+ 2.8	+ 1.6
Narrow Holes 90 deg	-24.8	-31.2	-27.4
Narrow Holes 45 deg	-6.5	-6.0	-6.3
Narrow Holes 30 deg	-2.0	-2.5	-2.2
Narrow Holes 15 deg	+ 0.8	-0.2	+ 0.4

Conclusions: Study 2: Angled Fuel Holes (Pressure Inlets)

This study showed that for the configuration studied, there is a tradeoff between mixing performance and the deviation of the total inlet mass flowrate of air from the baseline case. It is understood that this tradeoff may or may not exist if the holes are placed at different locations on the fuel injector. Overall the Narrow Hole cases outperformed the Wide Hole cases.

Study 3: Horizontal Holes

Objective: Study 3

The objective of study 3 was to test different horizontal hole configurations with respect to mixing performance and resultant mass flowrate of air. Horizontal hole geometries were primarily explored since they can easily be drilled into the injector from the upstream side. The individual cases ran can be seen in Figure 13.

Ease of Manufacture Study 3	
5 - Wide Hole Cases at various positions (pres. inlet)	
- Horizontal High.....	(case 17)
- Horizontal Middle.....	(case 18)
- Horizontal Low.....	(case 19)
- Horizontal Alter. High & Low.....	(case 20)
- Alter. Horizontal Low/45°.....	(case 21)
1 - Narrow Hole Case (pres. inlet)	
- Horizontal Low.....	(case 22)

Figure 13. Diagram showing the CFD cases ran for study 3.

Results and Discussion: Study 3

The Horizontal Holes study showed promising results for the wide horizontal low hole configuration which outperformed all previous cases ran. The unmixedness and total mass flowrate of air can be seen in Figures 13 & 14, and Tables 5 & 6. The wide horizontal low hole configuration had the lowest unmixedness and also a very close total inlet mass flowrate of air as the baseline case.

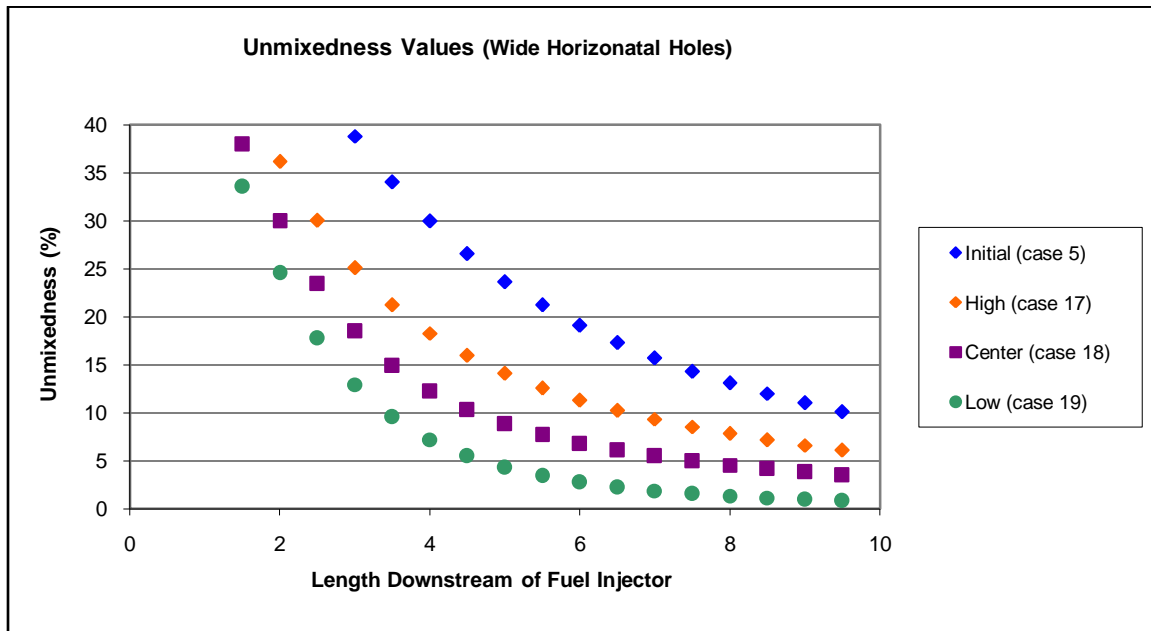


Figure 14. Unmixedness for wide horizontal holes at different heights of study 3.

Table 4. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff. (%)	total air diff. (%)
Initial	+ 0.8	+ 2.8	+ 1.6
Wide High	+ 7.2	-7.3	+ 1.2
Wide Center	+ 7.7	-7.1	+ 1.6
Wide Low	+ 6.5	-5.3	+ 1.7

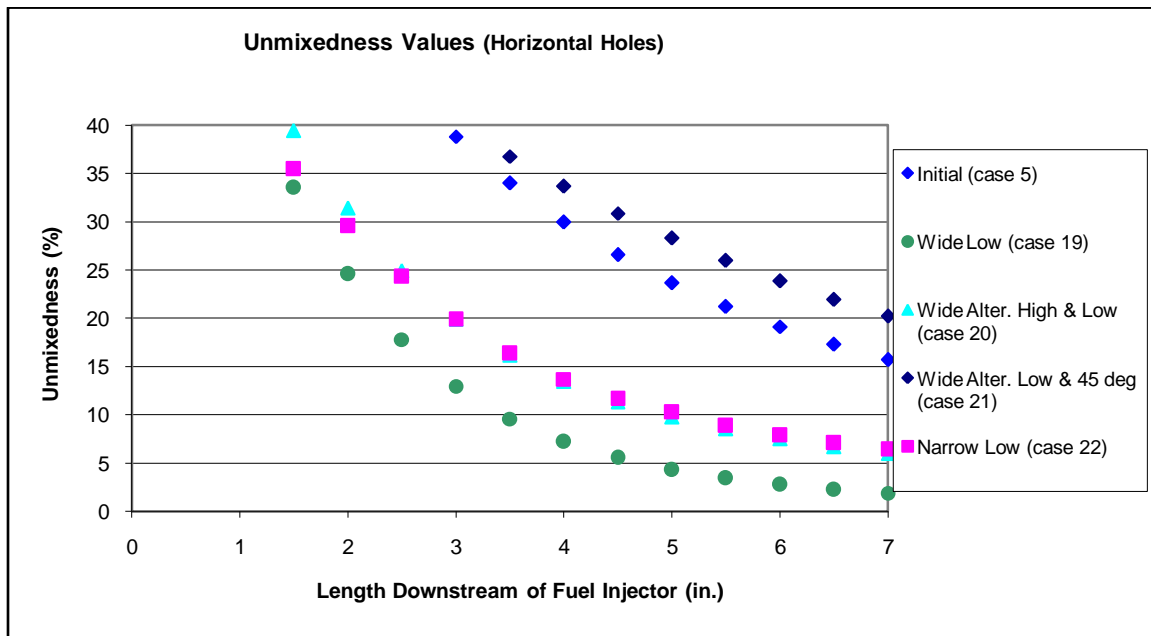


Figure 15. Unmixedness values for various configurations of study 3.

Table 5. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff. (%)	total air diff. (%)
Initial	+ 0.8	+ 2.8	+ 1.6
Wide Low	+ 6.5	-5.3	+ 1.7
Wide Alter. High & Low	+ 6.9	-6.1	+ 1.6
Wide Alter. Low & 45 deg	-0.1	-6.1	-2.6
Narrow Low	+ 12.4	-10.0	+ 3.2

Conclusions: Study 3

The wide horizontal low hole configuration outperformed all previous cases run and is selected as the best case. This simple configuration incorporates the same hole size and number of holes as the current RCL premixer configuration, but improves the mixing performance considerably. This case was selected for further investigation to determine mixing performance at alternative loading levels.

Study 4: Alternative Loading Performance

Objective: Study 4

The objective of study 4 was to test the best configuration case to determine the mixing performance at different loading levels of interest. The individual cases ran can be seen in Figure 15. Both fifty and seventy five percent loading conditions were selected since these are of interest to the gas turbine community.

Alternative Loading Level Study 4	
2 - No Fuel Cases at alternative loadings	
- 75% loading.....	(case 23)
- 50% loading.....	(case 24)
2 - Baseline Case at alternative loadings (pres. inlet)	
- 75% loading.....	(case 25)
- 50% loading.....	(case 26)
2 - Best Configuration Case at alternative loadings	
- 75% loading.....	(case 27)
- 50% loading.....	(case 28)

Figure 16. Diagram showing the CFD cases ran for study 4.

Results and Discussion: Study 4

The unmixedness values were fairly constant at the three different loadings, and the total air mass flowrate matched the baseline case extremely well. The unmixedness and total mass flowrate of air can be seen in Figure 16 and Table 7. The total mass flowrate for the alternative loading cases matched the baseline very well.

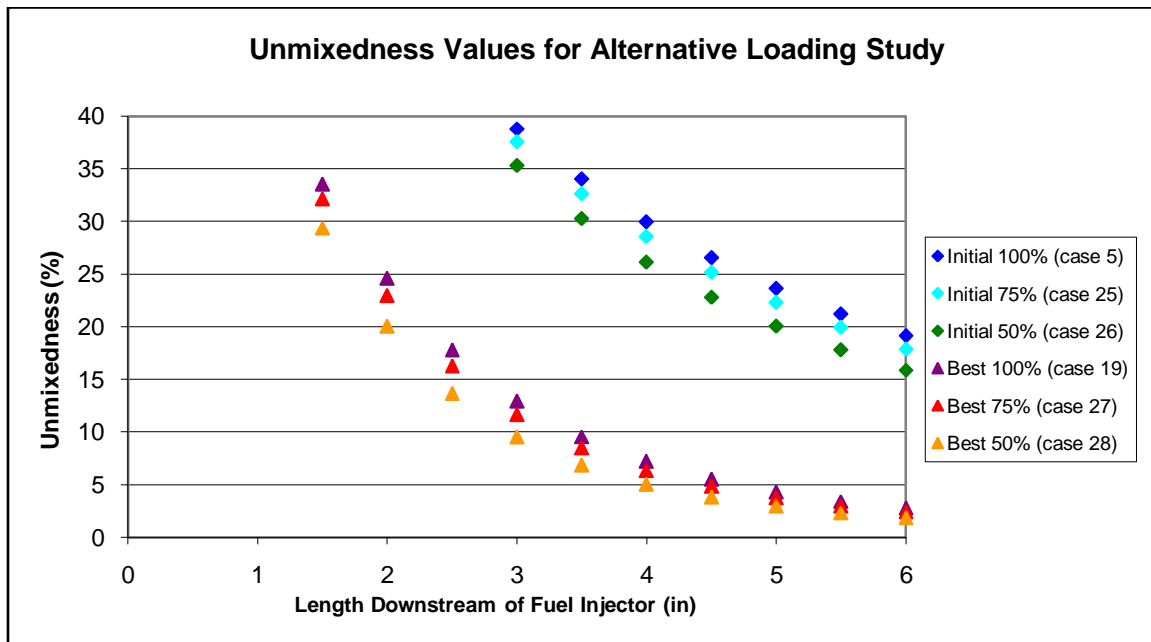


Figure 17. Unmixedness values for Initial and Horizontal Wide Low case at 100%, 75%, and 50% loadings of study 4.

Table 6. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff (%)	total air diff (%)
Initial 100%	0.8	2.8	1.6
Wide Low 100%	6.5	-5.3	1.7
Initial 75%	1.4	3.6	2.3
Wide Low 75%	7.8	-5.2	2.5
Initial 50%	2.5	5.1	3.6
Wide Low 50%	10.3	-5.4	3.9

Conclusions: Study 4: Alternative Loading Performance

The horizontal wide low hole configuration showed very good unmixedness performance at 50 and 75 percent loading. The horizontal wide low alternative loading cases showed a different air mass flowrate split to the top and bottom inlets from the baseline case, but the total air mass flowrate of air was matched extremely well. The configuration was concluded to be ready for a grid refinement study to validate the results.

Study 5: Grid Refinement

Objective: Study 5

The objective of study 5 was to verify the results for the best case by performing a grid refinement study. The individual cases can be seen in Figure 17. For this study the best case configuration was run on a very fine grid. The coarse grid was determined to be sufficiently refined if the results of the coarse and the fine were very close.

Grid Refinement Study 5

- 1 - Initial refined (1.1 million cells).....(case 29)
- 2 - Best Case refined
 - 1 - (1.1 million cells).....(case 30)
 - 1 - (1.8 million cells).....(case 31)

Figure 18. Diagram showing the CFD cases ran for study 5.

Results and Discussion: Study 5

The unmixedness and mass flowrate of air results of the fine and coarse grids for both configurations matched well. The results can be seen in Figure 18 and Table 8. The baseline configuration unmixedness values matched well. The best case coarse configuration had a small difference in unmixedness from the first refinement, but a second refinement was shown to match the first one very well for the range of interest. The difference in mass flowrate of air was negligible.

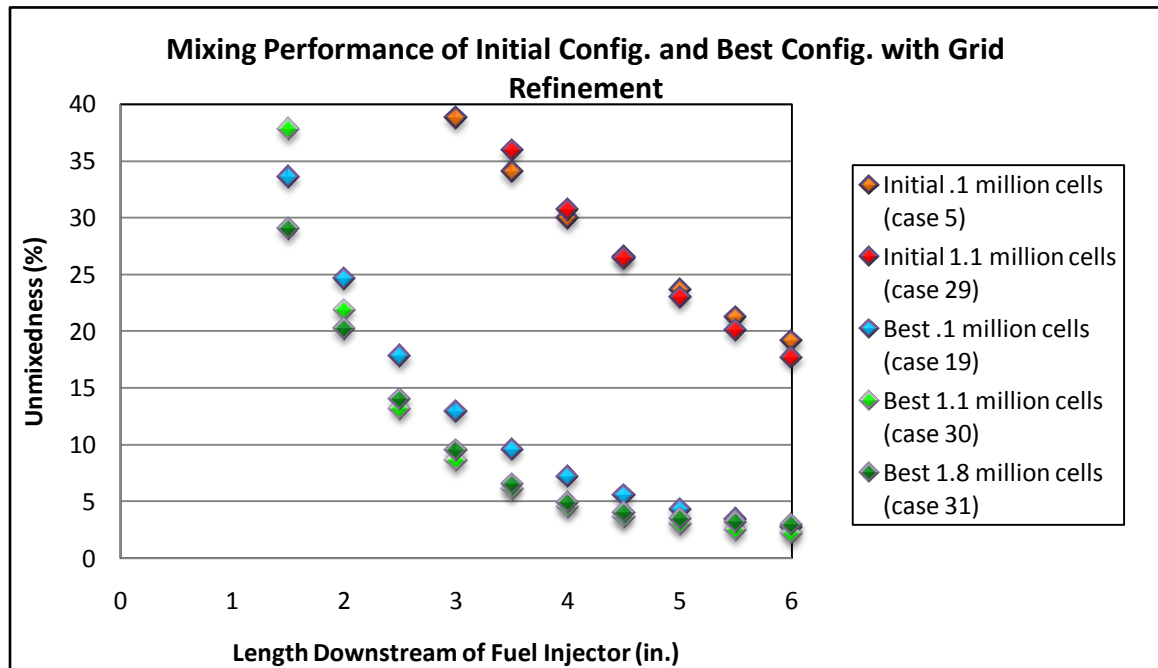


Figure 19. Unmixedness of coarse and fine grids of the Best & Initial cases for study 5.

Table 7. Difference in mass flowrate into top and bottom air inlets from the No Fuel case for cases ran. The sign denotes whether the mass flowrate of air is greater or less than the No Fuel case.

Case	top air inlet diff. (%)	bot. air inlet diff (%)	total air diff (%)
Initial .1 million cells	0.8	2.8	1.6
Initial 1.1 million cells	0.6	2.1	1.2
Best Case .1 million cells	6.5	-5.3	1.7
Best Case 1.1 million cells	4.8	-3.1	1.6
Best Case 1.8 million cells	4.8	-2.7	1.7

Conclusions: Study 5

The grid refinement study verified the unmixedness and air mass flowrate results for the baseline and best configuration cases. A second refinement was necessary to show a converged best case unmixedness solution. The differences in air mass flowrates for both cases were negligible.

Conclusions and Recommendations

Five different studies were performed to select and then verify a best case that optimizes mixing performance while maintains manufacturability. These studies are listed as follows: Air Mass Flowrate Inlets vs. Pressure Inlets, Angled Fuel Holes, Ease of Manufacture, Alternative Loading Performance, & Grid Refinement. The first three studies were used to select the best case. It was shown that the mass flowrate of air is highly dependent on the fuel injection hole configuration, and it is desired to maintain the same flowrate as the Initial case. This was used as an additional requirement to be met by the best case.

The wide horizontal low hole case showed very promising results and had the best mixing performance, a similar mass flowrate of air as the initial case, and would be easy to manufacture. This case was selected as the best case and achieved unmixedness levels below 5% at 4 inches downstream of the fuel injector nose. In addition, this case showed outstanding performance at 50% & 75% alternative loading levels and a grid refinement study was performed that verified its performance. It is therefore recommended that the horizontal wide low hole case be taken to the next step and be tested experimentally to validate the reliability of the CFD study.

The CFD studies suggest that the mixing performance is highly sensitive to the premixer fuel injection hole configuration. Further mixing improvements are likely through continued investigation and research in this area. Additional studies could determine which Fluent model most closely matches experimental results, and how different flow disturbances downstream of the fuel injector can improve mixing performance.

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