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# EXPERIMENTAL INVESTIGATION ON IGNITION PERFORMANCE OF LESS COMBUSTOR

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## ABSTRACT

In the design of next-generation civil aviation gas turbine combustors, there is high demand to improve the efficiency of combustion technology to decrease the amount of fuel consumed and to reduce the emissions in an effort to lessen the environmental impacts. This paper introduces a novel, ultra-low emissions combustor, namely Low Emission Stirred Swirl (LESS) combustor, employing the lean premixed prevaporized (LPP) approach. The LESS combustor is a single annular layout. Its dome is comprised of two stages – the pilot stage and the main stage. The pilot stage is a typical swirl cup design which uses a pressure swirl atomizer with dual counter-rotating radial swirlers to atomize the fuel and form a diffusion flame, and is located in the centerline of the combustion chamber. The main stage surrounding coaxially the pilot stage includes one annulus as premixer and 14 plain orifice atomizers with 14 small dual counter-rotating radial swirlers arranged uniformly on the dome of the annulus, which lead to the main premixed flame.

Five different igniter locations are chosen according to the CFX-simulated non-reacting flow field of a simplified main-stage combustor. Only the pilot pressure swirl atomizer is operated in the present ignition performance tests. The model combustor is a single module rectangular combustor with normal inlet temperature and normal inlet pressure. Under the test conditions of air pressure drop of 0.5%–9%, the ignition performance of the model LESS combustor is analyzed. The lean lightoff fuel/air ratio (LLO FAR), characterizing the ignition performance of a combustor, is investigated herein. In addition, the effects of igniter locations and pilot fuel nozzles on LLO FAR are studied. Specific to the LESS combustor, the igniter location has minor effect on the LLO FAR values. However, as expected, the combustor dome pressure drop and attendant reference velocity along with spray SMD impact LLO FAR. Furthermore, CFX-simulated results of the flow field, spray characteristics, and gas-liquid interactions under the typical condition of combustor operation are presented and discussed to provide insight into the ignition processes and performance.

## NOMENCLATURE

| | |
|---|---|
| CAEP | Committee on Aviation Environmental Protection |
| CFD | Computational Fluid Dynamics |
| $CH_4$ | Methane |
| CO | Carbon Monoxide |
| FAR | Fuel/Air Ratio |
| FN | Injector Flow Number, lb/(hr-psi$^{0.5}$) |
| GE | General Electric Company |
| ICAO | International Civil Aviation Organization |
| LDI | Lean Direct Injection |
| LESS | Low Emission Stirred Swirl |
| LLO FAR | Lean Lightoff Fuel/Air Ratio |
| LPP | Lean Premixed Prevaporized |
| NOx | Nitrogen Oxides |
| OPR | Operating Pressure Ratio |
| PIV | Particle Imaging Velocimetry |
| RQL | Rich-Burn, Quick-Mix, Lean-Burn |
| RRD | Rolls-Royce Deutschland |
| SMD | Sauter Mean Diameter, microns |
| TAPS | Twin Annular Premixing Swirler |
| UHC | Unburned Hydrocarbon |
| VOF | Volume-of-Fluid |
| Vr | Combustor Reference Velocity, m/s |

| | |
|---|---|
| $P_{31}^*$ | Liner Inlet Air Total Pressure |
| $T_3^*$ | Liner Inlet Air Total Temperature |
| $P_4^*$ | Liner Outlet Air Total Pressure |
| $(P_{31}^*-P_4^*)/P_{31}^*$ | Liner Pressure Loss Over Inlet Loss |
| $\Delta P_a$ | Air Pressure Drop, Pa |
| $\Delta P_f$ | Fuel Nozzle Pressure Drop, MPa |
| $\Phi$ | Equivalence Ratio |

## INTRODUCTION

Lower emissions have become one of the key characteristics of advanced civil aviation gas turbine engines over the past 30 years. A number of new combustor design strategies, including LPP, RQL, and LDI, are being investigated widely in order to meet the more and more stringent international standards on civil aviation engine emissions set by ICAO. All the standards, including CAEP2, CAEP4, CAEP6, and CAEP8, demand reducing the emissions of NOx without increasing the emissions of CO，UHC, and smoke [1]. Reducing the emissions of NOx at flight altitudes is important because of the climatic effects on the ozone balance. In the design of ultra-low emissions combustors, lean-burn technology holds the potential of reducing emissions of NOx as compared to rich-burn technology, especially at high OPRs [2].

Of primary importance to the gas turbine engines is the need for smooth and reliable lightoff during ground starting, and an additional requirement is for rapid relighting of the combustor after a flameout in flight [3], indicating that the engine safety is closely related to the ignition performance. Since the ignition of the current aircraft gas turbines is usually accomplished through electric spark ignition and since the ignition performance determines the flame stabilization, the LLO FAR is the key concern in the ignition performance assessment [4].

Lean-burn combustion technology has been explored in the field of aero-engine combustion for meeting future emissions requirements, e.g. the TAPS family of low NOx combustors developed by GE [5-7] and a lean-burn low NOx combustor developed by RRD [8,9]. The design of the LESS combustor introduced herein also adopts lean-burn combustion technology. Most of previous studies have concentrated on emissions, combustion efficiency, and flame-flow interactions [cf. 5-10]. Although the ignition performance has been studied in several investigations, the results of the TAPS combustor ignition performance referred in Ref. [5] were not published and only part of the lean-burn combustor ignition results were shown in Refs. [8,9]. To further fundamental understanding of the ignition characteristics of the lean-burn approach, the ignition performance of a novel, ultra-low emissions combustor employing the LPP approach is therefore systemically investigated. LLO FAR is used as the key parameter in the ignition performance evaluation under normal inlet temperature and normal inlet pressure. The effects of igniter locations and pilot fuel nozzle flow numbers on LLO FAR are studied. The present work also includes numerical analysis of non-reacting flow field and spray characteristics to help interpret experimental results.

## LESS COMBUSTOR

The LESS combustor is a single annular layout. The combustor channel height, overall length, and effective length (defined as combustor volume/combustor reference area) are 120, 190, 160 mm, respectively. The dome of the LESS combustor is comprised of two stages – the pilot stage and the main stage. Figure 1 shows the schematic of the LESS combustor, while Fig. 2 is a photo of the test combustor.

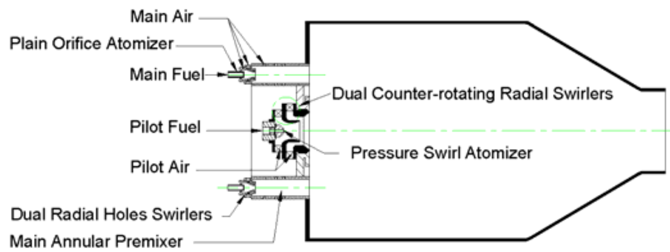



**Fig. 1** Schematic of LESS combustor.

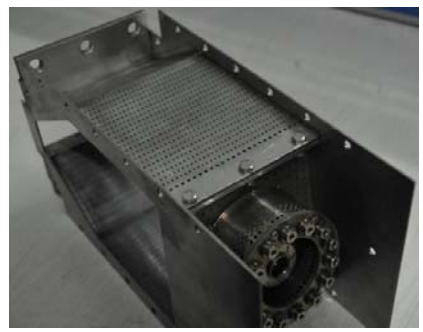


**Fig. 2** The single module test combustor.

The pilot stage is a typical swirl cup design which uses a pressure swirl atomizer with dual counter-rotating radial swirlers to atomize the fuel and form a diffusion flame, and is located in the centerline of the combustion chamber. The pilot stage is used for easy and reliable lightoff during ground starting, rapid relighting of the combustor after a flameout in fight, extending lean blowout limits, increasing combustion efficiency at low power conditions, and reliably igniting the main stage fuel/air pre-mixture at high power conditions. The main stage surrounding coaxially the pilot stage includes one annulus as premixer formed by two steel pipes of different radius and 14 plain orifice atomizers with 14 small dual counter-rotating radial swirlers arranged uniformly on the dome of the annulus. There are a number of straight and inclined holes on the surfaces of the main stage annulus. Furthermore, the air injected through the inclined holes can form swirl within the annulus, and hence the fuel can be premixed with the air and prevaporized in the annulus by jet stirred swirl before entering combustor chamber, thereby leading to the main premixed flame. This therefore allows some degree of fuel/air premixing within the passages with attendant reduction in NOx and improved combustor exit temperature quality.

It is also noted that there are no primary-zone holes and dilution air holes on the LESS combustor, and all the air for combustion is injected through the dome air path. The total air flow rate through the pilot, the main, and the dome cooling is 72%Wa31 whereas the remaining 28%Wa31 is used by the multi-hole (effusion) cooled liner walls. Here Wa31 represents the combustor through flow air excluding the amount of air used for cooling the side walls of the single injector sector rig. Multi-inclined-hole liner cooling technology is adopted in the design of the current LESS combustor, and there is no side wall cooling air.

## IGNITION TEST

The test combustor is a single module rectangular combustor, and igniter locations are chosen according to the CFX-simulated non-reacting flow field of a simplified main-stage combustor. In the simulation model, the flow paths include the liner passage, dome aero, pilot stage, and main stage, although the cooling holes of the dome and the liner are not included. The non-reacting flow field is simulated under the condition of normal inlet temperature and normal inlet pressure. The combustor operating conditions selected are $P_{31}^*$=104800 Pa, $T_3^*$=310 K, and $(P_{31}^*-P_4^*)/P_{31}^*$=3.0% with the resulting reference velocity of 86.1 m/s. Additionally, mass flow inlet and pressure outlet are adopted as boundary conditions. Five igniter locations are chosen, as shown in Fig. 3, based on where the simulated airflow comes across the liner surface. The distances of the five igniter locations from the exit of the pilot swirl cup are 85, 75, 60, 50, 40 mm, respectively.

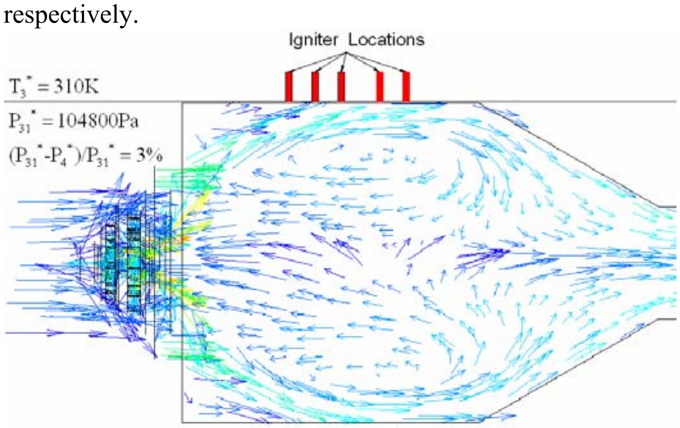



**Fig. 3** Schematic showing the five igniter locations.

Experimentally, a surface-discharge igniter is used in conjunction with a high-energy ignition unit of 12 J, with the igniter tip being flush with the liner surface. A quartz window is installed on the side wall of the test rectangular combustor for visualization of ignition phenomena and flame.

A schematic of the ignition test facility is shown in Fig. 4. It includes an air delivery system, a pressure regulator, a measurement section, a flow straighter section, a test combustor, a cooling section, and a vent-pipe. The fuel delivery system is comprised of a fuel tank, a fuel pump, and a valve. Instruments used in testing include total pressure piezometers, a pressure drop piezometer, fuel nozzle pressure gages, a fuel Corioli's force flowmeter, and a K-type thermocouple with 0.5% measurement precision. Flow rate of the total air stream is computed via the air pressure drop of the measurement section with pressure measurement precision of 1%, and the relative error of the computed air flow rate is approximately 2.1%. The fuel flow rate controlled by a valve is measured using a Corioli's force flowmeter with accuracy of 1%. The relative error of the computed FAR is around 6.3%.

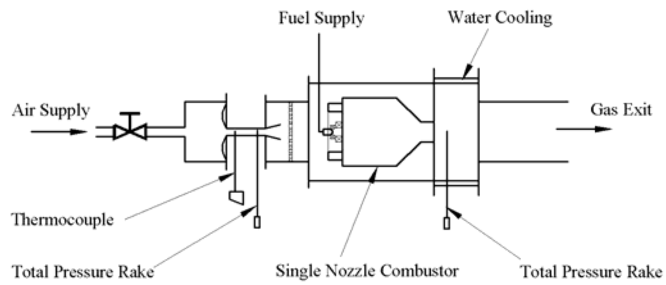



**Fig. 4** Schematic showing the ignition test system.

Only the pilot pressure swirl atomizer is operated in the ignition test. The test fuel used is Chinese aviation kerosene RP-3, which has fuel properties very similar to Jet-A. Methane is also used in the ignition test. Two pressure swirl atomizers are used herein, namely No1 nozzle of FN=2.3 lb/(hr-psi$^{0.5}$) and No2 nozzle of FN=2.0 lb/(hr-psi$^{0.5}$). The ignition tests are operated with normal inlet temperature and normal inlet pressure. After establishing rig's steady-state operation at the desired Pt3, Tt3, and Wa3 values, the igniter is turned on followed by preset values of the fuel flow rates to determine the two adjacent values, where appearance of the steady-state flames occur at, so that the corresponding ignition fuel flow rate can be determined. The test is repeated to achieve the desired conditions and record the measured values of fuel flow rates and the deduced ignition fuel/air ratios. After successful ignition, the test was operated with constant air mass flow and reduced fuel flow rate, and the minimum LLO FAR is discovered by reducing the fuel flow rate gradually at the same air mass flow until ignition unsuccessfully. And then the ignition test is operated at increased air mass flow, and the minimum LLO FAR at this increased air mass flow can be also discovered with the same approach as mentioned above.

## TEST RESULTS

With normal inlet temperature and normal inlet pressure, ignition performance tests are operated for a range of mass flows at various values of FAR. Figure 5 maps the ignition tests conducted for RP-3 with nozzle No1 and the igniter location at 40 mm from the exit of the pilot swirl cup, at varying sets of FAR and air pressure drop. The results of Fig. 5 are re-plotted as a function of the combustor reference velocity in Fig. 6. The minimum LLO FAR at different air pressure drops can then be determined based on the lean ignition boundary separating the scenarios of ignition and no ignition. A flame photo of No2 nozzle operation at 3.2% air pressure drop is demonstrated in Fig. 7.

Figure 8 further compares the lean ignition boundaries with No1 nozzle runs at five different igniter locations. It is seen that ignition performance remains similar irrespective of the changes in igniter location, 40–85 mm from the exit of the pilot swirler cup. In general, when the air pressure drop is below 2%, the LLO FAR increases with decreasing air pressure drop. On the other hand, when the air pressure drop exceeds 5%, the LLO FAR increases with increasing air pressure drop.

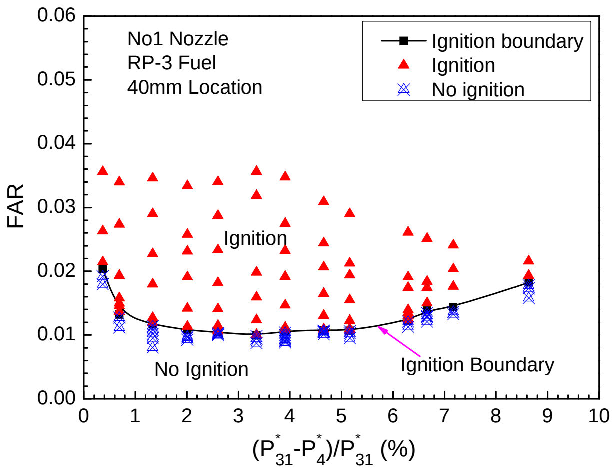



**Fig. 5** FAR as a function of air pressure drop for RP-3 using No1 nozzle and igniter location at 40 mm from the exit of the pilot swirl cup.

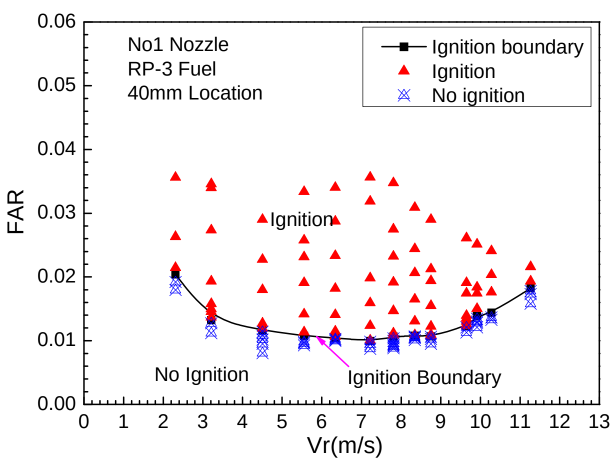



**Fig. 6** FAR as a function of combustor reference velocity for RP-3 using No1 nozzle and igniter location at 40 mm from the exit of the pilot swirl cup.

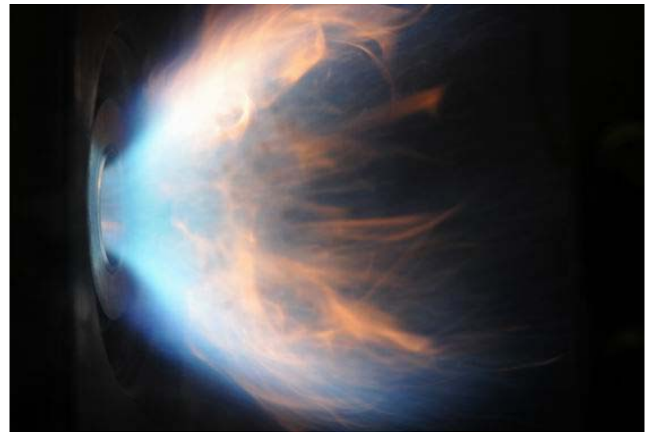


**Fig. 7** Flame visualization of No2 nozzle operation at 3.2% air pressure drop.

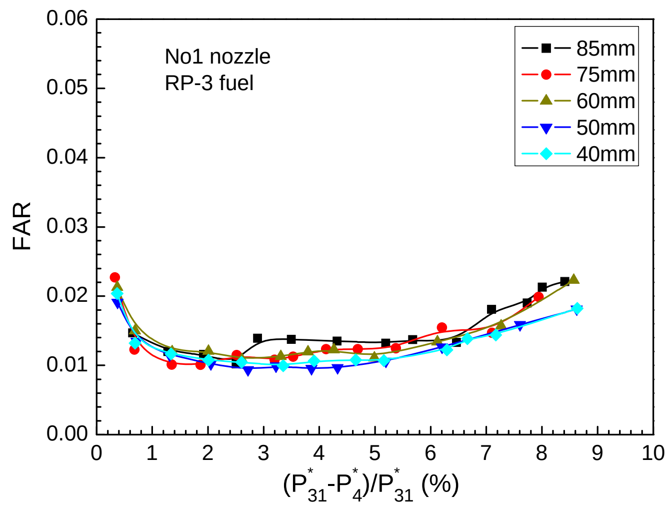



**Fig. 8** Comparison of lean ignition boundaries for No1 nozzle tests obtained at different igniter locations.

The pilot dual swirlers and No2 nozzle are the same ones adopted in Ref. [11], in which the SMD of a hybrid airblast atomizer was measured, as shown in Fig. 9. For the present LESS combustor, it is noted that the main air has no influence on the spray SMD, while it varies the distribution of the fuel drops in the chamber. Hence, the measured SMD reported in Ref. [11] can be representative of the current investigation.

Using No2 nozzle, Fig. 10 shows the fuel pressure drops at the lean ignition boundary with igniter locating at 50 mm from the exit of the pilot swirl cup. Based on Figs. 9 and 10, the corresponding SMD at the lean ignition boundary is estimated, as shown in Fig. 11. It is seen from Figs. 10 and 11 that when the air pressure drop is below 2%, the low fuel pressure drop along with the weak aerodynamic force due to reduced air pressure drop lead to increasing spray SMD. As such, the LLO FAR increases with decreasing air pressure drop. When the air pressure drop exceeds 5%, the variation of spray SMD with air pressure drop is insignificant. In addition, the air velocity in chamber is rather high because of high air pressure drop, which makes the propagation of the ignition kernel to the recirculation zone and flame stabilization more difficult. Thus, the LLO FAR increases with increasing air pressure drop beyond 5%.

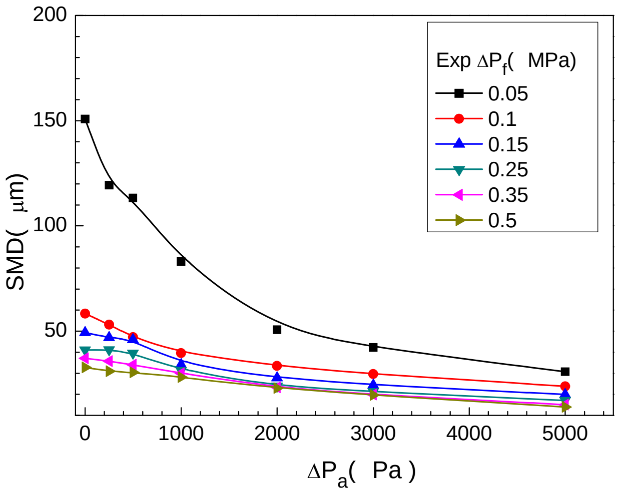



**Fig. 9** Measured SMD for the swirl cup using No2 nozzle, taken from Ref. [11].

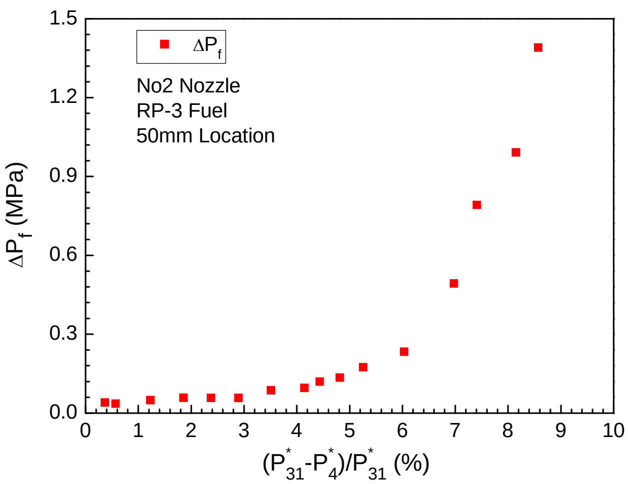



**Fig. 10** Fuel nozzle pressure drop at lean ignition boundary.

For a given igniter location of 50 mm, ignition tests with No1 and No2 nozzles are carried out and compared to illustrate the nozzle effect on the lean ignition boundary. Figure 12 shows that the lean ignition boundaries are similar for No1 and No2 nozzles. Since the flow numbers of No1 and No2 nozzles are respectively 2.3 and 2.0 lb/(hr-psi$^{0.5}$), the spray SMD is similar at the same air pressure drop for the two nozzles, thereby leading to similar LLO FAR.

Ignition tests using RP-3 and methane are also conducted with igniter location of 85 mm from the pilot swirl cup exit to examine the fuel effect on lean ignition boundary. It is seen from Fig. 13 that when the air pressure drop is below 2%, the critical Φ value corresponding to LLO FAR increases with decreasing air pressure drop for liquid RP-3 fuel while the critical Φ value holds almost constant for gaseous methane fuel. The dependence of the critical Φ value on air pressure drop for liquid fuel is due to the variation of spray SMD with air pressure drop, as discussed earlier.

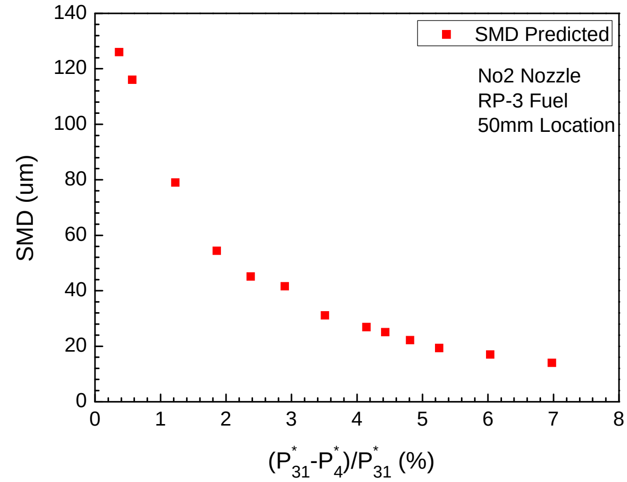



**Fig. 11** Estimated SMD at lean ignition boundary.

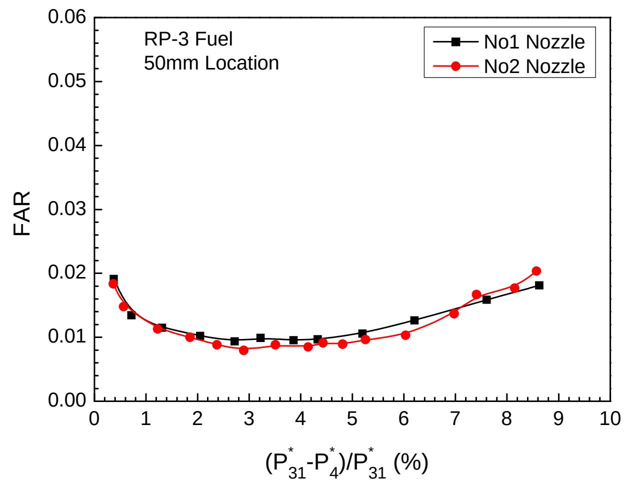
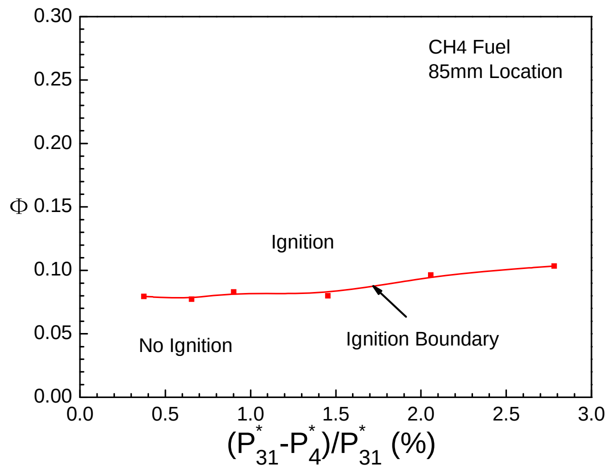



**Fig. 12** Comparison of lean ignition boundaries obtained using No1 and No2 nozzles.

## NUMERICAL ANALYSIS

To interpret and analyze the test results, the non-reacting flow field and spray characteristics in the model combustor are simulated. Recognizing the complexities of the boundary conditions and gas-liquid interactions, although it is challenging to accurately predict FAR distribution in the chamber, the simulated results can still provide insight into the basic trends of fuel spray distribution and further understanding of the tests results.

A commercial CFD code, CFX5.0, is used in this study. The current simulation model is a simplified main-stage combustor, and the main premixer is simplified as an annular model with inside diameter and outside diameter being respectively equal to those of the actual main stage exit. The flow paths include the liner passage, dome aero, pilot stage, and main stage, although cooling holes of the dome and the liner wall are not considered. Based on the experimental operating condition, the boundary conditions in CFD simulations are selected as $P_{31}^*$=105000 Pa, $T_3^*$=314.2 K, and $(P_{31}^*-P_4^*)/P_{31}^*$=3.2 %. A mass flow inlet and a pressure outlet are adopted, and the standard k-ε model is used for turbulence. 3-D non-reacting gas-liquid flow in the chamber is simulated employing the VOF method. Jet-A is used as the liquid fuel with the mass flow rate of 0.00114 kg/s and FAR=0.01146.



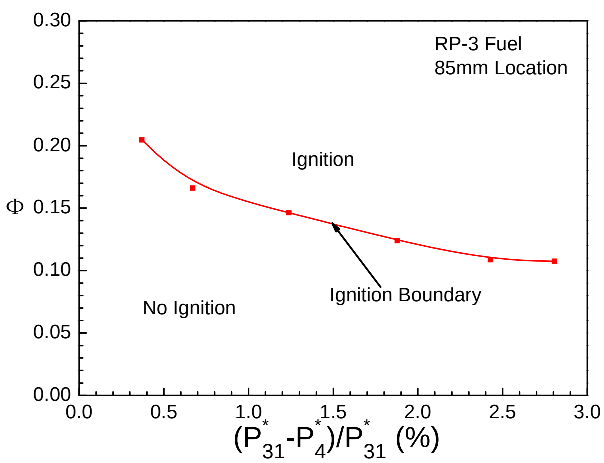




**Fig. 13** Lean ignition boundary comparison for gaseous $CH_4$ and liquid RP-3.

Figure 14 shows the simulated non-reacting flow field inside the chamber, while Fig. 15 plots the axial velocity profiles at 10 different axial locations, namely 5 mm to 95 mm away from the exit of the pilot swirler cup. It is clear that there is significant recirculation zone or low-velocity zone in the chamber. In particular, there exists a strong recirculation zone near the exit of the pilot swirler cup, and the extent of negative axial velocity along the centerline decreases with increasing axial distance downstream of the pilot swirl cup. Beyond a certain axial distance, the axial velocities near the centerline become positive and the recirculation zone moves outwardly. Based on these simulated results, five different igniter locations are selected accordingly.

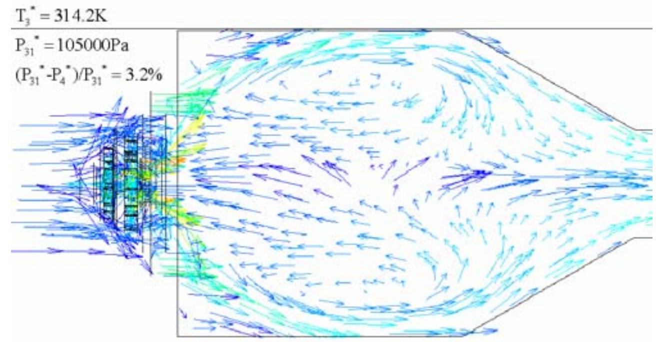



**Fig. 14** Computed flow field inside the chamber.

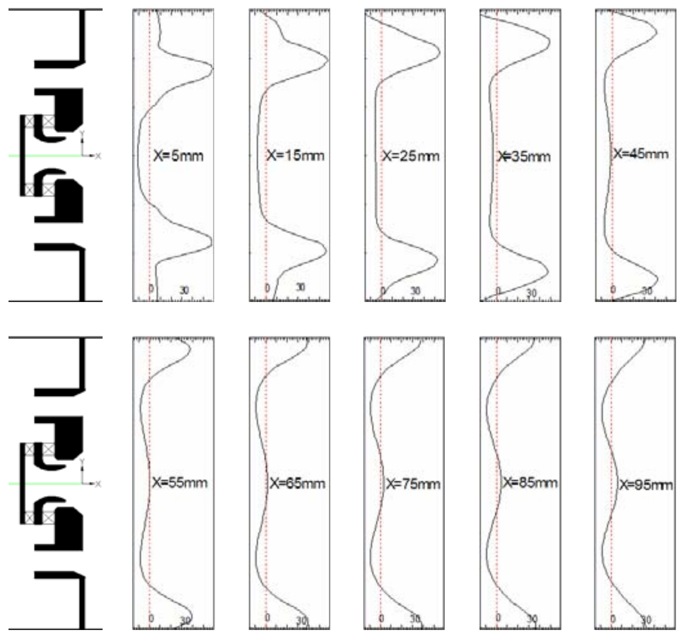



**Fig. 15** Computed axial velocity profiles.

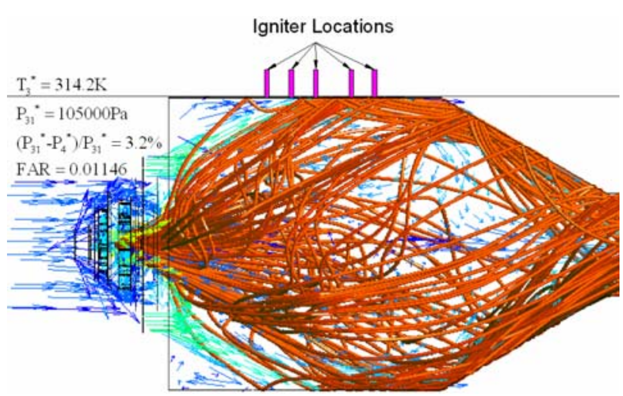



**Fig. 16** Particle tracks in the flow field.

Figure 16 shows the particle tracks within the flow field inside the chamber. The fuel particles come across all the five igniter locations, supporting the fuel/air mixing near the igniter locations. To further understand the ignition processes, the local equivalence ratios near igniter locations and recirculation zone are calculated. The regions of interest are denoted in Fig. 17 as red entities, while the computed Φ value for each entity is shown in Fig. 18. Here the local Φ values are calculated based on the average volume fraction data of liquid Jet-A obtained using CFD-Post. It is seen from Fig. 18 that the local Φ values of all the selected regions are sufficiently large to support the ignition kernel and the subsequent flame propagation.

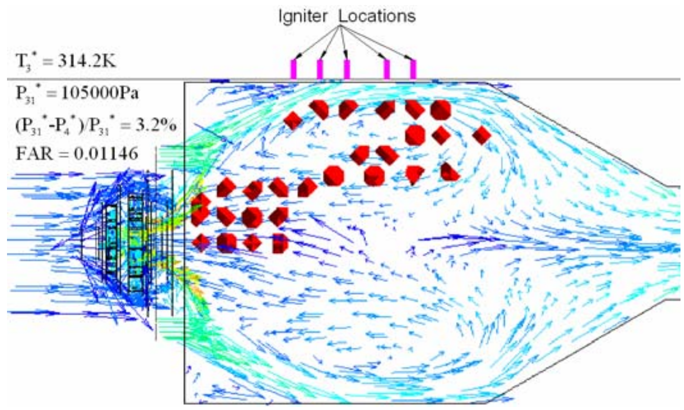



**Fig. 17** Regions of interest selected for calculating local Φ values in simulations.

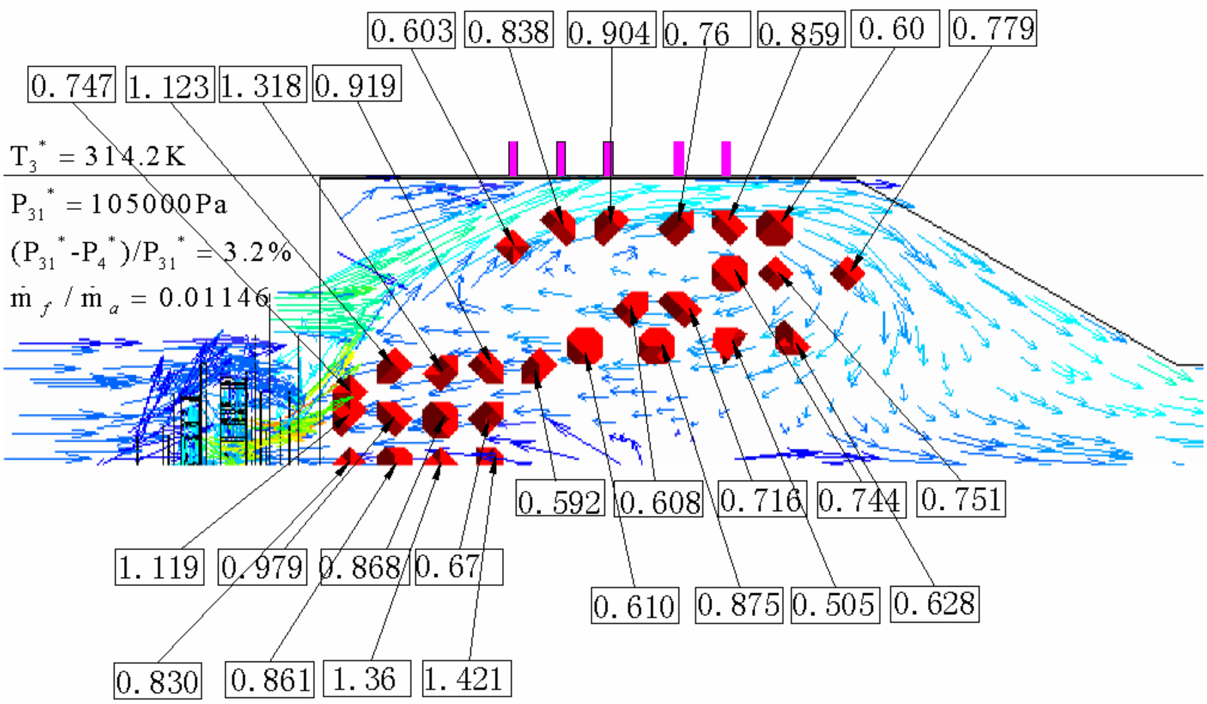



**Fig. 18** Distribution of Φ within the flow field.

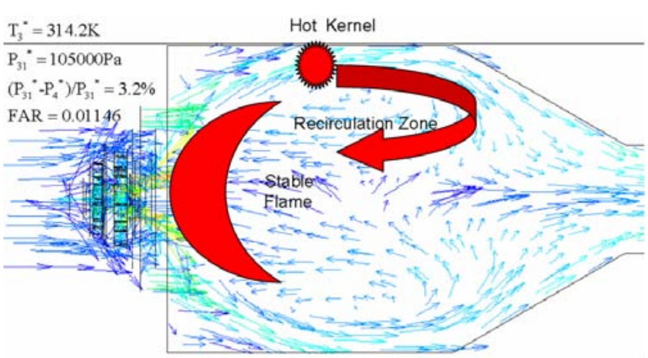



**Fig. 19** Schematic showing the ignition processes.

In view of the above simulated results, the ignition processes in the present LESS combustor are conjectured in Fig. 19. There is well-atomized fuel near the igniter locations with flammable Φ values to ensure the survival of the ignition kernel after spark penetrating through the near-wall air stream to ignite the fuel spray. The upstream propagation of the ignition kernel is facilitated due to the existence of recirculation zone together with the appropriate distribution of the local Φ values. In addition, there is a strong recirculation zone near the exit of the pilot swirl cup with high local Φ values, which favor the flame stability and subsequently lead to successful ignition within the combustor.

However, it has to be pointed out that the simulated equivalence ratio field using the standard k-ε model is only indicative of the potential of successful ignition, as the current CFD model does not take strong velocity gradients and high unsteadiness in the flow field into account. Further experiments and simulations of high fidelity are needed to fully understand the observed behaviors.

## SUMMARY

The ignition performance of a novel, ultra-low emissions combustor employing the LPP approach is demonstrated and investigated experimentally. The influence of igniter locations and pilot fuel nozzles on LLO FAR is studied using a single module rectangular combustor with normal inlet temperature and normal inlet pressure. Additionally, numerical analysis of non-reacting flow field and gas-liquid interactions are conducted to understand the underlying ignition processes. From the results of ignition tests and numerical analysis, the following conclusions are obtained.

For this novel combustor, the igniter locations have no significant influence over the lean ignition boundary for the conditions investigated. The lean ignition boundaries are found to be similar for the two pressure swirl atomizers employed that have slightly different flow numbers. When the air pressure drop is low, the LLO FAR increases with decreasing air pressure drop for liquid RP-3, while the LLO FAR holds fairly constant for gaseous methane. CFD-simulated results further demonstrate that there exist adequate recirculation zone and equivalence ratio distribution in the chamber, which help interpret and understand the ignition processes.

## ACKNOWLEDGEMENTS

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