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NUMERICAL SIMULATION OF COLD FLOW FIELD OF AERO-ENGINE COMBUSTORS FOR LEAN BLOW OFF ANALYSIS

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ABSTRACT

Lean blow off (LBO) performance is critical to the operational performance of combustion system in propulsion and power generation. Current predictive tools for LBO are based on decades-old empirical correlations that have limited applicability for modern combustor designs. Recent advances in computational fluids dynamics (CFD) have provided new insight into the fundamental processes that occur in these flows. In this paper, it is envisaged a new methodology for the LBO predictions that is predicting the LBO fuel/air ratio based on the cold flow field of the combustor. Comparing to the traditional tools, this methodology has the lower prediction cost, especially in the designing stage of the combustor. The study presented here is the preliminary study of this method.

According to the Lefebvre's LBO model, a new load parameter ($m_r \cdot V_f$) *extracted from the cold flow field is obtained for LBO analysis. Commercial software FLUENT is used to simulate the velocity and concentration field without combustion in different combustors. LBO fuel/air ratios are obtained from the model combustor experiments.*

Flammable zone volume (V_f) *is used instead of* V_c *(as defined in Lefebvre's model: combustor volume ahead of the dilution holes) in this LBO analysis.* V_f *is defined according to the lean/rich limits and increased with the increase of* φ_{LBO}*. In addition, the mass flow rate of back-flow air which enters the flammable zone* (m_r) *is used to account for the combustion air.* φ_{LBO} *is increased in a parabolic way with the increase of* m_r*.*

The load parameter ($m_r \cdot V_f$) *could represent the actual combustion load of the combustor near LBO and relates* φ_{LBO} *to the cold flow field of the combustor. It will be encouraging and beneficial to the study of LBO prediction in the future.*

NOMENCLATURE

A_e=effective area, mm^2
A_i= inlet area of swirler, mm^2
A_o=outlet area of swirler, mm^2
B= vanes heights of swirler, mm
C_p=heat capacity, J/kg·K
D_r= mean drop size
f_{PZ}= the fraction of fuel evaporated in primary zone
H_r= lower calorific value, J/kg
m_A=total mass flow rate of combustor inlet, kg/s
m_c=mass flow rate of combustion air, kg/s
m_{pri}=mass flow rate through primary swirler, kg/s
m_{sec}=mass flow rate through primary and secondary swirlers, kg/s
m_r=mass flow rate of the back-flow air which enters the flammable zone, kg/s
m_{co}= mass flow rate through the cooling holes in dome
m_{ph}= mass flow rate through primary holes, kg/s
N = vanes number of swirler
P_3= inlet pressure, kPa
q_{LBO} = overall fuel/air ratio at lean blow-off
R_o= outer radius of swirler, mm
R_i= inner radius of swirler, mm
SN= swirl number
T_3= inlet temperature of combustor, K
T_4= outlet temperature of combustor, K
T_{pz}= average temperature of primary zone, K
V_{pz}= volume of primary zone, m^3
V_c= combustor volume ahead of dilution holes, m^3
V_f= volume of flammable zone, m^3
v_{min-s}= the minimum axial velocity in SCR, m/s

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$v_{min\text{-}j}$= the minimum axial velocity in JCR, m/s
β= vane angle, °
δ= vanes thickness of swirler, mm
λ_r= effective evaporation constant
φ_{LBO}= overall equivalence ratio at lean blow-off

1 INTRODUCTION

Lean blow-off (LBO) is a very important aspect of combustion performance of aero-engine combustors. The aero-engine combustors sometimes operate at very low inlet pressure and fuel/air ratios (FAR) that lie outside the normal burning limits of hydrocarbon-air mixtures [1]. For a long time, the prediction of lean blow-off is mainly based on parameters testing and empirical correlations. Such approach is high cost but low accuracy. With the development of numerical simulation, Computational Fluid Dynamics (CFD) shows great advantages in the study of swirling flow, outlet temperature distribution, liner cooling, and pollutant emissions. Hence, it is necessary to develop a hybrid model based on numerical simulation and empirical correlations that allows the researchers evaluating the LBO performance of the combustor efficiently and accurately.

There are lots of theoretical models about lean blow-off. Most of them could be classified into two categories, Perfect Stirred Reactor (PSR)[2] model and Characteristic Time model[3]. PSR model was proposed by Longwell in the analysis of bluff-body flames (in the afterburner)[4]. Later it was improved by Lefebvre so that it could be used in the combustors for lean blow-off predictions[5]. In Lefebvre's LBO model, the factors included entrainment, heterogeneity of the fuel/air mixture, fuel atomization and evaporation were introduced. It considered the LBO performance of the combustor was mainly determined by four parameters representing the inlet condition, combustor structure, fuel property and atomization[6][7]. Characteristic time model was proposed by Zukoski[3] and improved by Mellor and Plee[8]. It defined three characteristic times in combustion process: the shear layer mixing or residence time τ_{sl}, the fuel vapor ignition delay time τ_{hc}, and the droplet evaporation time τ_{eb}.[9][10][11]. The flame would be blown-off if the τ_{sl} was too short that the fresh mixture could not be ignited as flowing through the shear layer.

Mongia and Rizk merged the Lefebvre's model for Lean blow-off with 3-D computer code[12]. The 3-D computations were applied to a combustor domain which was divided into a large number of finite-difference nodes along axial, radial and circumferential directions. The code was needed to run for two power conditions (47% and full power) to determine the empirical constants firstly, and then it could be used in LBO predictions at other power levels. Because the actual LBO data should be obtained to set the constants, these "prediction" are really correlations.

A hybrid modeling approach for LBO prediction was presented by Shouse and Sturgess[13][14]. The procedure began with a CFD calculation at representative operating conditions of interest. The field solutions resulting from the CFD calculation were post-processed using a dissipation gradient analysis and topology methods to represent the fluid dynamics by means of a connected network of fuel/air mixers, Perfect Stirred Reactor (PSR), and plug-flow reactors. Detailed chemistry was solved on the network over the required range of operating conditions near LBO to yield the desired solutions.

Menon and his group[15] considered that local extinction played an important role in the process of lean blow-off. So a combined model (LES+LEM) was used by Menon to study the effects of different vortexes scales on local extinction[16]. The results showed that not all the vortexes affect the local extinction, but only the vortexes in specific scale. Although numerical simulation could capture the flame distortion and variation of flame spread velocity, it was unable to capture the vortexes which have great effects on local extinction. So the numerical simulation method should be improved yet.

Kim and Jeffrey studied the turbulent reacting flows behind the bluff body flame holder using LES and simple combustion model (EBU)[17]. It showed an encouraging result that the LBO fuel/air ratio (FAR) obtained by this model was equal to that in experiment. However the result is only limited in their one configuration, it could be problematic when applying the model under other configurations and conditions. Besides, for a simple combustor (no liner), a typical LES calculation requires 20 days using 16900MHz PCs, the time would be dramatic increased when LES is used in aero-engine combustor. This is absolutely not accepted when the combustor is in the designing stage.

From the above, it is found that pure numerical simulation with high spatial and temporal resolution can't be used efficiently in the prediction of LBO performance due to the computational cost and complexity. Besides, the numerical simulation in combustion is usually competent for solution of combustion in stable condition but not applicable to accurately calculate the transient conditions yet (e.g. lean blow-off)[18]. So whether could it predict the LBO fuel/air ratio of the combustor based on empirical model and simple numerical simulation (RANS) of cold flow field is an urgent issue.

The purpose of this paper is to analyze the relationship between cold flow field and φ_{LBO} of gas turbine combustors based on Lefebvre's LBO model. It is understandable that once the inlet condition, combustor structure and property of fuel are fixed, φ_{LBO} should be determined and has none business with whether the incoming flow is ignited. So the cold flow field and φ_{LBO} should be related. According to this relationship, it is greatly possible to predict the φ_{LBO} through cold flow field of the combustors. In this study, commercial software FLUENT is used to simulate the velocity and concentration field without combustion in different combustors (RANS). LBO fuel/air ratios are obtained from the model combustor experiments.

In author's previous experiment research[19], it was found that the actual combustion zone near LBO can't pervade the whole combustor, even the combustor volume ahead of the dilution holes (V_c) defined in Lefebvre's model. It was just a small region located very close to the atomizer. In this paper, the flammable zone volume (V_f) is used instead of V_c in LBO analysis. V_f is defined according to the lean/rich limits calculated from fuel concentration. In addition, the mass flow rate of back-flow air which enters the flammable zone (m_r) is used to account for the combustion air.

Hence a new load parameter ($m_r \cdot V_f$) extracted from the cold flow field of the combustor is obtained. The load parameter could represent the actual combustion load of the combustor near LBO and is greatly beneficial to the study of LBO prediction in the future.

2 EXPERIMENT

The experiments are operated on a single dome (1/18 of the annular combustor) rectangular model combustor with dual-radial swirl cup in Fundamental Combustion Laboratory (FCL) of Beihang University (as shown in Fig.1-a). More Details of the geometry and measurements are described by Xie[19].

(a) (b)

Figure 1. Lean blow-off test rig and half-blocked configurations of primary holes and swirlers

The model combustor contains three components: primary swirler, second swirler and primary holes. Each component has an alternative design based on the reference configuration. The parameters of the reference configuration for each component are shown in table.1

Table 1. Configuration parameters of the reference combustor

Components	N	B (mm)	δ (mm)	β (°)	R_o (mm)	R_i (mm)	A_e (mm^2)	SN
Primary swirler	12	5.1	1.2	64	12.5	8	146.7	1.09
Secondary swirler	12	7	1.2	70	15	13.5	190.7	1.25
Primary holes	R 6.25×1, R 5.5×2							

Based on the reference configuration of each component, the flow areas are reduced in half (as shown in Fig.1-b). So the combustors with different combination of these components have different air splits in primary zone. It is noted that the blocked pattern of the swirlers is to block the inlet area of swirler A_i instead of the whole flow passage for convenience and reliability (as shown in Fig.2). This pattern was applied for a Chinese patent[20].

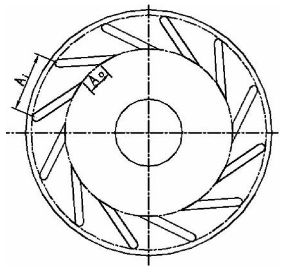

Figure 2. Schematic of blocked pattern of radial swirler

The labels of the combustors with different combination of the components are shown in Table 2.

Table 2. The combustors labels

Configuration label	Primary holes	Primary swirler	Secondary swirler
R-R-R	Reference	Reference	Reference
R-H-R		Half-blocked	Reference
R-H-H		Half-blocked	Half-blocked
H-R-R	Half-blocked	Reference	Reference
H-H-R		Half-blocked	Reference
H-R-H		Reference	Half-blocked
H-H-H		Half-blocked	Half-blocked

In the experiment, the stable combustion time for each adjustment of fuel mass flow rate is kept about 2 minutes. To validate the repeatability of the experiments, every operation condition is repeated three times. The LBO fuel/air ratio is obtained as follows: stable combustion is established at a fixed air mass flow rate, and then the fuel flow is decreased slowly until extinction occurs. Once extinction is achieved, the final fuel flow rate is recorded. The fuel employed in the experiment is JP-8 kerosene. The air mass flow rate is about 0.589kg/s, the fuel mass flow rate for ignition is about 3.2g/s, the temperature and gauge pressure in air inlet is 300K and 220KPa, respectively.

3 COMPUTATION

3.1 Turbulent model

Turbulent model of realizable k-ε is used. The realizable k-e model is developed recently which is used extensively in the solution of swirling flow[21][22]. A remarkable advantage of the realizable k-ε model is to accurately predict the flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation[23]. In this study, all the parameters contained in realizable k-ε model are kept default.

3.2 Computational Domain and Boundary Conditions

Fig.3 shows the computational domain and numerical boundary conditions. The origin is in the center of the flare. At the air inlet, the mass flow is 0.589 kg/s. The air temperature is 300 K. The turbulent quantities are defined by hydraulic diameter (36.34mm). The mass flow rate of the fuel (kerosene vapor obtained in FLUENT database is used) is determined by φ_{LBO} (obtained by experiment). The walls are assumed to be adiabatic. Pressure outlet boundary condition (321.325 kPa) is used for the outlet. The operating pressure is set to 0.0 Pa. Second order upwind of discretization is used in all cases.

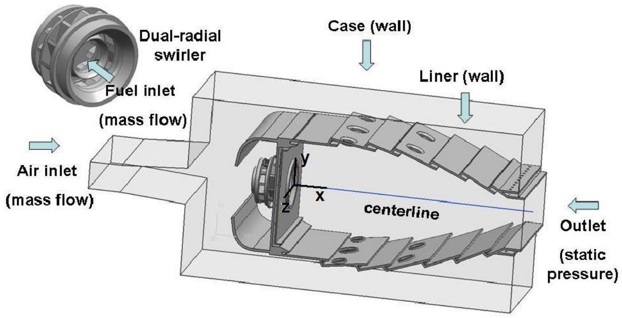

Figure 3. The computational domain and numerical boundary conditions

3.3 Computational grids

The grids are generated by commercial software GAMBIT. Because of the complicated configuration of combustor, the computational domain is divided into lots of small parts. Tetrahedral grids are generated in/around the dome and liner. The others are generated in hexahedral grids. The sum of the grids is about 4.5 million. The computational grids are shown in Fig. 4.

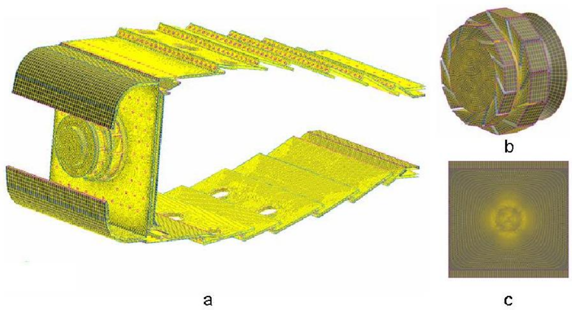

Figure 4. Various views of Computational grids: a, Integral grid of combustor. b, Computational grids of swirlers. c, Grids in y-z cross plane of primary zone

4 RESULTS AND ANALYSIS

4.1 LBO data in different combustors

The LBO fuel/air ratios obtained from experiments in different combustors are shown in Table 3. q_{LBO} is the average value of three LBO data in each operating condition. T_4 is the outlet temperature of the combustor at LBO which is used to perceive the extinction. The experiment error of q_{LBO} is approximate 1.87%.

Table 3. q_{LBO} in different combustors

Configuration label	q_{LBO}	T_4(K)
R-R-R	0.003622	445.28
R-H-R	0.003213	423.71
R-H-H	0.003261	422.04
H-R-R	0.004303	434.97
H-H-R	0.003870	426.85
H-R-H	0.004226	415.07
H-H-H	0.003541	359.15

4.2 Time-Averaged Velocity

4.2.1 Axial velocity along the centerline

The distributions of axial velocities along the centerline (obtained from numerical simulation) are shown in Fig.5. All the curves are start from the center of the venturi throat located at -0.009m. The primary holes are located at 0.05m.

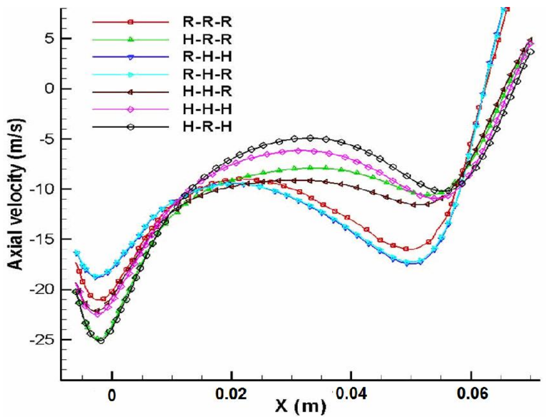

Figure 5. Axial velocities along the centerlines of different combustors

It is shown that there are two negative peaks in each curve: v_{min-s} and v_{min-j}. The v_{min-s} located upstream is formed by swirlers. The swirlers make the air rotate to build adverse pressure gradient downstream of them. Because v_{min-s} is close to the venturi, it is mainly affected by the primary swirler (m_{pri}). $|v_{min-s}|$ is increased almost linearly with the increase of m_{pri} (as shown in Fig.6). The mass flow rates through the secondary swirler (m_{sec}) and primary holes (m_{ph}) have little effects on v_{min-s}. In addition, the axial positions of v_{min-s} in different combustors are kept nearly unchanged and about 0.006m downstream of venturi throat.

The v_{min-j} located downstream is formed by the penetration of primary jets that would push the air upstream. The decrease of the area of primary holes will decrease the penetration of primary jets, and then weaken the jets collision. Hence, $|v_{min-j}|$ in the combustors with half-blocked primary holes is smaller than that with reference primary holes. Meanwhile, the axial position of $|v_{min-j}|$ in the combustors with half-blocked primary holes is moved downstream of that with reference primary holes.

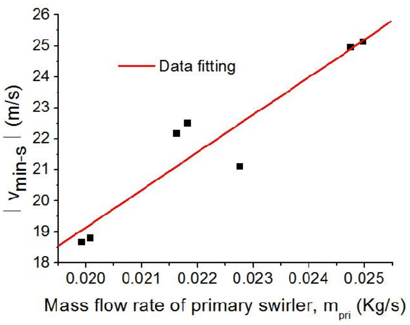

Figure 6. The relationship between v_{min-s} and m_{pri}

4.2.2 The relationship between v_{min-s} and φ_{LBO}

The relationship between $|v_{min-s}|$ and φ_{LBO} is shown in Fig.7. $|v_{min-s}|$ and φ_{LBO} is obtained from numerical simulation and experiment respectively. Fig.7 shows that φ_{LBO} is increased with the increase of $|v_{min-s}|$. From the experiment image it is found that near LBO the flame is anchored close to the atomizer and confined in a very small region in the primary zone (as shown in Fig.8). The increase of $|v_{min-s}|$ will cause the increase of the velocity gradient at venturi outlet. It is well known that the increase of the velocity gradient is not advantageous to flame stabilization. Hence φ_{LBO} will be increased.

In addition, near the LBO, the amount of the air in back-flow is much greater than the stoichiometric air. The increase of $|v_{min-s}|$ will cause the increase of back-flow rate and than decrease the average equivalence ratio in combustion zone. Therefore the flame is easy to be blown off.

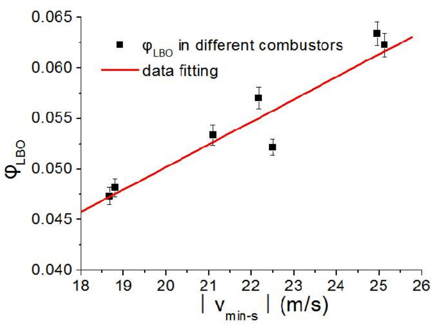

Figure 7. The relationship between $|v_{min-s}|$ and φ_{LBO}

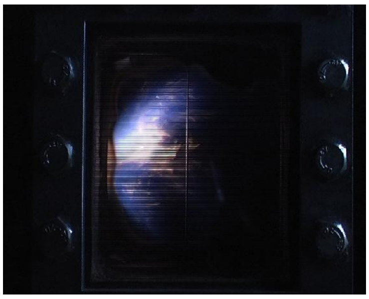

Figure 8. Image of time-averaged flame near LBO (obtained by optical camera)

4.3 Load parameter

Among all the LBO models, the PSR model improved by Lefebvre is employed extensively by designers in estimating the LBO performance of combustors[7]. For homogeneous mixtures (fuel vapor and air mixture), the correlation is:

$$q_{LBO} \propto \frac{m_A}{V_{PZ} P_3^n \exp(T_3 / b)} \quad (1)$$

For heterogeneous mixtures (liquid fuel), the fuel vaporized per unit air in the primary zone is considered. The overall fuel/air ratio at lean blow-off is expressed as:

$$q_{LBO} = \left(\frac{A' f_{PZ}}{V_c}\right)\left(\frac{m_A}{P_3^{1.3}\exp(T_3/300)}\right)\left(\frac{D_r^2}{\lambda_r H_r}\right)\left(\frac{D_0 at T_f}{D_0 at 277.5K}\right) \quad (2)$$

In Eq.2, the first item is a function of combustor configuration, the second item is a function of inlet conditions, and the third is a function of fuel properties and atomization. The last additional item accounts for the variations in drop sizes from the baseline fuel temperature of 277.5K. Lefebvre suggests that V_c is the combustor volume ahead of the dilution holes instead of the primary zone volume (V_{pz}) which is included in Eq.1. The parameter A' is a combustor-specific constant that must be determined with actual operation data.

Lefebvre considered Eq.2 to be universal because the value of ($A' f_{pz}$) remains nearly constant (0.22) for different combustors. Therefore if 0.22 is used for ($A' f_{pz}$) in Eq.2, it should be able to determine a lean blow-off fuel/air ratio within approximately 30%.

However it is found from the experiment images that the actual combustion zone near LBO can't pervade the whole combustor, even the V_c. It is just a small region located very close to the atomizer as shown in Fig.8. Hence how to define the combustion zone accurately is a key problem to improve the LBO model.

It is well known that not all the fuel-air mixtures with different fuel concentrations will burn or explode. Flame can only propagate within certain limits. In this paper, the combustion zone is defined according to the lean/rich limits calculated from the fuel concentration based on numerical simulation without combustion. This combustion zone is named flammable zone (V_f). The mass flow rate of back-flow air which enters the flammable zone (m_r) is used to account for the combustion air. Hence, the local parameter m_r and V_f is used instead of global parameter m_A and V_c in this study.

4.3.1 Flammable zone (V_f)

The flammable limits are strongly affected by temperature. In order to define the actual combustion zone accurately, it is necessary to obtain the temperature distribution around this region. Because of the restriction of the temperature measurement, this paper uses the average temperature of the primary zone (T_{pz}) that is calculated based on the energy conservation. The equilibrium equation is shown as follows:

$$0.5[0.5(m_{ph}+m_{co})+m_{\sec}+m_{pri}](T_{pz}-T_3)(C_{p,T_{pz}}+C_{p,T_3}) = 0.5m_A(T_4-T_3)(C_{p,T_4}+C_{p,T_3}) \quad (3)$$

The correlation between lean/rich limits and temperature is proposed by Michael G. Zabetakis[24].

For lean: $$L_T = L_{298.15K} - \frac{25285.71}{\Delta H_r}(T-298.15) \quad (4)$$

For rich: $$U_T = U_{298.15K} + \frac{25285.71}{\Delta H_r}(T-298.15) \quad (5)$$

Where T is the temperature in K, $\triangle H_r$ is the lower calorific value of kerosene in J/kg. L_T and U_T is the lean and rich limit (percent fuel by volume) at T, respectively. The rich/lean limits calculated in different combustors are shown in Table 4.

Table 4. T_{pz} and lean/rich limits in different combustor

Configuration label	T_4(K)	T_{pz}(K)	Lean limits (by weight)	Rich limits (by weight)
R-R-R	445.28	605.91	0.04601	0.33879
R-H-R	423.71	566.39	0.04699	0.33781
R-H-H	422.04	566.34	0.04700	0.33781
H-R-R	434.97	634.61	0.04530	0.33950
H-H-R	426.85	620.45	0.04565	0.33915
H-R-H	415.07	596.79	0.04624	0.33857
H-H-H	359.15	470.17	0.04940	0.33542

The shape of flammable zone likes a horn close to the atomizer (as shown in Fig.9). Because of the neglect of atomization and evaporation, the flammable zone (V_f) obtained in numerical simulation is smaller than the flame in experiment image. It is found that V_f is increased with the increase of φ_{LBO} (as shown in Fig.10). The possible reason is that the mass flow rate of fuel used in numerical simulation is obtained from the LBO experiment, so the increase of φ_{LBO} will cause the increase of fuel flow rate, and then enlarge the V_f.

In addition, the relationship between φ_{LBO} and V_f is in accordance with experiments, showing that the flame area near LBO obtained by optical camera is increased with φ_{LBO}. The lager flame volume represents the better fuel/air mixing within the whole combustor. That is no good for LBO performance. Hence the LBO limits will be deteriorated.

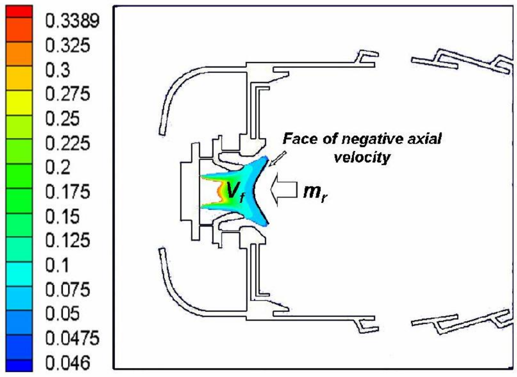

Figure 9. The flammable zone obtained through rich/lean limits in reference combustor

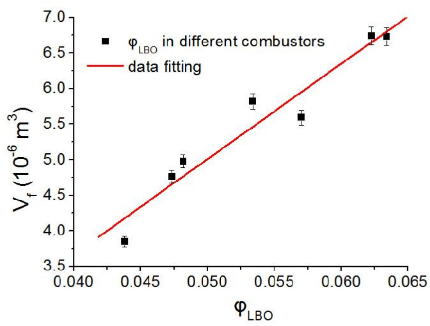

Figure 10. The relationship between φ_{LBO} and V_f

4.3.2 Combustion air

Theoretically, the combustion air (m_c) should be the air enters the flammable zone (V_f), that contains part of the air from primary swirler, secondary swirler, primary holes and cooling holes in dome. But in the flow field without combustion, it is difficult to calculate m_c. Some air that enters the V_f would be computed repeatedly due to the back-flow. In this paper it is assumed that the mass flow rate of back-flow air enters the flammable zone (m_r) should be proportional to m_c. Because under the design point condition, the fuel/air ratio in the primary zone is close to stoichiometric. The recirculation zone is full of burnt gases with high temperature that supply enough heat to ignite the fresh flammable mixture. With the decrease of fuel mass flow rate, the temperature in the recirculation zone is decreased and the amount of the air in the primary zone is excess to stoichiometry. The excessive air will further reduce the local fuel/air ratio in combustion zone. Hence, the variation of the mass flow rate of back-flow gases entering the flammable zone is very important to LBO.

In this study, m_r is obtained from numerical simulation by computing the mass flow rate across the negative velocity face which is shown in Fig.9.

Fig.11 shows that φ_{LBO} is increased in a parabolic way with the increase of m_r. That is because the increase of m_r will decreases the local fuel/air ratio in flammable zone and then the LBO limits will be deteriorated.

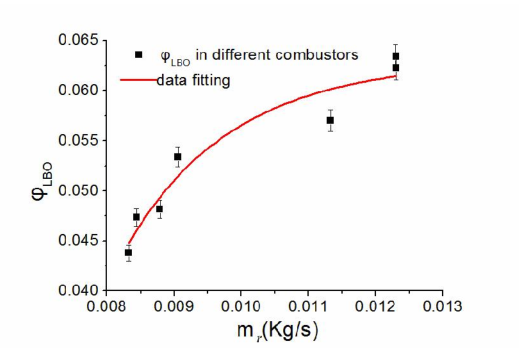

Figure 11. The relationship between m_r and φ_{LBO}

4.3.3 The load parameter of LBO

Based on m_r and V_f, the load parameter $m_r \cdot V_f$ extracted from cold flow field is obtained. The relationship between $m_r \cdot V_f$ and φ_{LBO} is shown in Fig.12.

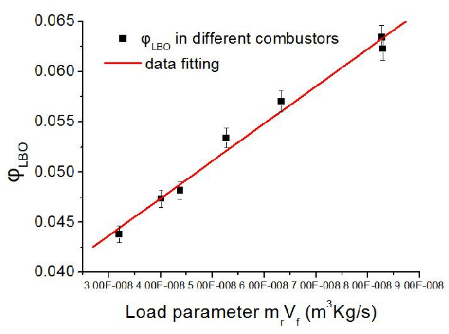

Figure 12. The relationship between $m_r \cdot V_f$ and φ_{LBO}

It shows a linear-like correlation between $m_r \cdot V_f$ and φ_{LBO}. The load parameter could represent the actual combustion load of the combustor near LBO and fits satisfactorily with experiment data. The fitting equation is as follows:

$$\varphi_{LBO}=0.03249+372337.1 m_r \cdot V_f \qquad (r=0.9968) \quad (6)$$

The work presented in this paper is an attempt to analyze the φ_{LBO} of combustors in simple numerical simulation without combustion. In the future, further studies will be operated on the extension of this approach. Eventually, an improved LBO model based on simple numerical simulation would be obtained to predict LBO limits with high accuracy and low cost for different combustors.

5 CONCLUSIONS

In order to analyze the relationship between cold flow and φ_{LBO} of the gas turbine combustor, both numerical simulation and experiment are operated. Some conclusions are obtained as follows:

1) The negative peak of axial velocity that formed by swirling flow ($|v_{min-s}|$) has great effect on LBO performance: φ_{LBO} is increased with the increase of $|v_{min-s}|$.

2) Flammable zone volume (V_f) is used instead of combustor volume ahead of the dilution holes (V_c) in LBO analysis. V_f is defined according to the lean/rich limits calculated from fuel concentration. The shape of flammable zone likes a horn close to the atomizer. V_f is increased with the increase of φ_{LBO}.

3) The mass flow rate of back-flow air which enters the flammable zone (m_r) is used to account for the combustion air. m_r is obtained by computing the mass flow rate across the negative velocity face. φ_{LBO} is increased in a parabolic way with the increase of m_r.

4) A new load parameter ($m_r \cdot V_f$) extracted from the cold flow field is obtained for LBO analysis. The load parameter could represent the actual combustion load of the combustor near LBO and relates φ_{LBO} to the cold flow field of the combustor. It will be encouraging and beneficial to the study of LBO prediction in the future.

REFERENCES

[1] A. H. Lefebvre, 1983, Gas Turbine Combustion, McGraw-Hill Book Company, New York.

[2] John P. Longwell, Malcolm A. Weiss, 1955, "High Temperature Reaction Rates in Hydrocarbon Combustion", Industrial and Engineering Chemistry, Vol. 47(8).

[3] E. E. Zukowski and F. E. Marbel, 1955, "The Role of Wake Transition in the Process of Flame Stabilization on Bluff Bodies", AGARD Combustion Researches and Reviews, pp: 167~180.

[4] John P. Longwell, Edward E. Frost, and Malcolm A. Weiss, 1953, "Flame Stability in Bluff Body Recirculation Zones". Industrial and Engineering Chemistry, Vol. 45(8), pp: 1629~1633

[5] D. R. Ballal and A. H. Lefebvre, 1979, "Weak Extinction Limits of Turbulent Flowing Mixtures", ASME Journal of Engineering for Power, Vol. 101(3).

[6] D. R. Ballal, A.H. Lefebvre, 1980, "Weak Extinction Limits of Turbulent Heterogeneous Fuel/Air Mixtures",

Journal of Engineering for Power, Vol. 102.
[7] A. H. Lefebvre, 1985, "Fuel Effects on Gas Turbine Combustion-Ignition, Stability and Combustion Efficiency", Journal of Engineering for Gas Turbines and Power, Vol. 107.
[8] Mellor A. M., 1990, Design of Modern Turbine Combustors, Academic Press.
[9] T. A. Jarymowycz, A. M. Mellor, 1986, "Correlation of Lean Blowoff in an Annular Combustor", J. Propulsion, Vol. 2(2).
[10] W. S. Derr, A. M. Mellor, 1987, "Characteristic Time for Lean Blowoff in Turbine Combustor", J. Propulsion, Vol. 3(4).
[11] P. A. Leonard, A. M. Mellor, 1983, "Correlation of Lean Blowoff of Gas Turbine Combustors Using Alternative Fuels", J. Energy, Vol. 7(6).
[12] Mongia, H. C., Reynolds P. S., Srinivasan, 1986, "Multidimensional Gas Turbine Combustion Modeling: Application and Limitations", AIAA paper, NO. 6 Vol. 24, pp-890-904.
[13] G. J. Strurgess, D. T. Shouse, 1996, "A Hybrid Model for Calculating Lean Blow-outs in Practical Combustion", 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, NO. 1996-3125.
[14] G. J. Sturgess, D. G. Sloan, A. L. Lesmerises, et al., 1992, "Design and Development of a Research Combustor for Lean Blow-out Studies", Journal of Engineering for Gas Turbine and Power, Vol. 114(13).
[15] S. Menon, G. Eggenspieler, N. Patel, 2004, "Structure of Locally Quenched Swirl Stabilized Turbulent Premixed Flame", AIAA Paper, NO. 2004-979.
[16] S. Menon, C. Stone, N. Patel, 2004, "Multi-Scale Modeling for LES of Engineering Designs of Large-Scale Combustors", AIAA Paper, NO. 2004-0157.
[17] Won-Wook Kim, Jeffrey L. Lienau, Paul R. Van Slooten, et al., 2006, "Towards Modeling Lean Blow Out in Gas Turbine Flameholder Application", Journal of Engineering for Gas Turbine and Power, GT2004-53967.
[18] Thierry Poinsot, Denis Veynante, 2005, Theoretical and Numerical Combustion, R.T. Edwards, Inc., Philadelphia, PA, USA.
[19] Fa xie, Yong Hang, Wang Fang. 2010, "Visualization of the Lean Blowout Process in a Combustor with Swirl Cup", Proceedings of ASME Turbo Expo, GT2010-22534.
[20] Yong Huang, Fa Xie, Fang Wang, et al. "A Adaptive Mechanism for Improving the Lean Blowoff Limits of Aero-engine Combustor with Radial Swirl Cups", Patent, Application NO. 200910120464.5 (in Chinese).
[21] Yu-Fang Zhang, Yong Huang, Fang Wang. 2010, "Small Scale Mixing Enhancement of Fuel/air Using Multi-source vortex technology" Journal of Aerospace Power, Vol.25.
[22] Yao-Zeng Wu, Yong Huang, Fang Wang. 2010, "Investigation of Cold Flow Field of a Multi-injection Combustor with Different Geometries" Journal of Aerospace Power, Vol.25.
[23] Fluent Inc., "Fluent 6.3 User's Guide", 2006.
[24] Michael G. Zabetakis, 1965, "Flammability Characteristics of Combustible Gases and Vapors", U. S. Bureau of Mines, Bulletin 62.