Effects of Spent Cooling and Swirler Angle on a 9-Point Swirl-Venturi Injector

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This paper presents multipoint lean-direct-injection (LDI) emissions results for flame tube combustion tests at an inlet pressure of 1034 kPa and inlet temperatures between 835 and 865 K; these are the combustor inlet conditions that the High Speed Research (HSR) program used for supersonic cruise. It focuses on one class of LDI geometry, 9-point swirl-venturi LDI (SV-LDI). Two parameters are compared in this paper: the use of dome cooling air and the swirler blade angle. Dome cooling air is called “spent cooling” and is at combustor inlet conditions. Three cooling variations are studied: cooling at the venturi throat, cooling at the dome face, and no cooling at all. Two swirler blade angles are studied: 45° and 60°. The HSR 9-point SV-LDI emissions are also compared to a similar 9-point SV-LDI design which was used in the later ultra-efficient engine technology (UEET) program. The HSR and UEET designs cannot be compared directly due to different UEET combustor conditions. Therefore, this paper uses previously published UEET correlation equations to make comparisons. Results show that using a 45° swirler produces lower NOx emissions than using a 60° swirler. This is consistent with the later UEET results. The effects of spent cooling depend on swirler angle, spent cooling location, and the test conditions. For the configuration with 45° swirlers, spent cooling delivers lower NOx emissions when it is injected at the throat. For the 60° swirler, spent cooling does not have much effect on NOx emissions. These results might be caused by the location and the intensity of the flame recirculation zone.

1. Introduction

Burning hydrocarbon fuel produces many effects on the environment. One of the major pollutants is nitrogen oxides (NOx). Through several complex chemical reactions, nitrogen oxides emissions have caused problems like photochemical smog, green house gas generation, as well as depletion of the protective ozone layer in the stratosphere [7]. In aircraft engines, nitrogen oxides reduction relies on advanced combustor design. Low-NOx combustor designs have been investigated by NASA in collaboration with engine and fuel injector companies since the 1970s; since the 1990s, NASA has investigated Lean Direct Injection (LDI) combustion concepts. The LDI concept is designed to burn fuel as lean as possible to avoid high flame temperatures because NOx emissions are an exponential function of combustion flame temperature. To avoid local hot spots, fuel is mixed with air as quickly as possible. In order to avoid the problems of flashback and premature autoignition that plague premixed lean combustion concepts at high temperatures and pressures, in LDI fuel is injected directly into the combustion zone.

The LDI geometry that is studied in this paper is called 9-point Swirl-Venturi. With this geometry, fuel is injected into the combustor through nine small fuel injectors. Each injector is accompanied by an air swirler that generates highly turbulent air to break up the fuel and promote quick mixing. Throughout this paper the fuel injector and air swirler will be referred to as an “element” or a “fuel/air mixer.”

These experiments were conducted in a flame-tube combustor at high-speed-research (HSR) supersonic cruise conditions. Two parameters were investigated in this study: the use of cooling air and the swirler blade angle. The cooling air is called “spent cooling” and is injected at combustor inlet conditions. Flame produced by this LDI geometry has a very short flame length (~25-mm) [3]. To address the concern that the flame would be too close to the dome and damage the hardware, spent cooling air is applied. There are two spent cooling variations and a configuration with no spent cooling. The effects of these spent cooling methods on NOx emissions were studied with injectors that configured of either 45° or 60° blade angle swirlers.

Four configurations were compared in this report: 45° blade angle swirlers with both types of spent cooling, 60° blade angle swirlers with one type of spent cooling, and 60° blade angle swirlers with no spent cooling. These HSR 9-point SV-LDI emission results were also compared to those from a similar 9-point SV-LDI design which was used in the later ultra-efficient engine technology (UEET) program. The HSR and UEET designs could not be compared directly due to different UEET combustor conditions. Instead, two previously published UEET correlation equations were used to predict the NOx values at HSR conditions, and then both results were compared with each other.

2. Experimental Setup and Procedure

All the tests were conducted in CE-5, a flame-tube combustion test facility at the NASA Glenn Research Center [2]. A drawing of the CE-5 flame-tube is shown on Figure 1. Nonvitiated air was pre-heated to a maximum temperature of 865 K and a maximum pressure of 1380 kPa. Commercial Jet-A aviation fuel was used. The fuel flow rate was measured by a turbine meter, and air flow rate was measured by a venturi meter. The fuel-air mixture was injected into a flame tube that contains ceramic liners with no liner cooling. A gas probe was placed downstream of the injector to collect combustion products for analysis. The rest of the combustion products were cooled down to 450 K by mixing with sprayed water before exiting to a low pressure exhaust system. The combusted gas samples were analyzed according to the standard gas-analysis procedure, SAE-ARP1256 [5]. As for NO and NO_2, the simultaneous chemiluminescence method was used.

The SV-LDI module described here contains 9 identical fuel/air mixers in a 3x3 array occupying a 76.2-mm by 76.2-mm square area, as shown in Figure 2. The 9 fuel/air mixers replace a single conventional fuel injector. Each fuel/air mixer consists of an air passage with a helical axial air swirler followed by a converging-diverging venturi section (see Figure 2a). For the HSR SV-LDI configurations, the swirlers have 5 blades; for the UEET configurations, the swirlers have 6 blades. A simplex fuel injector is inserted through the center of the air swirler; the fuel injector tip is at the venturi throat.

Two types of spent cooling are used in the HSR SV-LDI configurations: cooling at the dome face ("straight through") and cooling at the venturi throat ("at throat"). For both types of spent cooling, the cooling air was at the combustor inlet conditions. Figure 2b shows straight through spent cooling (ST). For straight-through spent cooling, 4 holes were drilled straight-through the dome plate in between the nine elements. Figure 2c and 2d show spent cooling at the throat (AT). For cooling at the venturi throat, the cooling air was split among the nine elements. Four small holes were used to cool the center element, and one larger hole was applied in the venturi throat for other eight elements.

No spent cooling was used in any of the UEET 9-point configurations. The correlations that were used to calculate the UEET NOx emissions are given in equations (1) and (2). For the UEET configuration with 45° swirlers [6]:

$$EINOx = 0.11 * {P_3}^{0.59} * e^{\frac{T_3}{194}} * \Phi^{5.07} * \left(\frac{\Delta P}{P}\%\right)^{-0.56} \tag{1}$$

For the configuration with 60° swirlers:

$$EINOx = 0.013 * {P_3}^{0.59} * e^{\frac{T_3}{194}} * \Phi^{1.69} * \left(\frac{\Delta P}{P}\%\right)^{-0.56} \tag{2}$$

Equations (1) and (2) were used to predict the UEET 9-point NOx emissions at the HSR inlet temperatures, inlet pressures, equivalence ratios, and mass flow rates.

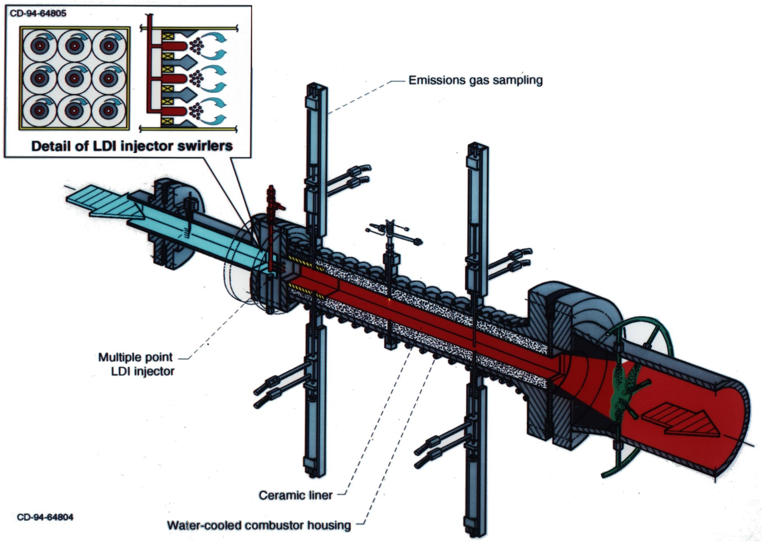


Figure 1: Drawing of CE-5 flame tube.

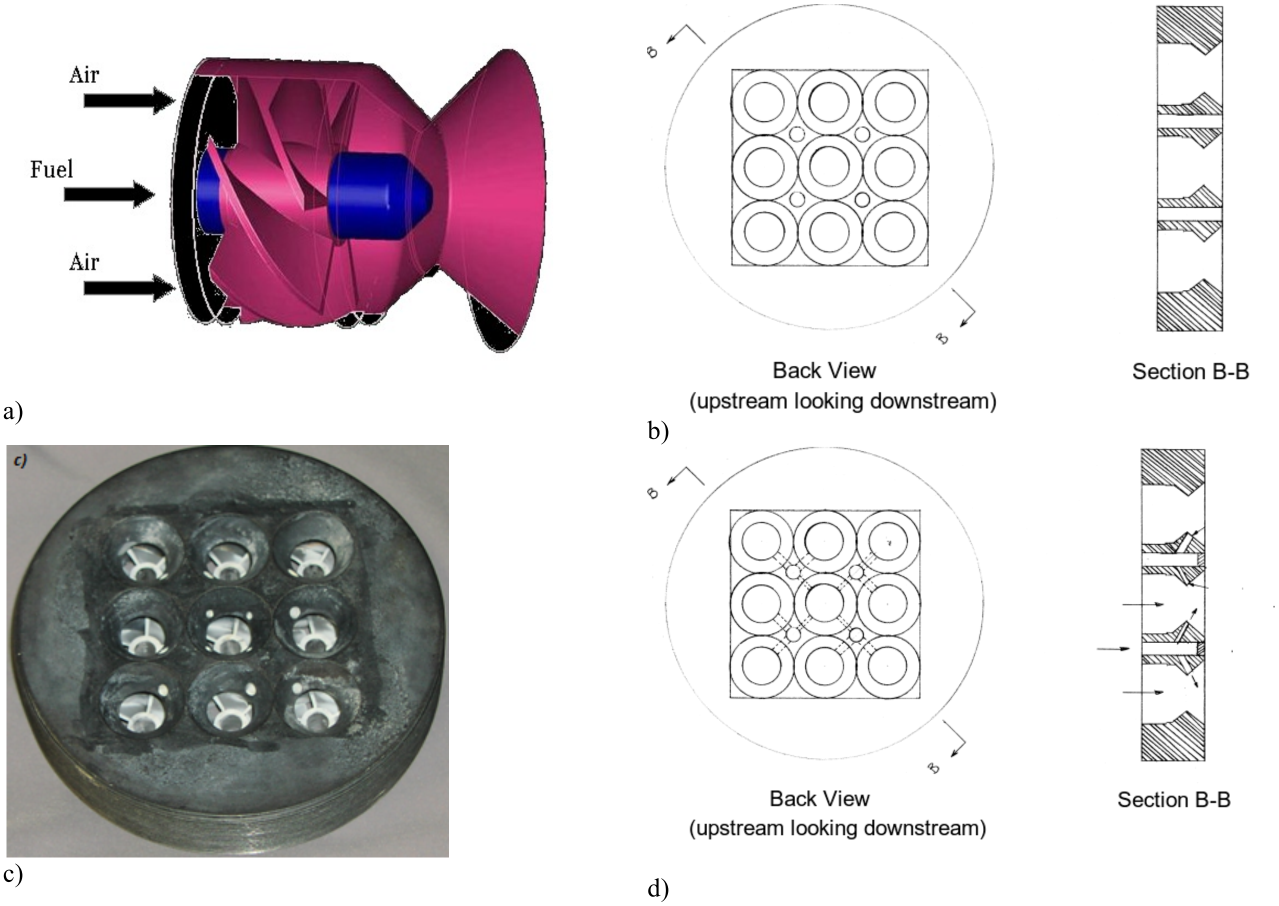


Figure 2: Experimental hardware: a) drawing of a fuel/air mixer, b) drawing of a 9-point injector with straight through spent cooling, c) and d) picture and drawing of a 9-point injector with spent cooling at the throat.

3. Results and Discussion

Testing of the HSR configurations showed that the spent cooling was not needed at HSR conditions: a post-testing visual inspection of the 60° configuration with no spent cooling showed no damage. In the testing with the UEET configurations, post-testing inspections also showed no damage, and thermocouple measurements showed acceptable dome temperatures. Nevertheless, spent cooling might be needed at the higher inlet pressures of next generation aircraft engines, especially when burning alternative fuels with a shorter ignition delay time. Therefore, understanding the effects of spent cooling may be important for future SV-LDI designs.

Table 1: Average ACd and flow number for each configuration of the 9-point injectors.

	45° /ST	45° /AT	60° /ST	60° /no cooling	UEET 45°	UEET 60°
ACd	1.745	1.644	1.477	1.37	1.48	1.35
FN(total)	17.9	17.16	18.49	18.24	26.1	26.1

Air and fuel pressure drops are important parameters in designing the aircraft combustor. For the simplex fuel nozzle, fuel pressure drop across the injector affects the fuel drop size [4]. Higher the fuel pressure drops, the smaller is the fuel-drop size, which results in a better fuel-air mixture. The same type of simplex fuel injector was used in all four HSR configurations. As shown in Table 1, the flow numbers for these four configurations were about the same, which were around 18. The flow number is a function of fuel pressure drop across the injector and fuel mass flow rate and is defined as FN=fuel mass rate/sqrt(ΔP). Therefore, fuel drop sizes at a given fuel flow rate should be similar among the four HSR configurations. However, the flow numbers for the UEET configurations were about forty percent higher than these four HSR configurations. According to the correlations found in Lefebvre[4], this 40% higher flow number will result in the UEET fuel drop sizes being about 30% higher the the HSR fuel drop sizes at a given mass flow rate.

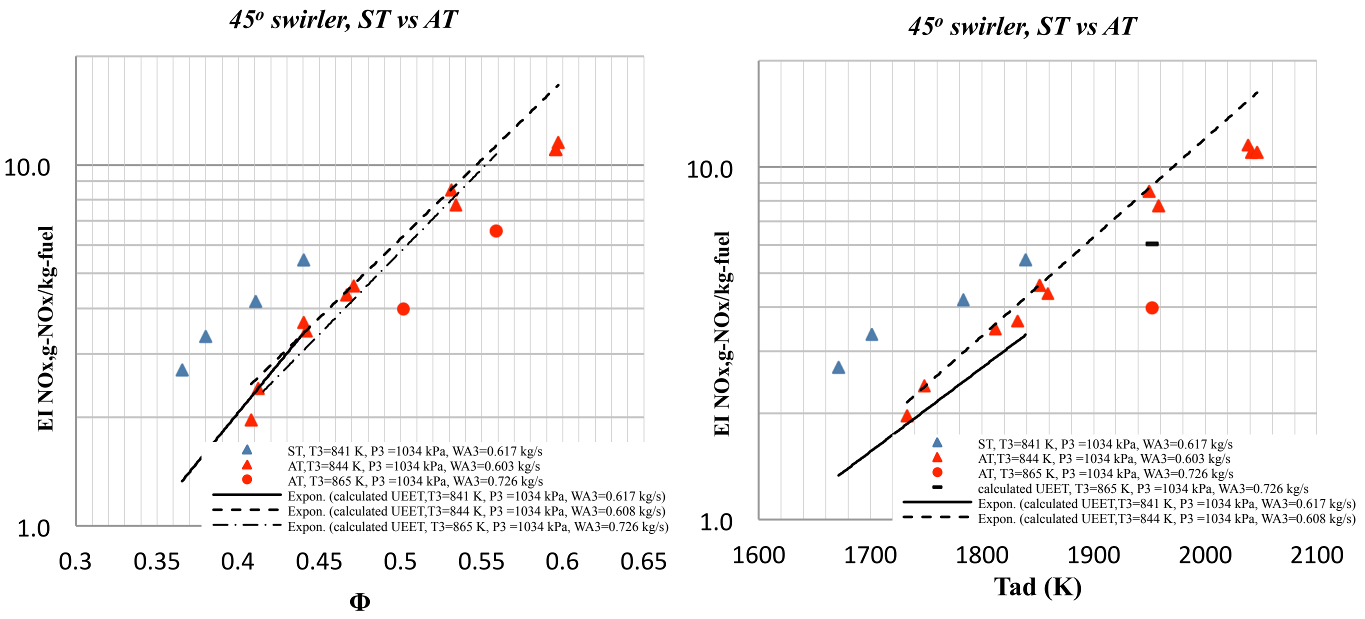
Figure 3 compares the effects of mass flow rate and two types of spent cooling methods on the NOx emission for mixers configured with 45° swirlers at various equivalence ratios (Φ) (Figure 3a) or adiabatic flame temperature (Figure 3b). For a typical fuel/air mixer configuration, NOx emissions mainly depend on fuel-air ratio, combustion inlet air temperature and pressure, as well as the air pressure drop across the dome. When NOx data was plotted against the adiabatic flame temperature, the effect of the combustion inlet temperature was minimized, allowing for easier comparison. Comparing the NOx emissions of the two spent cooling methods, the straight-through spent cooling produced higher NOx than spent cooling at the throat (at least 25 percent higher). This is consistent with the result expected from the UEET NOx correlations. At a given air mass flow rate, the straight through configuration's larger effective area (ACd) decreased the air pressure drop across the dome. Based on the UEET correlations, NOx emissions decrease with increasing pressure drop: NOx is proportional to pressure drop to the -0.56 power [6]. Assuming the dependence of NOx on air pressure drop was similar between UEET and HSR configurations, straight-through spent cooling should produce 8 percent higher NOx emissions than cooling at the venturi throat.

Figure 3 also includes the predicted NOx values for the UEET 9-point configuration with 45° swirlers. The predicted UEET NOx emissions were lower than the HSR configuration with straight-through spent cooling, but about the same with spent cooling at the throat for an air flow rate of 0.603 kg/s. At a higher air flow rate (0.726 kg/s), spent cooling at the throat had lower NOx than predicted UEET NOx emissions. When cooling air is applied at the venturi throat, the air jets might promote faster fuel air mixing, and thus lower NOx emission.

In Figure 4, the straight-through spent cooling was compared with no cooling on the HSR 9-point configuration that was configured with 60° swirlers. These data indicated straight-through spent cooling produced slightly higher NOx emissions than no cooling, but the difference was small. In addition, with a higher air mass flow rate, the NOx emissions were lower. For this 9-Point-Swirl Venturi design, fuel was injected into the high turbulent region that was created by the air swirler. As the air velocity increases, the fuel-air mixing is enhanced by stronger air turbulence. The combustion residence time is also reduced to shrink the NOx emission. Figure 4 also compares these experimental data to the predicted NOx values of a UEET 9-point configuration with 60° swirlers. Overall, the predicted UEET NOx values were lower than experimental HSR data.

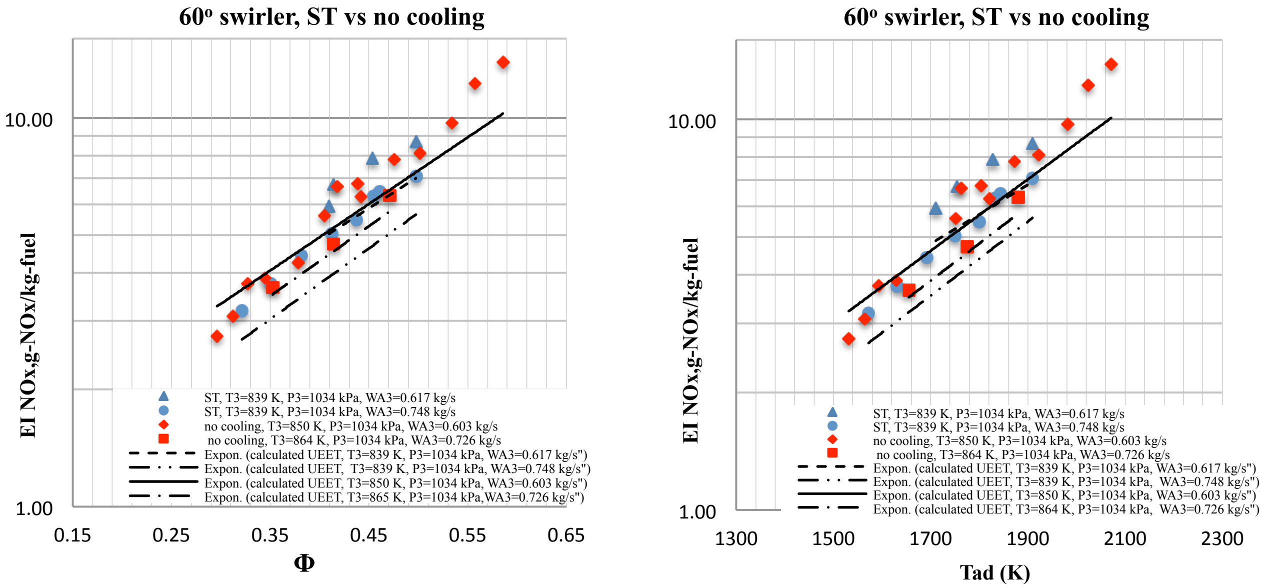
Figure 5a compares two straight through spent cooling configurations; one had 45° swirlers and the other had 60° swirlers. Using the 45° swirlers, the NOx emissions were lower. This was consistent with the later UEET results as shown on Figure 5b. According to the past LDV measurements and recent CFD studies [1, 6], the differences between using the 60° swirler and the 45° swirler were the intensities and locations of the flame recirculation zone in the combustor. The 60^{o} swirler produced a more stable recirculation zone, and its location was on the axis of the swirler in the gas stream. When the hot recirculation zone is located on the axis of the swirler, fuel and air might be burned before uniform mixing could occur. Thus, more NOx is produced. The 45^{o} swirler produced a relatively weak recirculation zone, and its locations were attached to the dome face in between the swirlers, which gives more time for fuel and air to mix before burning. This could be the reason for the lower NOx emissions when using the 45^{o} swirler.

The effects of spent cooling depend on spent cooling location, swirler angle, and test conditions. By applying spent cooling at the venturi throat, the cooling air is coming out at the same location as the swirled air (or combustion air). It will change the swirl number, and thus affect the air flow dynamic inside the combustor. The straight-through spent cooling method applied cooling air through the dome plate at the locations between the fuel injectors. These locations were at the same location of the circulation zones that the 45^{o} swirlers produced. Since the recirculation zones were relatively weak, applying straight-through spent cooling at the dome plate might change the location of the recirculation zone and lead to the change in NOx emission. For configuration with 60^{o} swirlers, the recirculation zone was strong and it was located on the axis of the swirlers in the gas stream. As a result, straight-through spent cooling did not show much effect on this configuration.



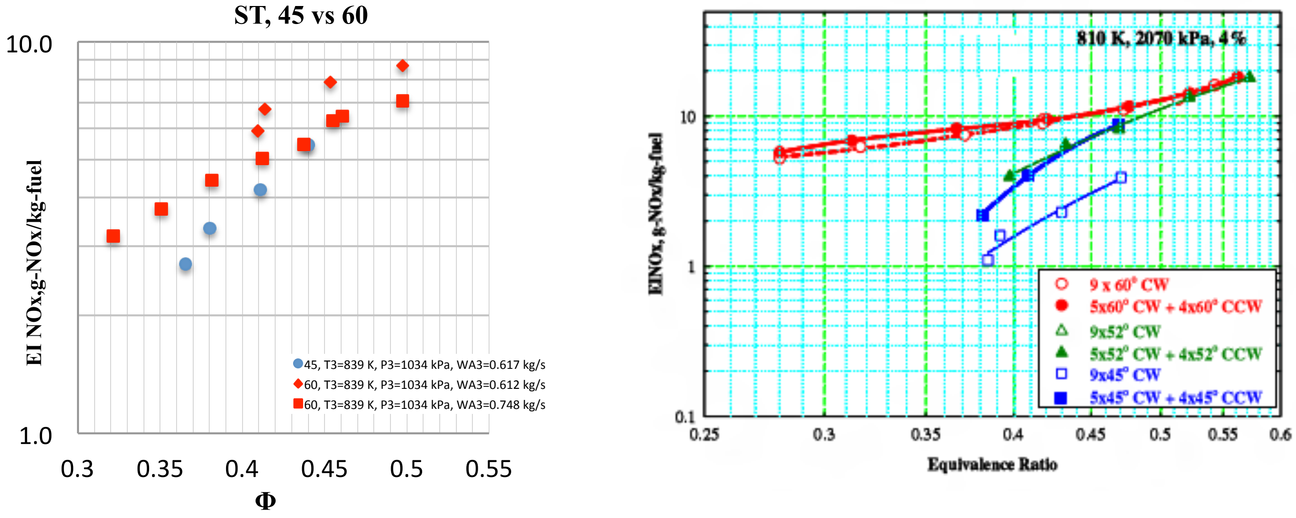
a) b)

Figure 3: Straight-through spent cooling vs. spent cooling at the throat for a 9 point injector with a 45^{o} swirl angle.



a) b)

Figure 4: Straight-through spent cooling vs. no spent cooling for a 9 point injector with a 60° swirl angle.



a) b)

Figure 5: a) Comparison of the HSR straight through spent cooling configurations with 45° and 60° swirlers, and b) Comparision of UEET configurations with 45 ° °, 52°, and 60° swirler angles[6].

4. Conclusions

This paper explores the effects of dome cooling and swirler angle on SV-LDI low NOx combustion configurations. This dome cooling is called "spent cooling" and its original intent was to protect the fuel/air mixer hardware from the flame burning too close to the dome plate. However, testing and thermocouple measurements at the dome plate showed that the spent cooling was not needed at HSR or UEET conditions studied here. But spent cooling might be needed at the higher inlet pressures of next generation aircraft, especially when burning alternative fuels with a lower ignition delay time. Therefore, understanding the effects of spent cooling may be important for future SV-LDI designs.

The data presented in this paper showed the effect of applying spent cooling at two locations. The first location was at the dome face in between fuel/air mixers and the second location was at the venturi throat. The effects of spent cooling depend on spent cooling location, swirler angle, and test conditions. For fuel/air mixers configured with 45^o swirlers, NOx emissions were significantly higher when the cooling was applied at the dome face than when it was applied at the venturi throat. For the fuel/air mixers configured with 60^o swirlers, NOx emissions when spent cooling was applied at the dome face were not significantly different from NOx emissions when no spent cooling was used.

HSR results also indicate that decreasing the swirler angle from 60^o to 45^o decreases NOx emissions: the straight through spent cooling configuration with 45^o swirlers had lower NOx emissions. This is consistent with results from the UEET configurations, which had no spent cooling.

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