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LBO PERFORMANCE COMPARISON BETWEEN TWO COMBUSTORS WITH DIFFERENT SWIRL CUPS

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ABSTRACT

Lean Blowout (LBO) performance is very important to the aero and ground gas turbine combustors. A typical liquid-fueled gas turbine combustor is the one with swirl cup dome which plays an important role to the LBO. The swirl cup dome comprises swirlers and nozzle usually. The swirlers serve to generate a toroidal flow reversal that entrains and recirculates a portion of the hot combustion products to mix with the incoming fresh air and fuel, so it makes the recirculation region the sustainable source of ignition. Swirlers in present study generally are two or three stages, and the nozzle takes different atomization styles, such as pressure-swirl atomization, prefilming and airblast atomization.

Different swirlers matching various nozzles form all kinds of swirl cup domes, and each swirl cup dome of combustor would have different LBO performance and other combustion properties resulting from its structure characteristics. The flow flux arrangement and spray distribution are the two important factors to determine the combustor performance.

Two combustor dome test rigs were investigated, of which one comprises with three air swirlers and a fuel prefilming nozzle (dome A), and the other is composed of two air swirlers and a fuel pressure nozzle (dome B). Tests were conducted to get the LBO fuel air ratio at atmospheric pressure. To explain the experimental results, numerical simulations were performed for cool flow fields of two combustors, also the cold flow field and spray of the two combustors' dome downstream were measured by PDA with water instead of kerosine. The flame pictures near LBO were taken.

The preliminary results indicated that the combustor with dome A had better spray uniformity than the one with dome B, but it had a little worse LBO performance.

The air flow mass percentage of the inner swirler of dome A should decrease to some extent in order to establish a lower pressure region at the outlet of dome A, which would be helpful to decrease the LBO fuel air ratio and so as to improve the LBO performance.

The two domes had their own advantages, and if the benefits of both were integrated, it was possible to design a better swirl cup dome.

Keywords: combustor, gas turbine, swirl cup, lean blowout, dome

INTRODUCTION

If the lean blowout fuel/air ratio of the aero-engine combustor near idle condition is less than or equal to 0.005 which is the design demand, the combustion in aero-engine could remain stable at high altitude and the flameout would not happen easily at maneuver flight [1-4]. The trend of the high temperature rise combustor development is that the fuel/air ratio at the design point needs further increase, while the smoke number is required to be less than a certain value.

These demands bring new challenges to the design of the dome assembly for atomization, the flow field structure in combustor, especially in the primary zone.

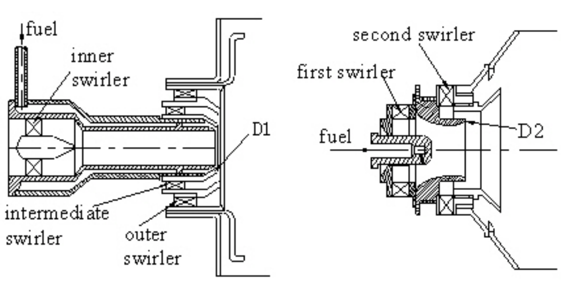
How to arrange the combustion process of the dome downstream is an important thing worthy of research. The relative references [5,6] have done some fundamental studies about lean blowout early. For decades, as the requirements of widening the stability range and smoke emission reduction, the air swirler in combustor dome has developed from single-stage [7] to dual-stage and three-stage [8-11], and the nozzle from the pressure-swirl atomization to the air-blast atomization and combined atomization [12].

The advantages of the air-blast atomization nozzle are that the combustor outlet temperature pattern is not affected by the change of the fuel mass flow rate, the temperature of the combustor liner is lower, and the smoke emission is relatively less at design point. The disadvantages are that the combustion stability range becomes a little narrower and the fuel atomization quality is very poor at take-off or altitude relight, which is due to the very low velocity of the air flowing through the combustor dome, so that the relative velocity between oil film and air is very low, therefore the air stream does not exert shearing action on the oil film strongly.

From the design viewpoint, the three-stage air swirlers may be used to enhance the control of the fuel-air mixing process at the dome outlet in the primary combustion zone, and to reduce the smoke emission. The research contents in this paper are the comparison of the experiments at blowout and numerical simulations between two combustors with two different domes, one is the three-stage axial swirl cup dome and the other is dual-stage radial swirl cup dome, in order to improve the design of the three-stage swirl cup dome and widen the combustion stability range.

2 TWO KINDS OF DOMES

Fig.1 (a) shows A-type swirl cup dome which contains three-stage swirlers: inner, intermediate and outer swirler. The intermediate swirler and inner swirler are counter-rotating, and the outer swirler and intermediate swirler are in the same swirling direction. The three are all axial swirlers and the swirl vanes are all helical. The fuel in dome A flows through helical



（a）Dome A （b）Dome B

Fig.1 The sketchs of two domes

channel and forms the film at the place D1 showed in Fig.1 (a) , then is discharged. The oil film is acted upon by the impact and shearing action of the air from the inner and intermediate swirlers, which belongs in air-blast atomization.

Fig.1 (b) shows B-type swirl cup dome which has dual-stage swirlers: the first stage and second stage swirlers whose swirling directions are opposite, and these two are all radial swirlers with which the pressure atomization nozzle matches.

The two domes's test rigs are shown in the Fig.2.

（a）Dome A

（b）Dome B

Fig.2 The test rigs of two domes

The inner swirler of dome A provides the central swirling air of the dome, while the intermediate axial swirler with helical vanes provides the air which blows to the oil film directly, and the outer swirler (the third stage) is used to improve atomization distribution.

The first-stage swirler of dome B provides the air to help the fuel to impinge on the venturi wall to form the oil film, while the second-stage swirler provide the air to impact and shear the film into droplets, so that the fuel can be atomized.

The test rigs used in the experiments are typical rectangular combustors with single swirl cup dome. The opening area percentage of the combustor liner is as follows: the opening area of the dome accounts for 28.8%, the primary holes 29.4%, the dilution holes 19.4 %, and the air film cooling orifices 22.4%.

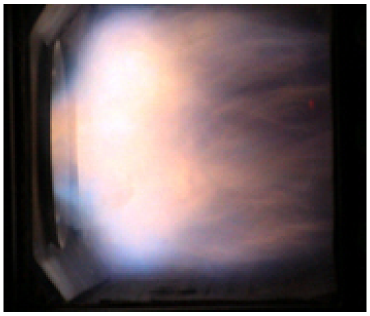
3 LEAN BLOWOUT EXPERIMENT

In the lean blowout experiments, the combustor inlet air was provided by the centrifugal fan, and the inlet air was heated by electric heater. The flow rate were changed by adjusting the electric control valve, and the inlet air temperature was changed by adjusting the power of the electric heater.

The lean blowout experiments of the single dome combustors with dome A or dome B were performed at atmospheric pressure condition. The key experimental processes in turn were to as follows: keep the inlet air velocity almost constant; change the fuel (kerosine) flow rate by adjusting the needle valve to near lean blowout; and then make fine tune of fuel flow rate slowly until flameout, record the fuel flow rate of the flameout time at each of air flow rates studied, so the lean blowout fuel/air ratio and its changing trend with different inlet temperatures could be achieved.

The flame pictures near lean blowout were taken, as shown in Fig.3.

（a）Dome A downstream



（b）Dome B downstream

Fig.3 The flame pictures near lean blowout

The comparison of experimental results at lean blowout are shown in Table 1, where $\dot{m}_a$ is the inlet air flow rate of the combustor, P^* is the combustor outlet pressure, T_3^* is the inlet air temperature, $(f/a)_{LBO}$ is the lean blowout fuel/air ratio.

Table 1 The lean blowout experiment results of two combustors at atmospheric pressure

Dome Type	$\dot{m}_a$ (kg/s)	P^*(Pa)	T_3^*(K)	$(f/a)_{LBO}$
Dome A	0.1313	101470	360	0.0065; 0.0066
Dome B	0.1364	101470	355	0.005; 0.0051

As shown in Table 1, the lean blowout fuel/air ratios of the two combustors with dome A and dome B respectively are much more different under the very similar experimental condition, which indicates that the different types of dome have great influence on the lean blowout experimental results.

In addition, the combustion phenomena of the two combustors near lean blowout could be compared from Fig.3. Their main features are shown in Table 2.

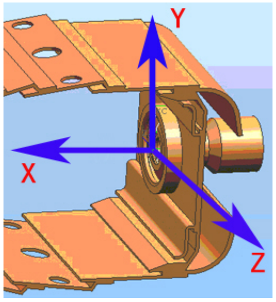
Table 2 The lean blowout flame phenomena comparison of the two domes at atmospheric pressure

Dome type	Combustion phenomena
Dome A	a) There is not a flame ball obviously, and the flame is scattered. b) The flame is stretched longer along the centerline of the combustor dome A downstream.
Dome B	a) There exists a flame ball obviously. b) The flame is very short along the center line of the combustor dome B downstream.

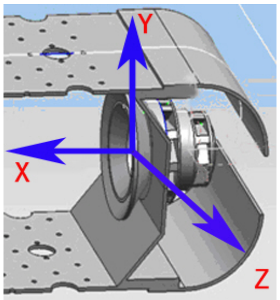
As shown above, the combustion phenomena at lean blowout of the dome downstream of the two combustors with different domes are very different, which may be relative to the difference of the lean blowout fuel/air ratios of the two combustors. As the organization and structure of the flow field in the combustor dome downstream may have great influence on combustion performance, the numerical simulations are performed below to analyze the flow field in the primary combustion zones of two combustors with different domes, and the flow field and spray size distribution of the two different domes are detected by PDA (Phase Doppler Analyzer), in order to explain the combustion phenomena above.

4 NUMERICAL SIMULATION OF COLD FLOW FIELD

4.1 Geometry and boundary conditions



（a）with dome A



（b）with dome B

Fig.4 3D geometry and coordinates of the combustor

As shown in Fig.4, the geometries used in the numerical simulations of the single-dome combustor refer to the typical modern aero-engine. The air flows through the diffuser and then is divided into four parts mainly to enter into combustor, one of which enters from the dome, the second part from primary holes, the third from dilution holes, and others from the film cooling holes. The mass flow percentage of the four streams refers to the typical percentage. The numerical simulations are three-dimensional, and the origin of coordinates is located at the center of the exit of the outer swirler or the second swirler. As the geometry structure is complex, the unstructured grids are applied, and the local grids of the swirler, the primary holes and the dilution holes have been refined. The total number of the cells of two combustors is around 1.8 million respectively.

The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) is taken as the numerical solution method, and a steady flow is assumed. RNG $k-\varepsilon$ turbulence model and the standard wall function method are taken. The inlet mass flow rate and outlet pressure are given as boundary conditions, and their values are consistent with those in Table 1 above. For the sake of reasonable simplification, the two vertical sides of the single dome rectangular combustor are treated as adiabatic solid walls. The momentum conservation equation's discretization uses the first order upwind scheme. The convergence acceleration of multigrid is performed during calculation process.

4.2 Numerical results

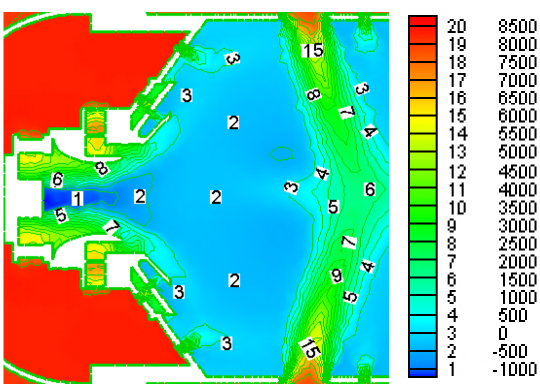


Fig.5 The relative total pressure distribution of dome B downstream(Z = 0 cross section)

As shown in Fig.5, the relative total pressure of dome B downstream along the axial direction (X direction) is in turn: -1000 Pa (contour number 1), -500 Pa (contour number 2), 0 Pa (contour number 3), 500 Pa (contour number 4), 1000 Pa (contour number 5), 1500Pa(contour number 6), obviously it is to say, the relative total pressure increases gradually. In Fig.5, the absolute total pressure value equals the relative total pressure plus 102500 Pa. It can be found that there is a large region of low relative total pressure at the axis center of swirl cup outlet of dome B, which can help the air flow backward to form recirculation.

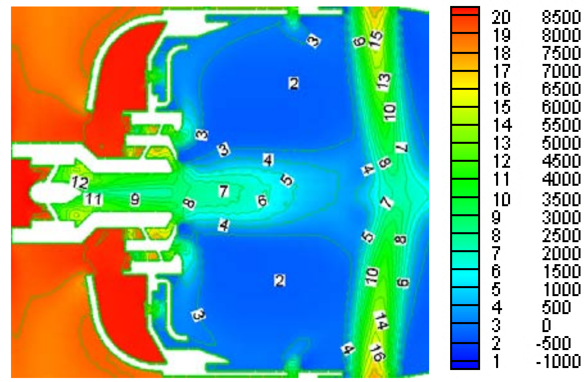


Fig.6 The relative total pressure distribution of dome A downstream (Z = 0 cross section)

As shown in Fig.6, the relative total pressure of dome A downstream along the axial direction (X direction) is in turn: 4000(contour number 11), 3000(contour number 9), 2500(contour number 8), 2000(contour number 7), 1500(contour number 6), 1000(contour number 5), 500Pa(contour number 4), obviously, the relative total pressure decreases gradually. In Fig.6, the absolute total pressure equals the relative total pressure plus 102500, and their unit are all Pascal.

It can be found that the relative total pressure distribution of dome A downstream compared with dome B has very different characteristics as follows: First, the region of low total pressure near the dome B downstream is larger than dome A downstream; Second, the direction of relative total pressure' decrease along the center axle in Fig.5 is exactly opposite with the one in Fig.6, although the low static pressure distributions in the dome A and dome B downstream are similar, which can be further seen from the Fig.7 and Fig.8 below.

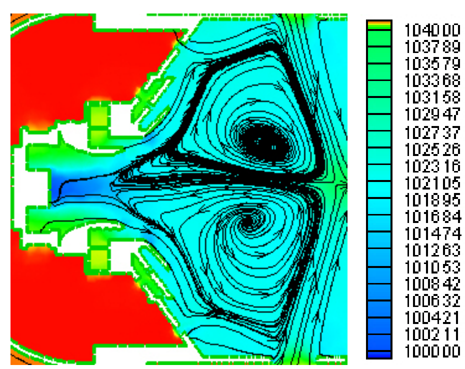


Fig.7 The static pressure distribution and streamline map of dome B downstream (Z = 0 cross section)

It can be known from Fig.5 and Fig.7, since there is a large region of low static pressure and low relative total pressure, the air flows backward to the swirl cup dome under the adverse pressure gradient, and the big recirculation zone of approximate axial symmetry is formed in the primary zone with the assistant help of the two rows of primary holes, as shown in Fig.7. This flow field structure is conducive to improve the combustion stability.

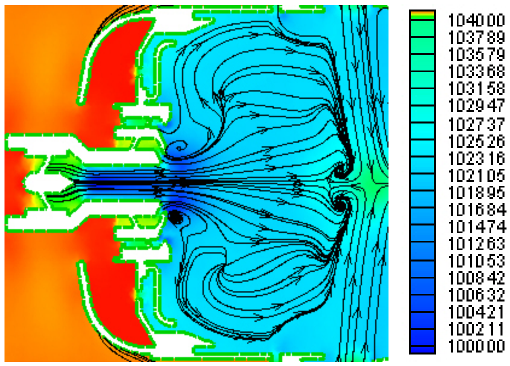


Fig.8 The static pressure distribution and streamline map of dome A downstream (Z = 0 cross section)

It can be found in Fig.8 that there is not recirculation zone obviously in the Z=0 cross section of dome A downstream. Meanwhile, there is also not a little recirculation in the short channel after the inner swirler vanes, and this is mainly because the flow in the short channel is a full flow.

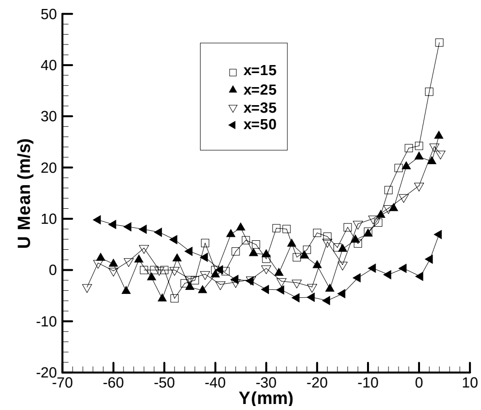
As shown in Fig.8, the air flow through the inner swirler has been always going straight forward, and then meets with the jet air from the primary holes at last, this flow structure is not appropriate for the formation of the big and strong recirculation zone in the Z=0 cross section. Even though the recirculation zone may be found in other cross section of dome A downstream, it would be not so strong as well as the one of of dome B downstream.

In addtion, the pressure drops of the combustors with dome A or dome B are almost the same. It can be found from the comparison above, the organization and structure of the flow field may have a very significant impact on the combustion performance. Specially, the conditions of the recirculation zone have a direct impact on the combustion stability. Moreover, the air mass flow percentage of inner swirler of dome A may be too great (the air flow mass percentage of the inner, intermediate and outer swirlers is 24% / 32% / 44%), which isn't conducive to the formation of the recirculation zone and the reduction of the lean blowout fuel/air ratio, so the air mass flow ratio of the swirlers should be reapportioned. Meanwhile, the channel of the inner swirler in dome A should be designed in a streamline shape which means the flow area decrease gradually at first and then expand, so then it can not only inhibit the growth and separation of the boundary layer, but also help the formation of the low pressure region near the dome A outlet.

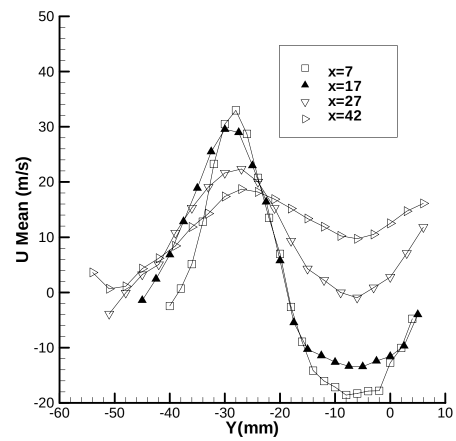
5 EXPERIMENTAL SIMULATION OF TWO DOMES

The spray drop size distribution measures of the two domes are performed. Just taking account of the influence on the spray of air flow in the dome, the primary holes and the dilution holes have been taken off when doing PDA tests of the two domes, which is different with the geometry structure and the numerical simulation described above. The coordinate system used in the PDA measures is same with the one used in the numerical simulation above.

The spray simulations are performed at atmospheric pressure condition. The dome downstream's outlet pressure is atmospheric pressure. Water is used to simulate the kerosine, which means the atomization in real combustor dome could be better than the test results here, because the surface tension of water is larger than the kerosine. The pressure drops of the dome A and dome B are almost alike. The air/water mass ratio is 4.86 when test to dome A (the air mass flow rate is 0.035kg/s, and the water mass flow rate is 7.2g/s); the air/water mass ratio is 4.15 when test to dome B (the air mass flow rate is 0.032kg/s, and the water mass flow rate is 7.7g/s). It is generally believed the air/liquid mass ratio large than 3 is enough. The representative measurement results are shown in Fig.9 and Fig.10.



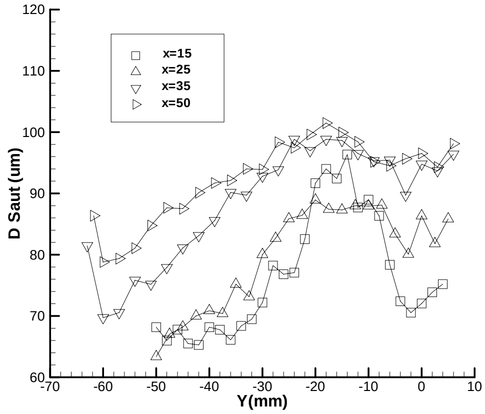
(a) Dome A



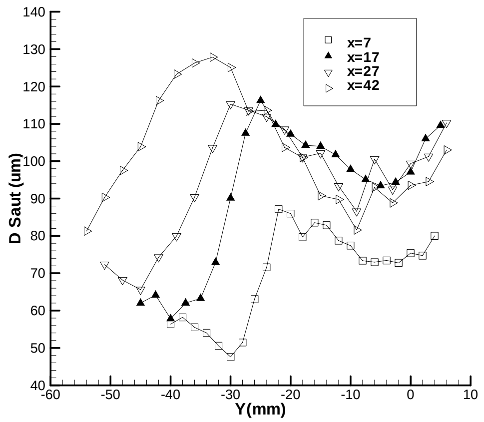
(b) Dome B

Fig.9 The average axial velocity of the two domes downstream

As shown in Fig.9, the different symbols represent the average axial velocity values measured at different axial distances of X (unit is mm) off the origin. It can be found in Fig.9 that the air flow at axis centerline of dome A goes strongly straight forward and the recirculation zone is neither centralized nor distinct. However, the recirculation zone of dome B downstream seems to be distinct and centralized. Obviously, dome B is more conducive to the stability of combustion.



(a) Dome A



(b) Dome B

Fig.10 SMD distribution the two domes downstream

It can be found from Fig.10 that dome A's atomization performance is good relatively, because the water droplet SMD (Sauter Mean Diameter) range covers from 60 to 100 micron, and the drop size distribution is more uniform relatively, While the SMD distribution of dome B is more scattered, ranging from 50 to 130 micron. For dome A, the air through the inner and intermediate swirler blows directly to the oil film exit, impacting and shearing the oil film, so that it has better atomization performance than dome B, which is helpful to reduce smoke number. However, the characteristics of more dispersive droplet size distribution of dome B (on the premise of meeting the requirements of atomization) contributes to the combustion stability at light load condition.

6 CONCLUSIONS

The results of numerical simulation and experiments indicate that:

a) The air-blast of dome A has a relatively better atomization uniformity performance, and the three swirlers of dome A do good at fuel-air mixing, whereas the lean blowout performance of the combustor with dome A is not as good as the one with dome B.
b) The air flow mass percentage of inner swirler of dome A should not be too great, otherwise it isn't conducive to the formation of the recirculation zone of the dome downstream.
c) The dual-stage swirl cup dome, like dome B, is a typical design, still needs to further improve its spray performance for the future use.

How to utilize comprehensively the respective merits of the two kinds of domes to design a better swirl cup dome, which can widen combustion stability range and improve the performance at the low load condition, is a subject to need further research.

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