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Swirl-Venturi Lean Direct Injection Combustion Technology for Low-NOx Aero Gas Turbine Engines

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Abstract: This paper summarizes research on the lean direct injection (LDI) combustor concept for aero-gas turbine combustors. The focus of this paper is one particular family of lean direct injection designs, swirl-venturi lean direct injection (SV-LDI). SV-LDI is characterized by the air-path: an air swirler followed by a converging-diverging venturi. For most SV-LDI configurations, a fuel injector is inserted through the center of the air swirler, with the fuel injector tip at or near the venturi throat. Several design variables were studied. These included fuel injector tip location, air swirler blade thickness, air swirler blade angle, and fuel-air mixer size. Moving the fuel injector tip slightly upstream or downstream of the venturi throat has at most a small impact on NO_x emissions. Changing the blade thickness also does not affect NO_x emissions. Changing the swirler blade angle has a significant effect on NO_x emissions. Decreasing swirler blade angle, and thus decreasing swirl number, decreases the NO_x emissions at lower flame temperatures (below about 1800 K). However, the slope of the NO_x vs. flame temperature curve is higher for lower swirl numbers. Finally, decreasing the fuel-air mixer size initially decreases NO_x emissions. However, there may be an optimum fuel-air mixer size below which NO_x emissions do not continue to decrease.
***Keywords:* gas turbine combustion, NO_x, emissions, lean direct injection**

1. Introduction

This paper summarizes the development of lean direct injection (LDI) combustor technology at NASA Glenn Research Center. LDI has been developed to reduce the emissions of the oxides of nitrogen (NO_x) in aircraft engine gas turbine combustors. As its name implies, lean direct injection has two distinguishing characteristics. First, LDI injects fuel directly into the flame zone, without a separate premixing section. Second, LDI burns fuel-lean throughout, without a rich front end: all combustor air except that used for liner cooling enters through the combustor dome. Like other fuel-lean combustor concepts, LDI reduces NO_x emissions by minimizing local flame temperature, since NO_x is an exponential function of flame temperature. Minimizing local flame temperature requires avoiding local near-stoichiometric zones, which in turn requires good fuel atomization, good fuel vaporization, and uniform fuel-air mixing. To promote this, multiple small fuel-air mixers replace one traditionally-sized fuel-air mixer.

LDI research at NASA Glenn was based on early collaborative work between NASA and the Department of Energy in the 1970s and 1980s[1] and on work by the G.E. Andrews group at the University of Leeds[2].However, sustained research on LDI did not begin until the early 1990s with the advent of NASA's High Speed Research (HSR) program, which focused on reducing NO_x emissions at supersonic cruise conditions to below 5 g-NO_x/kg-fuel[3–5]. The HSR program marked the start of sustained development of LDI combustor technology for both supersonic and subsonic aircraft. For subsonic aircraft, the focus is on reducing landing-takeoff NO_x emissions; projects include Advanced Subsonic Technology (AST), Ultra-Efficient Engine Technology (UEET), Fundamental Aeronautics/Subsonics, Environmentally Responsible Aviation (ERA), and Advanced Air Transport Technology (AATT). The two most recent programs, ERA and AATT, have also added a goal to reduce cruise NO_x. For supersonic aircraft, the focuses continues to be reducing cruise NO_x; projects include Fundamental Aeronautics/Supersonics and Commercial Supersonic Technology (CST).

This papers reviews several LDI configurations developed at or in collaboration with NASA Glenn Research Center. These configurations differ mainly in fuel-air mixing strategy. Typically, LDI configurations are multi-element, where several small fuel-air mixers will replace one traditionally-size fuel-air mixer. Depending on the LDI configuration, the size of an individual fuel-air mixer and the spacing between fuel-air mixers varies. In addition, the design of an individual fuel-air mixer can be varied.

Three broad classes of LDI configurations have seen the most sustained development. All three are multi-element concepts, distinguished by the type of fuel-air mixer used. The first class is swirl-venturi LDI. As shown in Figure 1a–c, each swirl-venturi LDI fuel-air mixer consists of an air swirler followed by a converging-diverging venturi. In first- and second-generation swirl-venturi LDI, a simplex or air assist fuel injector is inserted through the center of the air swirler, with the fuel injector tip typically at the venturi throat. In the first-generation swirl-venturi LDI configurations, called SV-LDI-1 and shown in Figure 1d–j, each fuel-air mixer was the same, except possibly for swirler blade angle. The air swirlers were axial with helical blades, and each fuel injector was fed by its own line. In second-generation swirl-venturi LDI, called SV-LDI-2 and shown in Figure 1k–n, the fuel-air mixers are split into a pilot stage and three main stages, which also differ in size and type of fuel injector (simplex or airblast). Again, each air swirler was axial and each fuel injector was fed by its own line, as shown in Figure 1n. In third-generation swirl-venturi LDI, a single fuel stem feeds all of the fuel-air mixers in a cup, as shown in Figures 1o–p. Each fuel stem contains three fuel lines; one of these lines feeds the center pilot fuel-air mixer, while the other two feed the outer main fuel-air mixers. Two types of fuel cups are used to allow for tight packing. One type, the "5-point", contains a pilot and 4 main fuel-air mixers, and the other type, the "7-point" contains a pilot and 6 main fuel-air mixers. Figure 1q shows a 3-cup sector configuration with two 7-point cups and one 5-point cup. Swirl-venturi LDI is described in more detail in References [4, 6–11].

The second class is discrete-jet LDI. As shown in Figure 2, the distinguishing feature of this class is discrete-jet air swirlers. There is no converging-diverging venturi. As with swirl-venturi LDI, in the first discrete-jet LDI configurations, all fuel-air mixers were identical. In later discrete-jet LDI, the fuel-air mixers are split into a pilot stage and two main stages, which differ in the design of the discrete jets and the type of fuel injector (pressure atomizer or airblast). Discrete-jet LDI is discussed in more detail in References [12–14].

The third class is macrolaminate LDI. As shown in Figure 3, the distinguishing features of this class are radial air swirlers, fuel injection upstream of the air swirlers, and the macrolamination fabrication method. Macrolaminate LDI is discussed in more detail in References [15, 16].

This paper reports emissions results from swirl-venturi (SV-) LDI configurations. In particular, this paper focuses on results from the original first-generation SV-LDI testing, much of which was unpublished. The original first-generation SV-LDI emissions are then compared to second- and third-generation SV-LDI emissions.

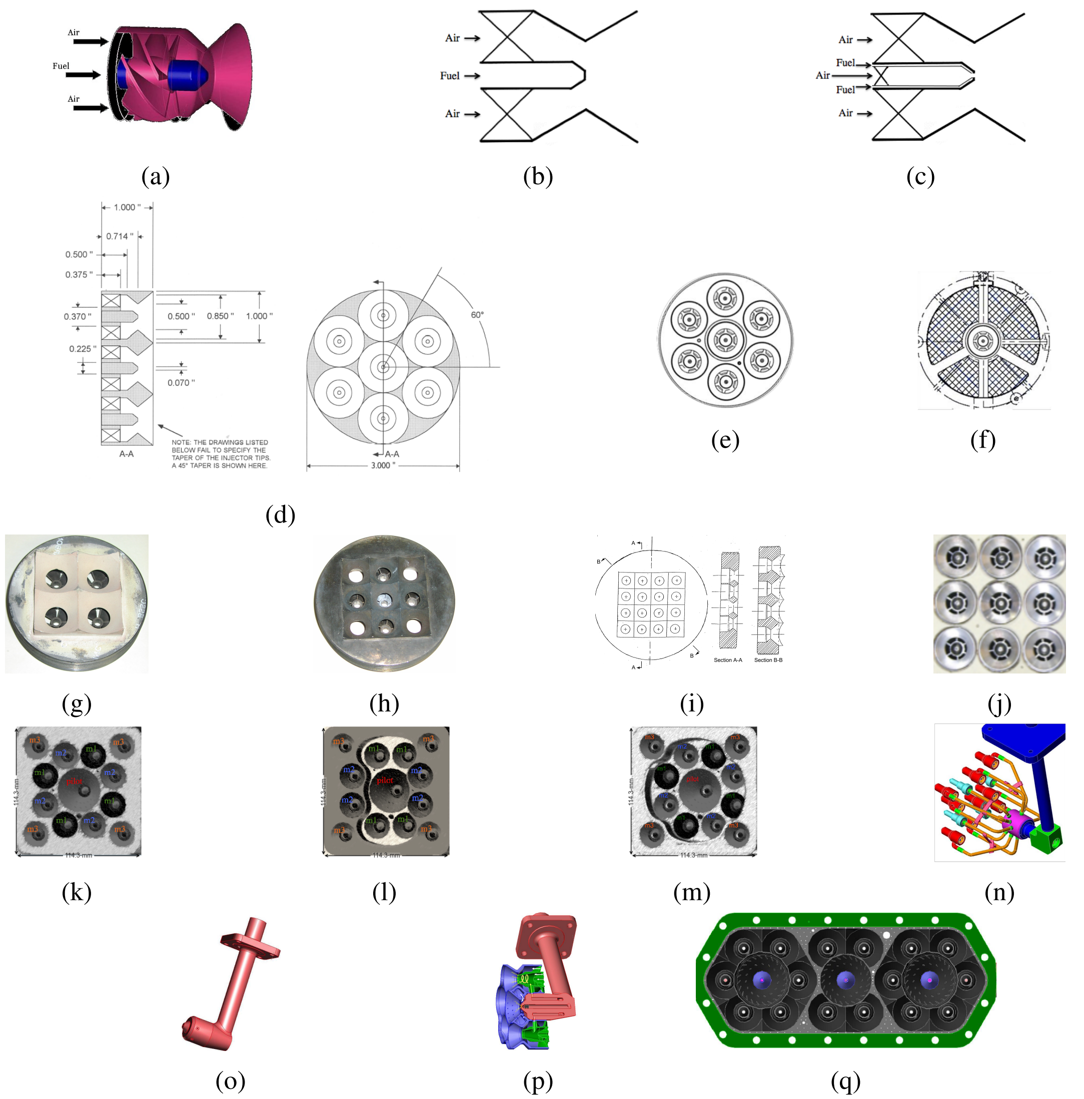
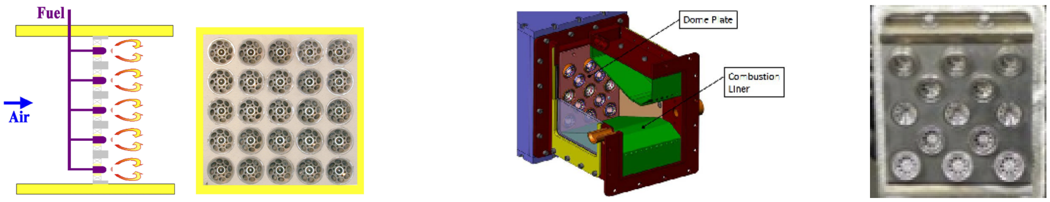
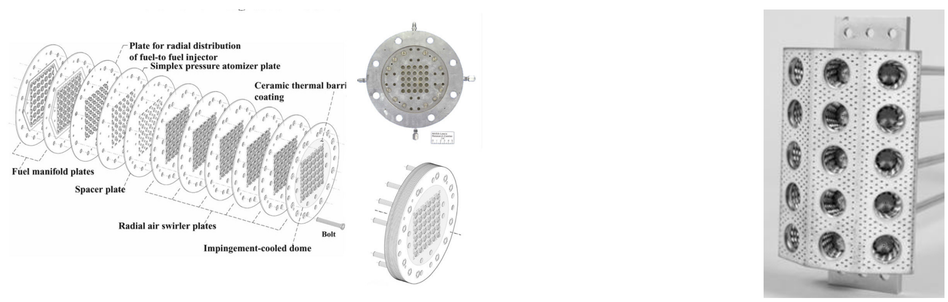


Figure 1: Swirl-venturi LDI. A single fuel-air mixer is shown in parts a–c: (a) isometric drawing of single SV-LDI fuel-air mixer with simplex fuel injector, (b) sketch with simplex fuel injector, (c) sketch with airblast fuel injector. Parts d–j show seven SV-LDI-1 configurations. The first three have a circular cross-section with a 76.2-mm diameter: (d) the original 7-element configuration, (e) newer 7-element research configuration, and (f) the single-element research configuration, in which a single fuel-air mixer is surrounded by a screen. The last four each have a 76.2-mm $\times$ 72.2-mm cross-section: (g) 4-element venturi-points, (h) 9-element venturi points, (i) 16-element venturi-points, and (j) 9-element venturi-flats. Three SV-LDI-2 configurations are shown in parts k–m, each with a 114.3-mm $\times$ 114.3-mm cross-section: (k) flat dome, (l) 5-recess, and (m) 9-recess. The fuel lines feeding SV-LDI-2 13-point cup is shown in (n). A SV-LDI-3 hardware is shown in (o)-(q): (o) a fuel stem for a single cup, (p) a 7-point cup, and (q) a 3-cup section consisting of two 7-point cups and one 5-point cup.



(a) (b) (c)

Figure 2: Discrete-jet LDI. Part a shows the first discrete-jet LDI configuration, with 25 injectors arranged in a 5×5 array in a 76.2-mm×76.2-mm array. Parts b-c show a later configuration; this later configuration has a dome area of more than 12 times that of the first configuration.



(a) (b)

Figure 3: Macrolaminate LDI. Part a shows the first macrolaminate LDI configurations, with a 76.2-mm×76.2-mm cross-sectional area containing *(top, photograph)* 25 injectors in a 5×5 array or *(side, bottom, drawings)* 36 injectors in a 6×6 array. Part b shows a later 3-zone macrolaminate configuration.

2. Experimental Hardware

2.1 General LDI design guidelines

Like other lean-front-end combustor concepts, LDI relies on rapid and uniform fuel-air mixing to avoid near stoichiometric-zones that will produce high NO_x emissions. One way LDI promotes rapid and uniform fuel-air mixing is to replace one traditionally-sized fuel-air mixer with multiple smaller fuel-air mixers. Reducing the fuel-air mixer size should promote fuel-air mixing by bringing the fuel and air into closer proximity. In particular, one nominally 76.2-mm (3-in) fuel-air mixer has been replaced by between 4 and 49 small fuel-air mixers. The nominal diameter of these fuel-air mixers ranges from 10.9-mm (49 fuel-air mixers) to 38.1-mm (4 fuel-air mixers). However, although reducing the fuel-air mixer size is expected to reduce NO_x emissions, there may be a optimal fuel-air mixer size below which the reduction in NO_x emissions is negligible. In addition, reducing fuel-air mixer size increases the complexity of the combustor design. Smaller fuel-air mixers will also fuel injectors with lower flow numbers; this could become problematic for pressure atomizers (e.g., simplex) because smaller flow numbers imply smaller orifice sizes and coking can become a problem. For this reason, later LDI designs had fuel-air mixers diameters around 25-mm; see Figures 1k-q, 2c, and 3b.

To promote mixing and combustion stability, the air path of each fuel-air mixer was designed with the expectation that a central recirculation zone would form downstream of each fuel-air

Table 1: Geometric details for various first-generation SV-LDI configurations.

Configuration	Figure	Flow Number per injector	Swirler Blades	Venturis Truncated?
original 7-element	1d	3	5	Yes
newer 7-element	1e	0.7	6	Yes
4-element venturi-points	1g	3.4	5	No
9-element venturi-points	1h	2.0	5	No
16-element venturi-points	1i	0.85	5	No
9-element venturi-flats	1j	2.9	6	Yes

mixer. To produce a central recirculation zone, data from Beer and Chigier[17] suggests the swirl number — the ratio of angular momentum to axial momentum – be at least 0.6. Thus, in LDI, the swirl number based on swirler geometry is typically between 0.6 and 1.0. For helically-bladed axial swirlers such as those used for most SV-LDI designs, this translates into swirler blade angles between 45^o and 60^o.

Later data, CFD simulations, and theory showed that the formation of a central recirculation zone depended on factors other than the swirl number, such as confinement, fuel-air mixer spacing, the design of the adjoining fuel air mixers, and the amount of heat release[18–24]. However, by this time, experience had shown that combustion was reasonably stable and NO_x emissions were low even without a recirculation zone behind every fuel-air mixer.

2.2 SV-LDI hardware

As stated in the introduction, each swirl-venturi LDI fuel-air mixer consists of an air swirler followed by a converging-diverging venturi. For first-generation SV-LDI, the fuel injectors are simplex and each air swirler has helical blades. There are three major design variables for the first-generation SV-LDI configurations: the fuel injector flow number FN_{US}[25], the number of blades per swirler, and the termination of each fuel-air mixers. There are two types of fuel-air mixer termination: in the venturi-points termination, the venturis are extended beyond the main plane of the dome face until they merge together. In the venturi-flats termination, the venturis are truncated at the dome face, so that the dome face is flat. Details for the first-generation SV-LDI configurations shown in Figure 1 are given in Table 1.

Details on the second-generation SV-LDI configurations are given in Tacina et al, 2014 and 2016[9, 26], and details on the third-generation SV-LDI configuration is given in Ajmani et al, 2017, and Tacina et al, 2017[10, 11].

3. Results

3.1 Circular 7-element configuration: Effect of swirler blade thickness, fuel injector tip location, and swirler blade angle

The original 7-element configuration was the first LDI configuration. Therefore, there were two geometric variations tested in this configuration that were not tested in most subsequent configurations.

First, the swirler blade thickness was varied. As Figure 4a shows, the swirler blade thickness did not have a large effect on NO_x emissions. It did, however, have a large effect on pressure drop: at a mass flow rate of 0.5 kg/s, the pressure drop across the combustor was approximately 7.5% for the thin swirler blades and approximately 9.5% for the thick swirler blades. The (cold flow) ACd was approximately 575 mm^2 for the thin swirler blades and approximately 485 mm^2 for the thick swirler blades[1]. Increasing the combustor pressure drop will decrease engine efficiency. Therefore, thin swirler blades were used for all subsequent configurations.

Second, the location of the fuel injector tip was varied. Four locations were tested: the fuel injector tip at the venturi throat, the fuel injector tip 0.125-in downstream of the venturi throat, the fuel injector tip 0.125-in upstream of the venturi throat, and the fuel injector tip 0.25-in upstream of the venturi throat. As Figure 4b shows, changing the fuel injector tip did not have a large effect on NO_x emissions. This is consistent with optical diagnostics of the spray done on the single-element research configuration shown in Figure 1f. As reported it Tedder et al[27], changing the fuel tip location had only a small effect on the spray characteristics. Since the fuel injector tip location had only a small effect on NO_x emissions, for subsequent configurations the tip of a simplex fuel injector was typically at the venturi throat.

In addition to these two geometric variations, the swirler blade angle and orientation were varied; see Figure 4c. The swirler blade orientation did not have a large effect on NO_x emissions. This is consistent with previous data for 60^o swirlers[6].

Figure 4c also shows that the effect of swirler blade angle depends on flame temperature. At lower flame temperatures, the configuration with the 45^o swirler blade angle had lower NO_x emissions. However, at flame temperatures above 1800 K, the 45^o configuration had approximately the same NO_x emissions as the 60^o configurations. This is consistent with the 9-element venturi-flats results reported in Tacina et al[6], which showed that the 45^o configurations had lower NO_x at lower flame temperatures (and equivalence ratios) but the slope of the NO_x vs. flame temperature curve was steeper for the 45^o configurations; see Figure 4d. This is also consistent with second- and third-generation SV-LDI results[9, 11, 26].

3.2 Square 4-, 9-, and 16-element configurations: Effect of fuel-air mixer size

The effect of fuel-air mixer size is examined in Figure 5. Figure 5a shows the effect of fuel-air mixer size when the mass flow rate of air is kept constant, and Figure 5b shows the effect when the pressure drop of air is kept constant. Decreasing the fuel-air mixer size from 38.1-mm (4-element) to 25.4-mm (9-element) decreases NO_x emissions. However, further decreasing the fuel-air mixer size to 29.5-mm (16-element) does not further decrease NO_x emissions.

This effect cannot be explained by changes in expected fuel drop size. According to Lefebvre[25], the drop size (Sauter mean diameter) depends on pressure drop to the -0.28 to -0.44 power. Mean drop size also depends on the fuel mass flow rate per injector to the 0.25 power. The 4-element and 16-element configurations have approximately the same total flow number (flow number per injector $\times$ number of injectors) but the 4-element has 4 times as much mass flow per injector. Therefore, Lefebvre's correlations estimate that the drop size for the 4-element will be approximately 40% higher than the drop size for the 16-element. The 9-element configuration has

[1]For all original 7-element configurations, the pressure drop measurements were not highly accurate, due to being the difference between two absolute pressure transducers instead of a differential pressure measurement.

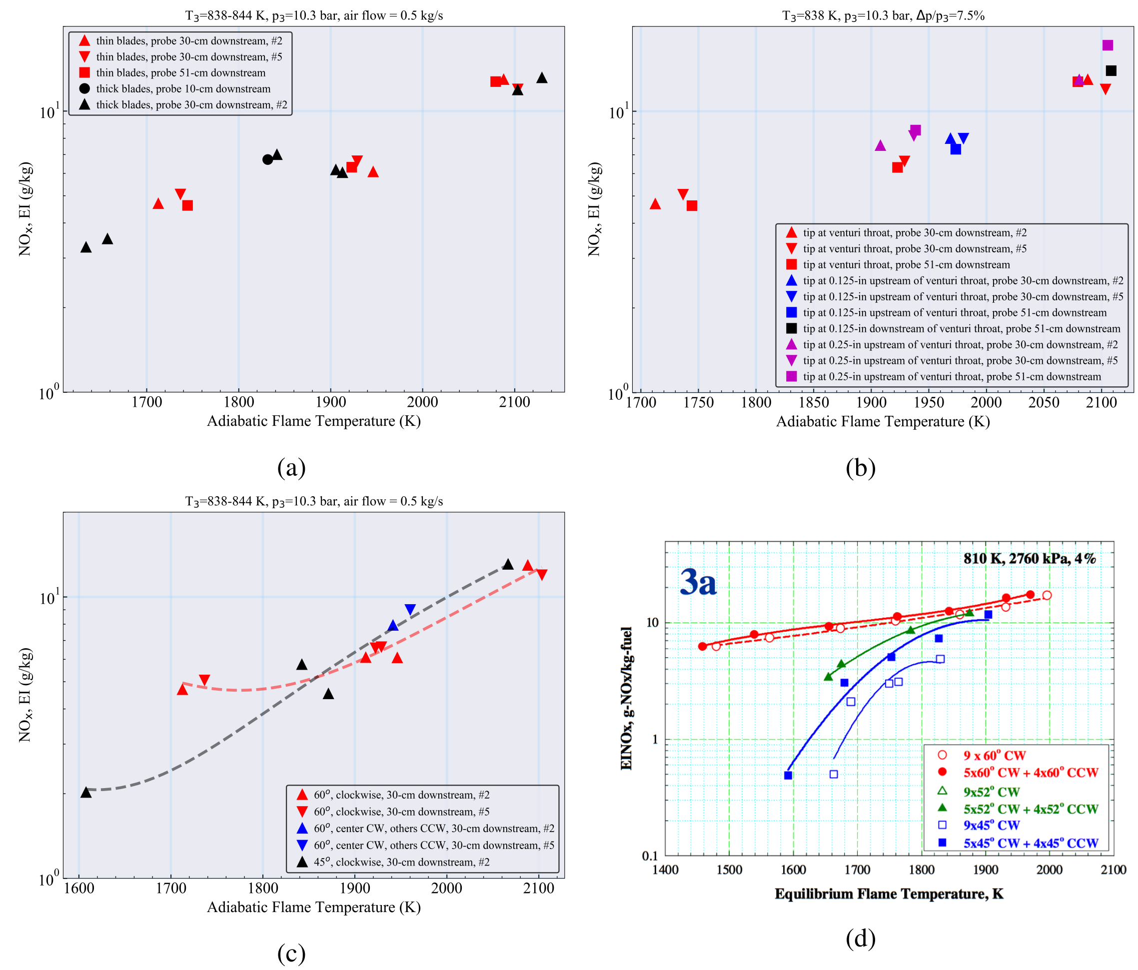
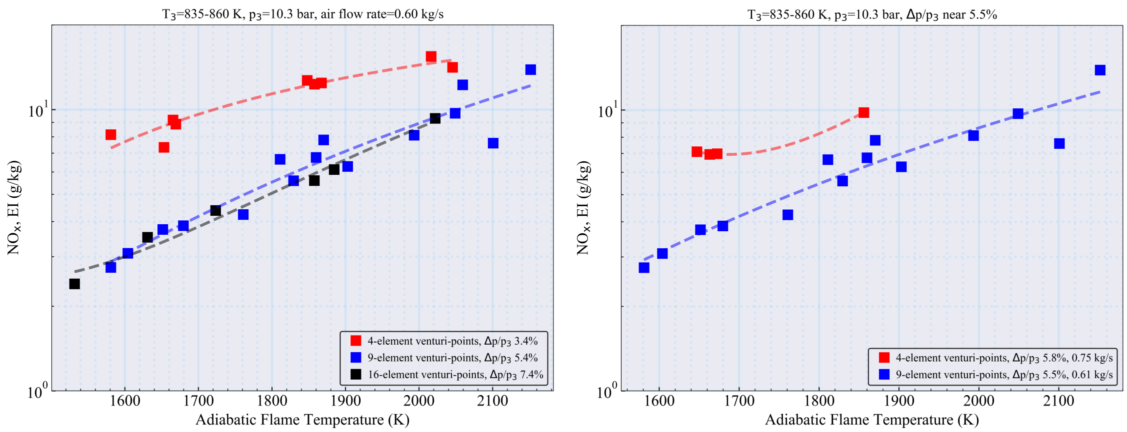


Figure 4: Results from the original 7-element SV-LDI configuration: (a) effect of swirler blade thickness on NO_x emissions; (b) effect of fuel injector tip location on NO_x emissions; (c) effect of swirler blade angle and orientation on NO_x emissions. For comparison, (d) shows the effect of blade angle on the 9-element venturi-flats SV-LDI NO_x emissions (from [6]). Unless otherwise specified, the swirler blades are thin, the fuel injector tip is located at the venturi throat, and the swirler blade angle is 60^o.



(a) (b)

Figure 5: Comparison of NO_x emissions from the 4-element venturi-flats, 9-element venturi flats, and 16-element venturi flats configurations. In (a, the mass flow of air (and thus the reference velocity) is kept constant. In (b), the pressure drop across the dome is kept (approximately) constant.

both a higher total flow number and a higher per injector mass flow rate than the 16-point. Its drop size should be between 35% and 48% higher than the drop size for the 16-element and about the same as the drop size for the 4-element.

It could be argued that decreasing the fuel drop size will decrease NO_x emissions because smaller fuel drops will vaporize more quickly. However, in this case, although the 16-element is expected to have a smaller drop size than the 9-element, the NO_x emissions were similar for both of these configurations. Thus, fuel-air mixer size also seems to be important.

Previous reports have tried to examine the effect of fuel-air mixer size on NO_x emissions[6, 12, 15]. Figure 6 reproduces a figure from reference [6]. This figure compares flametube NO_x emissions for five LDI configurations. For all five of these configurations, the flametube had a 76.2-mm $\times$ 76.2-mm square cross-section, so that increasing the number of fuel-air mixers decreases the fuel-air mixer size. Despite some similarity in naming schemes, the air flow passages for all five configurations are significantly different.

Figure 6 shows that all three 25-element configurations and the 49-element configuration have approximately the same NO_x emissions. The 36-element configuration had lower NO_x emissions. Reference [6] noted that both air flow passage geometry and fuel-air mixer size seem to be important factors in NO_x emissions.[2]

3.3 Comparison of first-, second-, and third-generation SV-LDI emissions

First generation SV-LDI NO_x emissions are compared to second-generation results in Figure 7 and to third-generation results in Figure 8. NO_x emissions from the second-generation 9-recess configuration are higher than those from the first-generation 9-element venturi-points configuration. NO_x

[2] On the other hand, reference [15] used the decrease in fuel-air mixer size and fuel drop size to explain why the 36-element MPIM configuration had lower NO_x emissions than the various 25-element MPIM configurations. However, this reference did not note that the swirler geometries also changed: 10-bladed radial swirlers were used for the 25-element MPIM configurations whereas 4-bladed radial swirlers were used for the 36-element MPIM configurations.

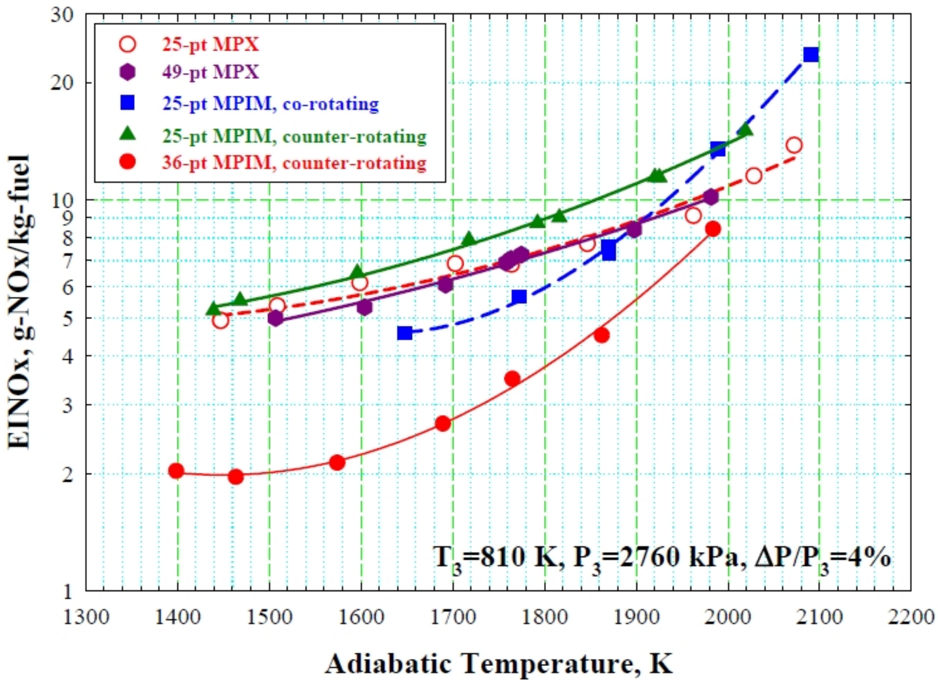


Figure 6: Comparison of several LDI configurations, from [12].

emissions from the second-generation are similar to the 9-element configuration. NO_x emissions from the third-generation configuration are lower at lower flame temperatures. However, the slope of the NO_x vs. flame temperature curve is much steeper for the third-generation configurations.

3.4 Summary

This paper summarizes research on aero-engine lean direct injection combustor concepts, focusing on NO_x emissions from first-generation swirl venturi lean direct injection. Several design variables were studied. These included fuel injector tip location, air swirler blade thickness, air swirler blade angle, and fuel-air mixer size. Moving the fuel injector tip slightly upstream or downstream of the venturi throat has at most a small impact on NO_x emissions. Changing the blade thickness also does not affect NO_x emissions. Changing the swirler blade angle has a significant effect on NO_x emissions. Decreasing swirler blade angle, and thus decreasing swirl number, decreases the NO_x emissions at lower flame temperatures (below about 1800 K). However, the slope of the NO_x vs. flame temperature curve is higher for lower swirl numbers. Finally, decreasing the fuel-air mixer size initially decreases NO_x emissions. However, there may be an optimum fuel-air mixer size below which NO_x emissions do not continue to decrease. NO_x emissions from second- and third-generation swirl-venturi lean direct injection designs were also compared to first-generation swirl-venturi lean direct injection NO_x emissions.

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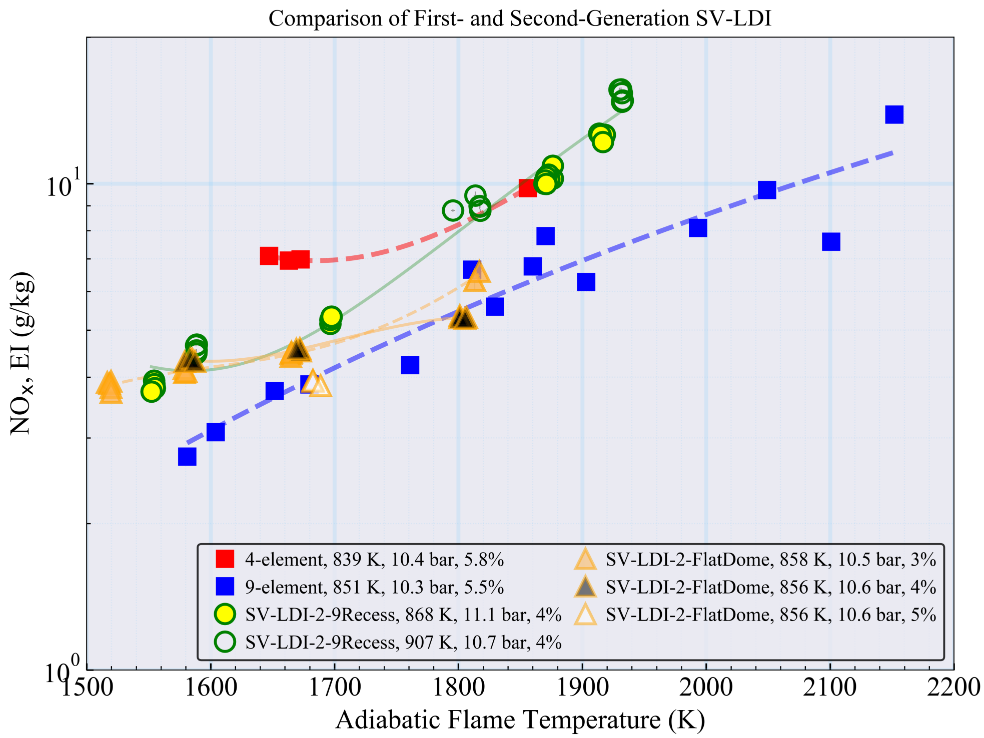

Figure 7: Comparison of NO_x emissions from first-generation SV-LDI configurations (SV-LDI-1, solid squares) and second-generation SV-LDI configurations (SV-LDI-2).

gies, and Advanced Air Transport Technology.

With the exception of the "newer 7-element" and single element research configurations, the research on all first-generation lean direct injection configurations was led by Robert R. Tacina. In particular, most of the first-generation SV-LDI NO_x emissions data in Figures 4 and 5 was previously unpublished.

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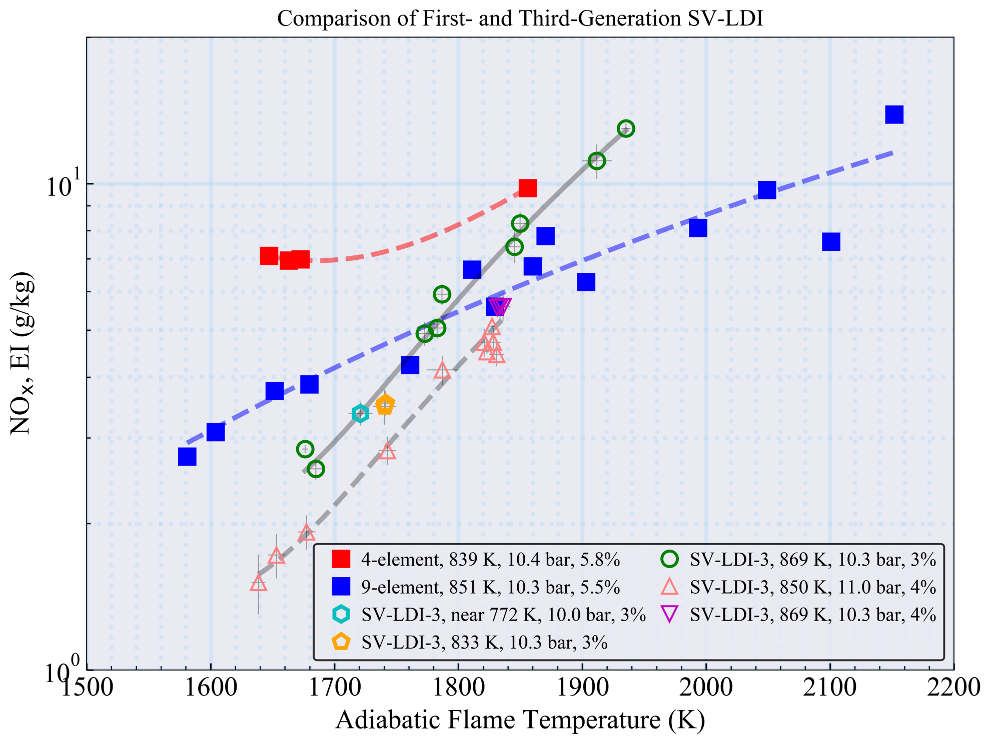

Figure 8: Comparison of NO_x emissions from first-generation SV-LDI configurations (SV-LDI-1, solid squares) and the third-generation SV-LDI configuration (SV-LDI-3).

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