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ORIGINAL ARTICLE

Fundamental investigations for lowering emissions and improving operability

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Abstract This paper first highlights recent developments in lean direct injection (LDI) combustion technology. In view of the needs and opportunities to lower emissions and expand the operability range of LDI, fundamental research has been undertaken to elucidate the effects of air swirler vane angle, air swirler rotation direction, and overall equivalence ratio on the LDI flow field and flame structure/response. Moreover, additional investigation has been conducted to understand the fundamental differences between representative LDI and airblast injectors in order to highlight the importance of the flare feature to LDI venturi geometry. The results of these fundamental studies are discussed to help identify possible areas for optimization to generic LDI designs that may improve individual swirler performance.

1. Introduction

Meeting the goal of reducing the environmental impact of aviation engines requires a focus on reducing NO_x emissions while maintaining high combustion efficiencies and low emission indices of CO_2, CO, UHC, and smoke, all of which exhibit harmful effects on the environment and human health. In addition to these emissions goals, aviation engines must meet other stringent design requirements, including adequate operability limits, reliable operation, and durability.

Reducing the emissions of CO_2, CO, UHC, and smoke can be accomplished by reducing specific fuel consumption; this typically requires operating at high pressure ratios, leading to high combustor inlet temperatures and peak

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operating temperatures. However, operating at high temperatures increases the production of NO_x. Several combustion strategies have been developed to mitigate the production of NO_x while maintaining the high temperatures required to reduce other emissions. These strategies fall into two broad categories: lean-front-end (lean dome) and rich-front-end (rich dome) combustors.

NASA and industry have been working continuously since early 1970 on developing energy efficient low-emissions aviation engines [1–3]. Much of the recent combustor research for commercial applications has focused upon the development of lean-dome combustor technologies such as lean prevaporized premixed (LPP) combustion [e.g., 4–6] and lean direct injection (LDI) combustion [e.g., 7–15]; due to their lean front-end nature, these concepts avoid the potential for the poorly-mixed high-temperature regions primarily responsible for NO_x generation that are inherent to the Rich-burn, Quick-mix, Lean-burn (RQL) operation concept. The LDI concept initiated in 1990 [7] shows promise for further technology development and demonstration, in part due to the avoidance of premixing chambers – such as in LPP – which have been found to be prone to autoignition and flashback problems [16]. In the LDI mode, air and liquid fuel are injected and mixed inside the combustor, while keeping the overall mixture equivalence ratio fuel lean. Since the LDI mode relies on vaporization of the fuel followed by rapid mixing with air, regions of locally higher equivalence ratio are possible; this would lead to local hot spots and high production of NO_x, compromising the intent of the concept. Thus, it is critically important to ensure thorough and rapid vaporization and mixing of the fuel after injection.

Based on one LDI concept with multipoint fuel-injection and multiple burning zones, the first generation of LDI consisted of 9 identical simplex injectors [8], as shown in Figure 1. Each fuel injector had an axial air swirler for quick mixing of the fuel and air before burning. Various swirl strengths were tested and the NO_x emissions were found to decrease as the swirl strength decreased, as shown in Figure 2. However, the operability range was also noted to suffer as swirl strength decreased.

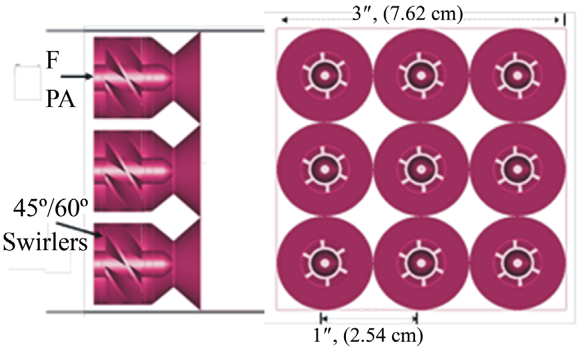

Figure 1 1st generation 9-element lean direct injection schematic, LDI-1 [8].

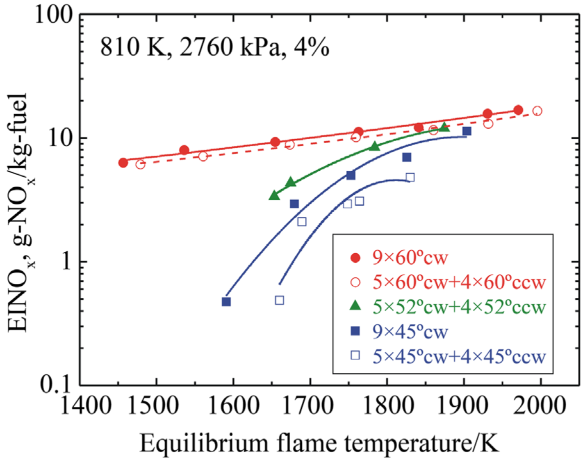

Figure 2 Typical LDI-1 $EINO_x$ versus combustor exit temperature T_4 at combustor inlet temperature of $T_3 = 810$ K, combustor inlet pressure of $P_3 = 2760$ kPa, and pressure drop of 4% [8].

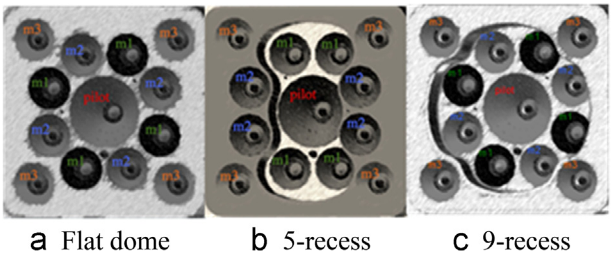

Figure 3 2nd generation 13-element lean direct injection schematic, LDI-2 [11].

The second generation of LDI (LDI-2), developed in conjunction with NASA's Environmentally Responsible Aviation (ERA) program, incorporated three variations based on the baseline 9-point swirl-venturi (SV) LDI configuration [11]. The three SV-LDI variations with 13-element injectors are called the flat dome configuration, the 5-recess configuration, and the 9-recess configuration, as shown in Figure 3. Table 1 also lists the specifications of injectors and swirlers used in the three LDI-2 configurations. It is noted that the second generation of LDI used both the simplex and airblast elemental injectors, as well as the co-rotating and counter-rotating configurations. Of particular importance, the LDI-2 configurations have improved NO_x emissions performance relative to the first generation (LDI-1) configurations. The 5-recess configuration has generally slightly lower NO_x than the flat dome or 9-recess configurations, as shown in Figure 4. In addition, the 5-recess LDI-2 configuration gives 85% landing takeoff (LTO) $EINO_x$ margin from the CAEP/6 standards, which is much better than two premier large engines, Trent1000 and GEnx, as shown in Figure 5.

Recognizing that an understanding of the performance of various single element LDI injectors is critical to lowering emissions and improving operability of future multipoint LDI combustors, a series of fundamental LDI studies have been conducted to better understand the important design