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INVESTIGATION ON THE LEAN BLOW-OUT CHARACTERISTICS IN CONCENTRIC STAGED COMBUSTOR

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ABSTRACT

Considering the flame stability of gas turbine combustor, acceptable Lean Blow-Out (LBO) limit at the idle state plays key role in the process of designing combustor. The high temperature rise resulting from the requirement of high thrust-to-weight ratio means high fuel-air ratio. It is inevitable for combustors to face the contradiction between the low exhaust smoke levels at operating condition and appropriate lean blowout performance at idle condition. The fuel-air ratio is an important design requirement for aero-engine combustor. In order to eliminate smoke, the design of the main combustion zone tends to be lean premixed. Under idle condition due to the main combustion area of the air greatly increased, the average flow velocity increases, which make the LBO fuel-air ratio seriously increased.

For the high temperature rise combustor, in order to compromise of lean blowout under idle condition and the smoke emission under operating condition, numerical modeling is carried out to investigate the relationship between lean blowout performance and combustor inlet air aerodynamic parameter. The paper designs a single-tube combustor model and put forward a kind of center-staged combustor whose head is divided into co-axial pilot and main modules. In addition, the influence of combustor inlet air aerodynamic parameter, including air inlet pressure, temperature and rate of flow, on the lean blowout performance at idle state was analyzed. To achieve these, the paper uses the eddy-dissipation concept model with ten step detailed chemical reaction mechanism to simulate the combustion process. Standard k-ε turbulence model and structure and non-structure hybrid grid are adopted to deal with the complexity of the combustor. The LBO fuel-air ratio of the combustor is obtained by the fuel steady approximation method. The results show that the main and pilot modules combustor produced the recirculation zone downstream of the pilot module, and the main module does not produce the recirculation zone. The main and pilot modules airsdo not interfere. The LBO fuel-air ratio of the combustor is 0.0043, and the outlet temperature rise of the combustor decreases with the decrease of the fuel-air ratio of the combustor. By consideration of this tendency and the reasons behind will provide meaningful suggestion to designing high performance combustor. [**Keywords:**gas turbine engine; combustor;lean blowout limit;inlet air aerodynamic parameter]

INTRODUCTION

Unceasing rise of aeroengine' s thermal parameters and thrust mass ratio lead to high temperature rise and high Fuel Air Ratio(FAR) in combustor. Correspondingly, the FAR in combustor primary zone also increase to the extent that result in the appearance of severe exhaust smoke under operating condition. Experiments conducted by Mellor et al[1] have found that if the equivalence ratio reach 1.4-1.5, the trouble of exhaust smoke is likely to happen, as we can see from the Figure1. With the increase of equivalence ratio in primary zone, the operating point will climb along the line A-E from 1.2 to the visible smoke threshold without little change of existing combustor structure. Another problem of high FAR combustor is the lean blowout at idle condition. At present, two main theories have been raised to explain the phenomenon. Lefebvre et al[2]put forward thermal balance theory and believe that the reason for the situation is that the heat produced by reaction between the fresh fuel and air is unable to ignite the coming fuel.Meanwhile, Three time scale, including fuel droplet evaporation time, chemical reaction consumption time, and residence time in shear zone of recirculating zonewere defined in characteristic time theory raised by Mellor et al[1]. The theory think that if the residence time in shear zone of recirculating zone is less than the sum of another two, The flame will extinguish.

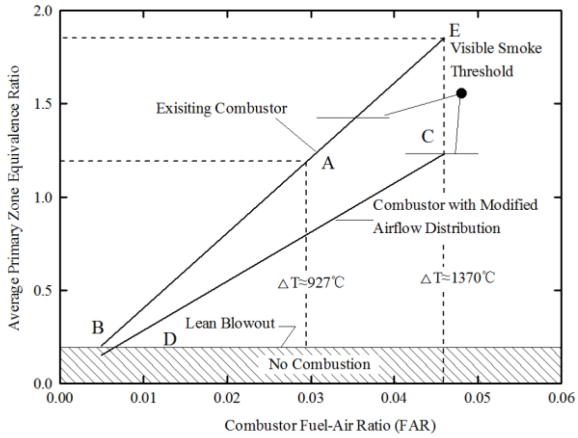


Figure 1 Primary Zone Equivalence Ratio - Combustor Fuel-air Relationships of F101 Combustor

To solve the problem above, many schemes have been designed. These approaches involve either fuel staging or air staging techniques, or combinations of both[3-6].Clean Combustor Programme implemented by NASA adopted selective injection to realize different nozzle group or series fuel kerosene at different working condition. The result of experiments indicated that the lean blowout limit was extended to lower levels, when CF6-50 combustor used this kind of domedesign[7]. Yuan Y.X.et al[8] and Li J.B. et al[9]design the double-head rectangular combustor to verify the effect of radial fuel staging on lean blowout performance. The experimental result shows that the falling range of lean blowout limit is up to 0.001. The tendency can be repeated at the state of local rich-fuel. Except the fuel staging, air staging is selectiveapproaches to improve lean blowout performance. These approaches include variable area features in the combustor inlet cowl, the dome swirl cups and the liner dilution ports, and combinations of these features[3].Based on these designs[10-11], the combustor display acceptable lean blowout characteristics.

The paper designs a scheme including concentric staged head consists of co-axial pilot and main modules and liner with effusion cooling structure.Pilot module nozzle operating at idle condition alone is located in the center and main module working with the pilot module together at takeoff condition encircle the former. The swirling flow fieldcreated by swirlers of two modules will not interfere with each other due to appropriate selection of distance between two modules. Swirling intensity should be controlled to avoid the quench to flame because of interference produced by swirling current that come from the main moduleswirler at idle condition. To optimize the scheme, combustion characteristic and flow field distribution should be analyzed based on the result of numerical modeling. Moreover, another purpose of the study is to test the effect of inlet aerodynamic parameter, including air inlet pressure, temperature and rate of flow, on the lean blowout characteristic at idle state.

DESIGN OF STRUCTURE OF COMBUSTOR

The scheme of combustor domeis shown in Figure 2, it is consists of main module and pilot module. The co-axial pilot and main module scheme was promoted based on the idea of staged combustion, the scheme aim to form separated pilot and main combustion zone[12]. Pilot modules including swirler, single nozzle and convergent section work at idle condition. The main modules that are composed of swirler, convergent section and multi-piont direct injection nozzles increase thefuel supply with the rise of power requirement at operating condition. The use of bladed swirler is one of the mosteffective means of generating swirl, and there does not appear to be a very significant difference between flat-bladed and aerodynamically shaped swiriler blades[13].Thus flat-bladed is adopted due to the convenience of manufacture. In addition, to deal with the problem of interference between two swirling flows, Non-swirling section of main module is designed to weaken the effect of swirling flow. Finally, the combinations of swirling and non-swirling flow are employed to separate mutual interference between two modules. The profile of center-staged combustor shown in Figure 3, The detailed parameters are shown in table 1.

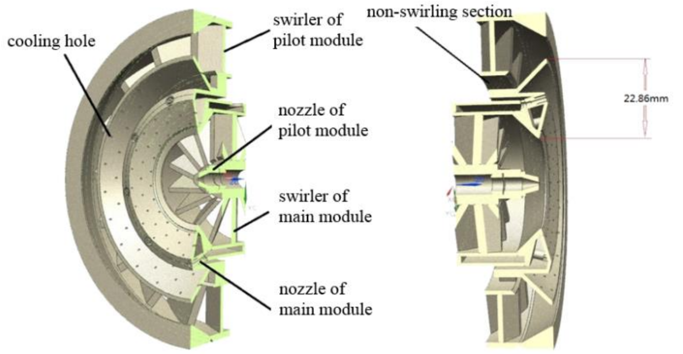


Figure 2 Scheme of Combustor Dome

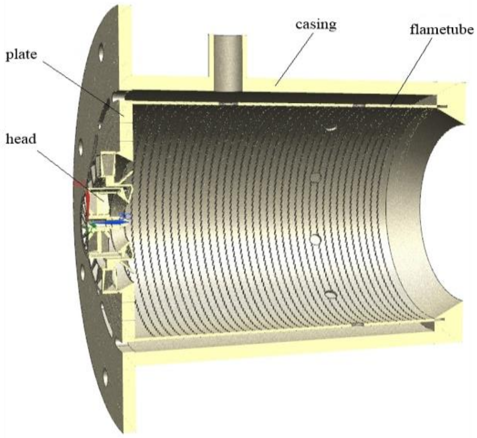


Figure 3 Profile of Concentric staged Combustor

Table1 Design Parameters of the Combustor

Parts	Parameters	Values
Pilot modules	SwirlerInternal Diameter	12mm
	SwirlerExternal Diameter	41mm
	Passage Length	13.94mm
	Outlet Diameter	26.77mm
Main modules	Air Ratio between Swirling and Non-swirling Flow	2:1
	Internal Diameter of Air passage	55.8mm
	External Diameter of Non-swirling Air Passage	63.8mm
	Swirler Internal Diameter	66.2mm
	Swirler External Diameter	93mm
	Passage Length	19.55mm
	Annular Internal Diameter	72.49mm
	Annular External Diameter	75.19mm
Flame Tube	Internal Diameter	165mm
	External Diameter	169mm
	Thickness	2mm
	Length	210mm
	Convergence Region Angle	45°
	Axial position of Mixing Hole	152mm
	Diameter of Mixing Hole	9mm
	Amount of Mixing Hole	10
	Diameter of Cooling Hole	0.55mm
	Amount of Cooling Hole	4320
Plate	Diameter of Cooling Hole	0.5mm
	Amount of Cooling Hole	437

High temperature rise means more air is needed to cooling falmetube or cooling efficiency should be enhanced obviously. To achieve these, effusion cooling structure with tangential inlet air was adopted to improve the efficiency of liner cooling. The structure has the advantages over the conventional cooling design in fields of manufacture, design and maintenance. Yu H., et al[14] study the cooling structure, the result shows thatthe scheme can satisfy the cooling requirement with only 20.87% cooling air in the combustor of same model as the paper.

Air flow distribution is an important portion of combustor design, the author distribute air flow percentage based on effective flow area after confirming flow coefficient of each flow section. The key to the process is estimating liner cooling air. Considering the design of advanced effusion cooling structure with tangential inlet air, according to empirical values and design experiences, dome and liner cooling air occupy 36% of total air. Detailed air flow distributions are shown in Table 2.

Table 2 Scheme of Air Flow Distribution

Parts	Parameters	Values
Combustion air	Main module air	39%
	Pilot module air	13%
	Dome cooling air	3%
Liner cooling air		33%
Dilution air		12%
Total		100%

NUMERICAL MODELING

In face of the high expense of the combustion experiments and difficulties of precise measurement, numerical modeling can be a good option.SturgessG. J. et al put forward the complex model to predict lean blowout by combining CFD and reactor network method[15][16]. RANS as a prevalent approach used in numerical simulation, is suitable to fully developed turbulent flow[17].Thus k-ε model is employed to satisfy the condition of high Reynolds number(Re). Mass flow inlet, adiabatic wall and pressure outlet was adopted as boundary conditions of the entrance, wall and exitrespectively. In order to ensure the accuracy of numerical simulation and predict the existence of some substance, the combustion model should be considered carefully. As the further development of the Eddy-dissipation model(ED), Eddy-dissipation concept model (EDC) was designed specially to improve the computational process of chemical reactions, which contains detailed combustion reaction mechanism and procedures. The basic principle of the model think that reactions happen inside small turbulent structure which is so called finestructure through a default time scale. The molecular formula of the hydrocarbon is assumed to be $C_{12}H_{23}$, and the supersonic freestream was composed of 21% O_2 and 79% N_2[18].Then ten steps chemical equations employed by the paper is described as follows.

$$4C_{12}H_{23}+47O_2 \rightarrow 48CO+46H_2O$$

$$H_2+O_2 \leftrightarrow H_2O+O$$

$$H_2+O \leftrightarrow H+OH$$

$$H+O_2 \leftrightarrow O+OH$$

$$CO+OH \leftrightarrow CO_2+H$$

$$H_2O+O_2 \leftrightarrow 2O+H_2O$$

$$CO+H_2O \leftrightarrow CO_2+H_2$$

$$N_2+O \leftrightarrow N+NO$$

$$N+O_2 \leftrightarrow NO+O$$

$$N+OH \leftrightarrow NO+H$$

The key to the numericalmodeling is obtaining the lean blowout limit exactly. To achieve the goal, steady approximation approach[19] has studied, the results of predictions are in agreement with corresponding experimental data. This method keep volume of inlet airflow constant during the whole computational process and decrease the FAR to a certain level gradually. The specific processes consist of the following steps: firstly, numerical simulation begins from state of idle condition that FAR is higher than lean blowout limit. Secondly, we will decrease FAR from original steady state of numerical calculation to next steady state and then judge whether the lean blowout has happened according to preset standard. Thirdly, iterating is needed. According to the engine operation process, the temperature rise of self-sustaining state which don't output power is about 80K, and therefore 80K temperature difference between inlet and outlet is set as the preset standard to judge the appearance of lean blowout phenomenon[20]. The empirical value is obtained from the report of NASA about double annular combustor. Finally, we can obtain the FAR at the state of lean blowout.

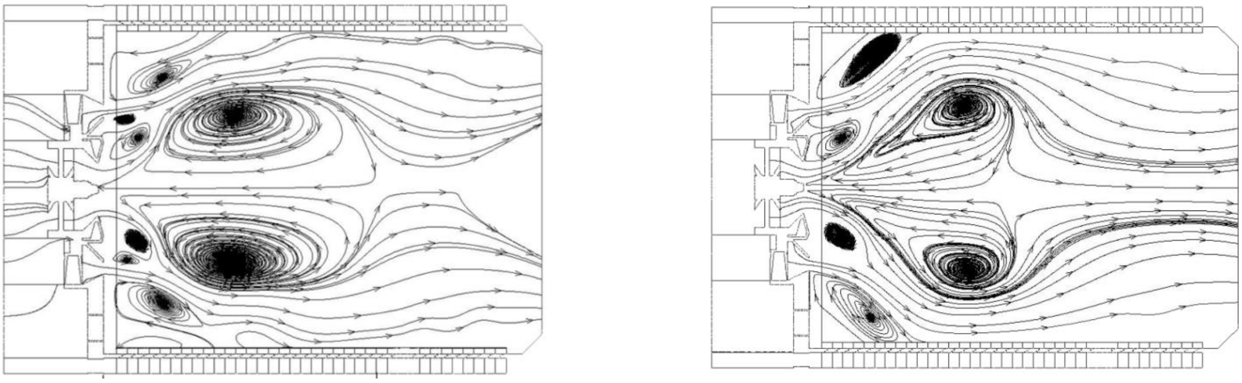
RESULTS AND DISCUSSION

The detailed working condition parameters are listed as Table 3. Figure 4 presents the flow field obtained from modeling work. The variable-controlling approach used in the following analysis of the effect of inlet aerodynamic parameter on lean blowout performance is based on the working conditions.

Table 3 Parameters of Basic Working Condition

Air inlet temperature	489.1K
Air inlet pressure	490238Pa
Inlet air flow	1.175kg/s
Fuel flow	0.0125kg/s

A pair of recirculation zones with axisymmetricdistribution is located in the center section of combustor, which form the primary zone. As we can see from the Figure 4, The difference of flow distribution between two working conditions is obvious. In thescheme of high temperature rise combustor, the primary holes in combustor tube are cancelled. That means the shape of recirculation zone mainly depend on the pilot module swirler. Furthermore, we can find that the size of recirculation zones at idle condition appeared bigger in radial direction but narrower in axial direction when compared with the recirculation zones at operating condition. At idle condition, the recirculation zone of the combustor ranges from 30mm to 169mm in the axial direction. At operating condition, the recirculation zone of the combustor ranges from 30mm to 95mm in the axial direction. Reasonable theoretical explanation is that feeble coupling between pressure and density due to low thermal parameter lead to weak swirl flow at idle condition which result in smaller and more flat recirculation zone, contrary to the situation at operating condition. Because of the drastic change of thermal parameters between two working conditions, more heat produced by combustion cause the variation of pressure gradient, density gradient and dilatation of airflow velocity. Then, the coupling effect of air pressure and density is very strong, the center of pressure and density move along radial direction to upstream section, forming a large-angle recirculation zone.



(a) At idle condition **(b) At operating condition**

Figure 4 Flow Distribution at Two Conditions

Figure 5 shows the superposition of flow field and temperature field and present fine results. High-temperature zone concentrate in recirculation zone entirely. The temperature in boundary of recirculation zone is below 1500K. That means the air coming from main module flow along the external frontiers of recirculation zone rather than participate in combustion, then guarantee the relatively high local equivalence ratio in primary zone so that lean blowout limit can be reduced to a lower level. On the other hand, appropriate temperature and flow field distribution illustrated that 22.86mm as the distance between two modules is so reasonable that the quench effect produced by swirling flow of main modules can be avoided. Moreover, double vortexes appeared in the area between the exit of main module and pilot module, which is so called lip vortex. The vortexes enhanced the heat transfer between the high temperature gas and the dome structure so that the temperature of solid wall will increase. Thus cooling holes should be considered in the scheme of combustor dome design.

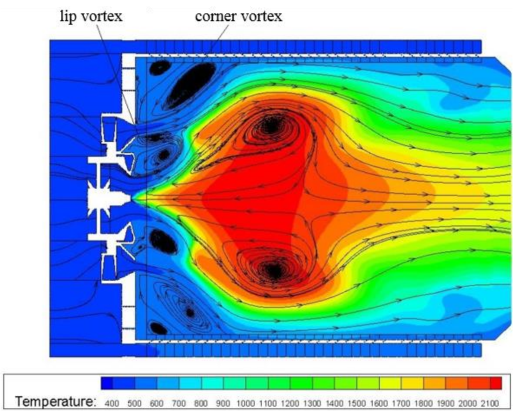


Figure 5 TheSuperposition of Flow and Temperature Field

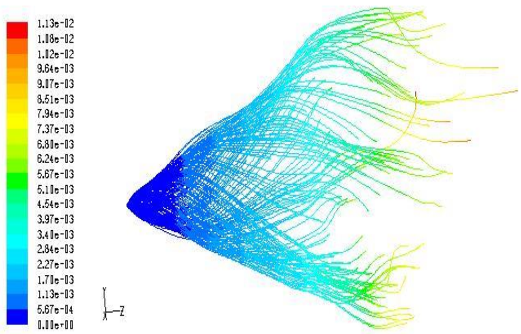


Figure 6 Distribution ofInjector Spray Droplet at Idle Condition

Figure 6 shows space distribution injector spray droplet at idle condition, it can be seen from the figure, the droplets along the flow direction are sprayed uniformly along cone angle 30º, form a good atomization. This can make the fuel and air mixing and combustion in the recirculation zone, improve combustion efficiency.

EFFCT OF INLET AERODYNAMIC PARAMETERS ON LEAN BLOWOUT LIMIT

Aerodynamic parameters have significant effect on the lean blowout performance. Therefore, the paper puts forward steady approximation approach to investigate the lean blowout limit of concentric staged combustor. Moreover, the paper also choses three critical parameters, including inlet air temperature, inlet air pressure and inlet air flow rate, to research the relationship between the aerodynamic parameters and lean blowout limit through the numerical modeling. The detailed research and analysis describe as follows.

With fuel steady approximation approach, when the fuel supply is close to the lean blowout limit until the combustor outlet temperature rise to less than 80K, the FAR in this moment is lean blowout FAR. The calculation of all the conditions, the combustor outlet temperature rise along FARis shown in Figure 7, it can be seen from the figure, the combustor outlet temperature rise decreases along with the FAR decreases.The outlet temperature riseof combustor reaches 143.5K when the FAR is 0.0043, then, the outlet temperature rise of combustor reaches 11.6K when the FAR is 0.0042, this moment the combustor has been lean blowout. The combustor blowout limit of FAR is 0.0043.

The lean blowout limit measured in the combustor test is 0.00571. The comparison shows that there is a certain gap between the test and the calculated parameter. This may be caused by the following two reasons. 1) The effect of heat transfer between combustor flame tube wall and gas is not considered in numerical simulation. However, there is still some heat exchange between the flame tube and high-temperature gas in the combustor during the experiment, which can reduce the gas temperature in the combustor to a certain extent. According to the flame stabilization mechanism in the combustor, higher reflux gas temperature will be more conducive to the ignition of fresh fuel air mixture. This will lower the lean shutdown point. Therefore, the fuel-air ratio of lean and flameout combustor calculated numerically is lower. 2) There is a certain deviation between the fuel atomization particles and their distribution in the numerical calculation and the experimental combustor. This will lead to a certain difference between the lean oil blowout limit value obtained by numerical calculation and the test value.

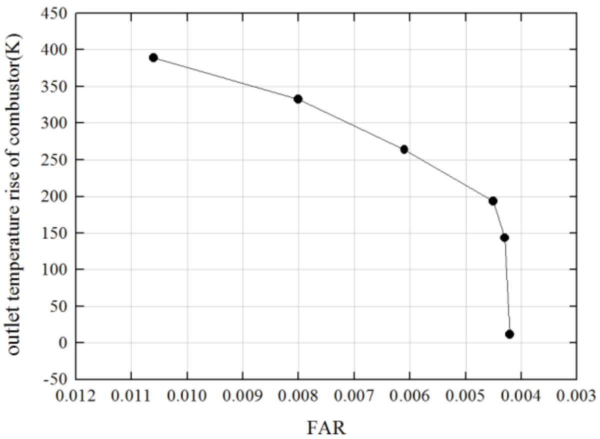


Figure 7 Outlet Temperature Rise of Combustor

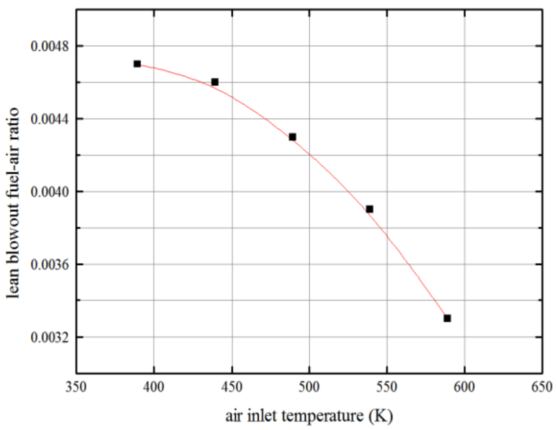


Figure 8 The Effect of Air Inlet Temperature on Lean Blowout

Effect of Air Inlet Temperature

Inlet air temperature is crucial to efficient operation of aeroengine. High inlet air temperature means high pressure ratio which is the developmental trend of advanced aeroengines. Thus, the research on the effect of inlet air temperature on lean blowout performance is very important. Five different inlet air temperatures are chosen to reveal their relationship with lean blowout limit. Five different temperatures was chosen to research the effect of air inlet temperature on lean blowout limit. It can be seen from Figure 8, lean blowout fuel-air ratio decreased progressively with the increase of temperature, so the lean blowout performance was improved.

Higher air inlet temperature leads to faster evaporation of fuel droplet and better fuel-air mixture, which bring higher heat release rate and combustion efficiency. The result indicate that the combustion efficiency will surge from 98.23% to almost 100%, when air inlet temperature rise from 389.1K to 589.1K. Meanwhile, the flame stability can be maintained in wider range. In addition, the increase of inlet air temperature mean less heat required to ignite the following fuel-air mixture so that lower the threshold of ignition. The lean blowout limit can be reduced to lower level correspondingly.

Effect of Air Inlet Pressure

As ideal gas, the air density will rise when the air pressure is increased. Of course, air molecular distance will decrease correspondingly. That can rise the probability of molecular collision and improve fuel liquid film breakup and droplet atomization, so that fuel-air mixing efficiency will be enhanced. At final, the lean blowout performance will be improved.

The author selected 5 different total air inlet pressures to carry out numerical modeling. As we can see from Figure 9, The results illustrated that the lean blowout limit decrease dramatically with the increase of total pressure.The falling range proved air pressure is an important factor that influence the lean blowout performance. Furthermore, the increased molecular collision promote the chemical reaction, accelerate flame propagation and rise heat flux density. These advantages will not only keep flame more stable, but also be beneficial for high temperature gas to ignite the following fuel-air mixture.

Effect of Inlet Air Flow

Fundamentally speaking, variation of inlet air flow means change of total fuel-air ratio. The paper select 5 different numerical values as inlet air flow to investigate the influence of inlet air flow on lean blowout performance. As we can see from the Figure 10, the decrease of inlet air flow lead to lower lean blowout fuel air ratio. The relationship between the both is basically linear. When the inlet air flow decreases from 1.175kg/s to 0.9005kg/s, the lean blowout fuel air ratio also decreases from 0.0043 to 0.0030; When the inlet air flow decreases from 0.9005kg/s to 0.692kg/s, the lean blowout fuel air ratio also decreases less, from 0.0030 to 0.0026. Inclination degree of the former curve is more than the latter.

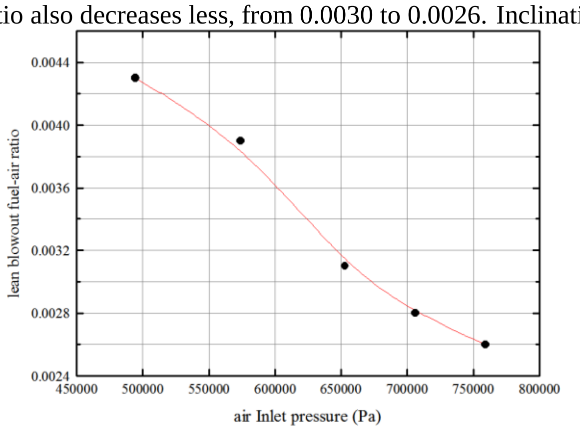


Figure 9 TheEffect of Air Inlet Pressure on Lean Blowout

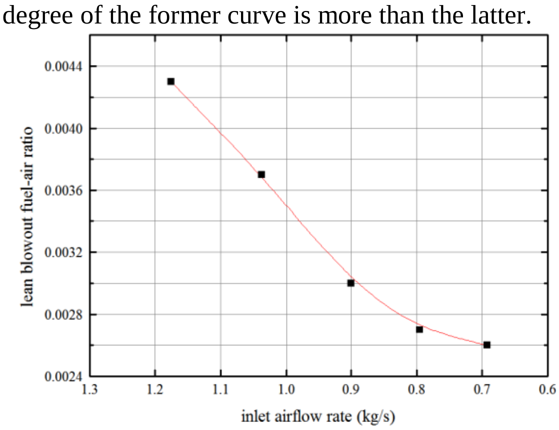


Figure 10 The Effect of Inlet Air Flow Rate on Lean Blowout

As mentioned above, the decrease of inlet air flow represent the increase of FAR, which means more fuel can be supplied to guarantee the following combustion. More fuel lead to more heat release so that lower the threshold of ignition and keep the flame more stable.

CONCLUSIONS

The investigation was carried out to research the lean blowout performance and its influencing factors in center-staged combustor with multi-injection nozzles. EDC model was adopted to enhance accuracy of numerical modeling. In addition, Steady approximation approach is put forwardto judge the existence of lean blowout. The results obtained from the numerical modeling indicate combustion organization and flow fluid property of this scheme of combustor. The lean blowout limit can be decreased at different levels by changing the inlet aerodynamic parameters.

The contradiction between the exhaust smoke at operating condition and lean blowout at idle condition in high-temperature rise combustor can be eased by the scheme of center-staged combustor. In addition, the paper choses reasonable distance between two modules and inject direct flow to resolve and separate the mutual interference of swirling flow between the main modules and pilot module.

The characteristic of combustion and flow field achieve the requirement of design. The recirculation zone was created by the pilot module. The swirling flow generated by the swirler of main modules flow along the periphery of recirculation zonerather than participate the combustion in primary zone. That means the interference between two swirling flows has been avoided.

Steady approximation approach is adopted to judge the existence of lean blowout. As a consequence, with the increase of inlet air temperature, inlet air pressure and decrease of inlet air flow rate, the lean blowout limit decline at different levels.

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