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A Hybrid Method for Prediction of Lean Blow Out in a Turbine Engine Combustion Chamber

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Three methods for prediction of lean blowout in a turbine engine has been introduced. The first method is a Hybrid Simulation-Test (HST), the second is a Hybrid Simulation-Semi empirical correlation (HSS) and the third one is based on Lefebvre's Semi-Empirical Correlation (LSC). Before this research, calculation of parameters is done only based on fuel species transport without taking evaporation and/or atomization into account. This issue reduces actual amount of flame volume. The values of q_{LBO} (overall fuel-air ratio at lean blow out) predicted by HST, HSS and LSC were compared to experimental results. The error of (HST-FM & SM) method was 11.48 and 1.86 percent and (HSS-FM & SM) method was 6.15 and 2.2 percent and (LSC) was 46.73 percent.

Keywords: LBO prediction, CFD, Species transport, Evaporation, Atomization.

1 Introduction

In the new generation of aero engines, reduction of pollutants emitted from the engine is necessary and this is addressed by adopting certain methods such as using premixed-prevaporized combustion chambers and lean direct injector. The two methods mentioned above require the operation of the combustion chamber at very low fuel to air ratio. The ratio is very close to the lean blowout limit (q_{LBO}) of combustion chambers as shown in Fig. (1) [1]. Therefore, prediction and operation at lean blowout limit are highly critical for aero engines because if fuel to air ratio is not predicted properly, the operational limit of combustion engine exceeds the combustion stability limit and flame blowout will occur [2]. In the case of rich mode, amount of fuel injected into the combustion chamber will exceed the allowable range and flame will blow out. The use of fuel rich mode for aero engines is undesirable due to increased fuel consumption, reduced efficiency, and high pollution. Therefore, the operation of the engine within the lean limit is highly desirable. A problem raised in this limit is combustion stability which could be realized hardly [3]. In this study, the concept of PSR as introduced by Longwell [6] was used for the prediction of LBO.

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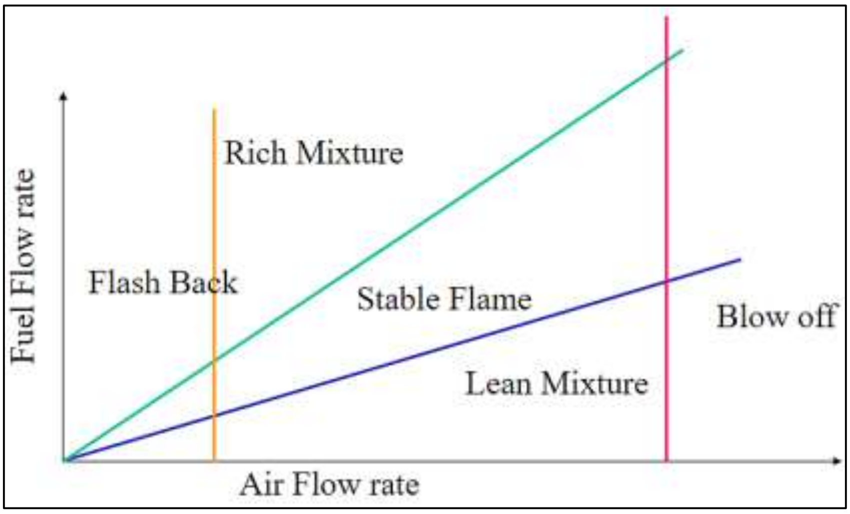

Figure 1 Combustion stability range in a gas turbine engine [2]

The model was first developed by Lefebvre and Ballal [8] for prediction of lean blowout limit (LBO). In this method, lean blowout analysis is done based on energy balance and this means that if the energy rate released in PSR is lower than the heat dissipation rate, the lean blowout will occur. Lefebvre's model is more often used in the industry but the model shows LBO prediction error for new combustion chambers up to 50 percent [9]. As a result, many studies for introducing a more precise model of LBO prediction have been conducted in recent years.

Hu. Bin et al [3] conducted certain tests on different combustion chambers and found out that the two parameters of flame volume and fractions of dome air are highly influential upon lean blowout phenomenon. Then they used Lefebvre's model and took values of the two parameters mentioned above (parameters obtained from numerical simulation) to suggest a model that is completely independent of experimental process and more inexpensive than experimental-based models.

Hu. Bin et al [9] determined the parameter of flame volume through numerical simulation and developed a new method called fuel iterative approximation (FIA). They improved the flame volume method and associated fuel flow rate with flame volume to add the ability to predict LBO to the model.

Ateshkadi et al [10] studied the effects of swirl-cup components (e.g. primary swirler, venturi and secondary-swirler) on LBO based on Lefebvre's model.

Xiao et al [11] used a rectangular combustion chamber with three type of swirler and Jet A and methane fuels to study the effects of swirling intensity and airflow on the LBO limit. The results suggested that flow dynamics influence LBO limit to a higher extent than the spray process. They also introduced a semi-empirical correlation for prediction of LBO.

Xie et al [12] studied three swirl-cup configurations (with two radial swirler). In the experimental measurement, structure, and area of the flame, flame color, location of flame and fuel-air ratio during lean blowout were measured. Finally, a correlation was developed for lean blowout through a code which associated flame area with the fluid-air ratio.

Huang et al [1, 13] based on Lefebvre's studies and cold air simulation introduced flame volume method premised on the PSR model to improve Lefebvre's correlation. In this model parameters such as the configuration of primary area and dome geometry is also considered. They considered 7 different configurations for primary swirler, secondary swirler and holes of primary area. In addition, they substituted flame volume and primary area air for the total volume of flame and total air to introduce a more accurate model than Lefebvre's model. However, one problem with the model is a determination of flame volume through empirical testing. In order to confirm the solution of this numerical simulation, an empirical model of lean direct injector combustion chamber was used [14].

Cavaliere et al [15] studied and compared the blow-off behavior of swirl-stabilized premixed, non-premixed and spray flames. The premixed flame was seen to change from a cylindrical shape at stable burning conditions, with the flame brush closing across the flow at conditions close to blow-off. The PLIF images show that for the gaseous non-premixed flame, holes appear along the flame sheet with increasing frequency as the blow-off condition is approached, while the trend is less obvious for the spray flame.

Moore et al [16] have investigated jet-flame blow-out with lean-limit considerations. They use digital image sequences of flames to better understand the blowout phenomenon. Methane flames are studied near blowout conditions. The blowout limits of these flames are established and a blowout parameter is empirically determined from the data. Results from flames in co-flow show agreement with the blowout parameter previously published; however, the analysis shows that the disappearance of the bulk diffusive reaction zone occurs at the lean flammability limit and is an accurate predictor of the blowout for diluted and non-diluted methane flames.

In this study, three different methods (i.e. semi-empirical, hybrid numerical simulation-empirical testing, and hybrid numerical simulation-semi empirical) were adopted for predicting LBO of a turbine engine. In refs. [3] And [7], calculation of parameters is done through cold air numerical simulation in Fluent Software. This is done based on fuel species transport without taking evaporation and/or atomization into account and this issue reduces flame volume in comparison with relevant experimental measurement. Based on the disadvantages of the earlier method, this study has improved the model by developing a novel method and taking atomization and fuel evaporation into account for the calculation of relevant parameters.

2 Principles of Analytical Methods

2.1 Lefebvre's Semi-empirical Model

The most significant semi-empirical model for prediction of LBO is Lefebvre's model Eq. (1) in which four significant parameters of inlet conditions, the configuration of the combustion chamber, fuel properties, and atomization, and evaporation are taken into account.

$$q_{LBO} = (\frac{\acute{A} f_{PZ}}{V_C}) \times (\frac{m_A}{P_3^{1.3} e^{(\frac{T_3}{300})}}) \times (\frac{D_r^2}{\lambda_r H_r}) \times (\frac{D_0 at T_f}{D_0 at\ 277.5\ k}) \quad (1)$$

Where A' is model constant defined in Lefebvre's model for LBO, f_{PZ} is air fraction in primary zone, V_C is combustor volume ahead of dilution holes, m_A is total mass flow rate of the combustor inlet, P_3 is inlet pressure of combustor, T_3 is the inlet temperature of combustor, D_r is the mean drop size on that for JP4, H_r is the lower calorific value on that for JP4, λ_r is the effective evaporation on that for JP4, and $\frac{D_0 at T_f}{D_0 at\ 277.5\ k}$ is Drop diameter changes on the initial temperature (277.5 k) of JP-4. In this study, this model was introduced as LSC (Lefebvre Semi-Empirical Correlation).

2.2 Hybrid Numerical Simulation-Empirical Testing Model

In Lefebvre's original model, the total volume of the combustion chamber (V_c) during the lean blowout is regarded as an effective parameter in Eq. (1). This is while reference [7] used new empirical tests to suggest that only flame volume (V_f) is influential on LBO. In addition, the studies suggested that the amount of reverse flow (m_r) in the vicinity of LBO is highly influential on q_{LBO}. Reference [7] used the two parameters referred above and results of the empirical test of 17 combustion chambers to develop Eq. (2) for prediction of LBO.

$$\emptyset_{LBO} = 0.00129 + 45196.88\ (m_r \times v_f) \quad (2)$$

In Eq. (2), $(m_r.V_f)$ signifying the parameter of combustion chamber loading and was determined through cold flow simulation. The disadvantage of this method is that it could be used for a specific number of new generation of combustion chambers with swirl stability. In this study, this model was introduced as HST (Hybrid Simulation-Test).

2.3 Hybrid Numerical Simulation-Semi Empirical Correlation

The empirical studies conducted in ref. [3] suggest that if a number of parameters of Lefebvre's model are improved, the model with proper error rate could be used for prediction of LBO range of all combustion chambers with swirl stability. The test results suggest that apart from parameters included in Lefebvre's correlation, the two parameters of flame volume (V_f) and percent of air flowing through dome holes are also taken into the correlation. According to these parameters, Lefebvre's semi-empirical correlation was corrected as Eq. (3). These two parameters are determined through numerical simulation in this study. As a result, the method for prediction of LBO is independent of expensive tests.

$$q_{LBO} = [\left(\frac{K}{V_C}\right)\left(\frac{\alpha}{\sqrt{\beta}} + (1-\alpha)\sqrt{\beta}\right)^2 \times (\frac{m_a}{P_3^{1.3}\exp\left(T_3/_{300}\right)}) \times (\frac{D_r^2}{\lambda_r H_r}) \times (\frac{D_0 atT_f}{D_0 at\ 277.5\ k}) \quad (3)$$

In Eq. (3), the parameter K is equal with the geometric constant $\dot{A}f_{PZ}$ and β is equal with ratio of flame volume to total volume $(^{V_f}/_{V_c})$ under the real condition which relates to the flame volume data (obtained through numerical simulation) as Eq. (4).

$$\beta = 16.8\ (\beta_N) - 0.004 \quad (4)$$

In Eq. (4), β_N refers to the ratio of flame volume to a total volume which is obtained through numerical simulation and represented as ($V_{f,N}/V_C$). In addition, $V_{f,N}$ signifies the flame volume which is determined through numerical simulation. This method is more precise than Lefebvre's model as it can model details and differences in the flow field in different combustion chambers, especially the new generation of combustion chambers [3]. In this model, determination of five parameters of inlet condition, the configuration of combustion chamber, fuel properties, flame volume and percentage of airflow through dome holes enables prediction of q_{LBO} as independent of flammability, combustion energy and condition of inlet mixture [3]. In this study, this model was introduced as the HSS (Hybrid Simulation-Semi empirical correlation).

3 Methodology

In refs. [3] And [7], calculation of parameters (V_f) and m_r in Eq. (2) and α and $V_{f,N}$ in Eq. (3) is done through cold air numerical simulation in Fluent Software. This is done based on fuel species transport without taking evaporation and/or atomization into account and this issue reduces flame volume in comparison with the relevant empirical test. This method is called the First Method (FM) and its hybrid kinds are HSS-FM and HST-FM.

Based on the disadvantages of the previous method, this study uses a combustion chamber with available results of experimental measurement and reviews the numerical method detailed in refs. [3] and [7]. Then, the models were improved by developing a novel method and taking atomization and fuel evaporation into account. The results of the two methods were compared with results of the code related to Lefebvre's method and results of the empirical test. The method is called second method (SM) and in regard to two hybrid methods, they are called HSS-SM and HST-SM respectively.

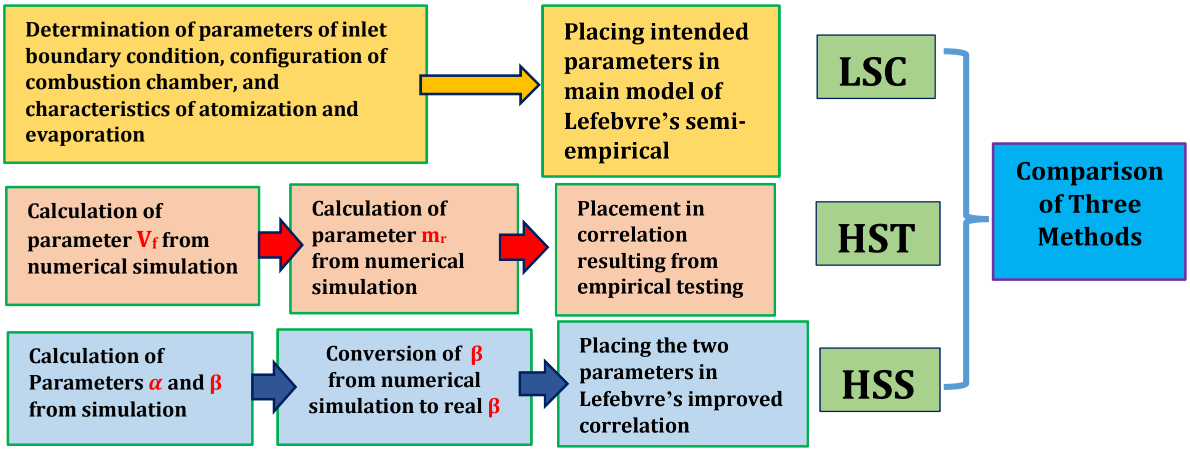

Figure 2 Schematic procedure of LBO prediction in present study

In order to confirm the solution of the cold flow field in the combustion chamber through numerical simulation, an empirical model of lean direct injector combustion chamber was used and obtained results were compared with empirical tests of ref. [14]. The prediction of LBO through the three methods adopted in the present study is schematically represented in Fig. (2).

4 Design of Geometry and Grid

Significant parameters and configuration of main and validation combustion chambers adopted in the present study are represented in Fig. (3) and Table 1 respectively.
In the next step, the geometric grid is developed through ICEM Software. Due to geometric complexity, the tetrahedral grid was used. In order to conduct grid dependence study, three different grids (i.e. 1255445, 569201, and 259110) were used for the geometry of validation

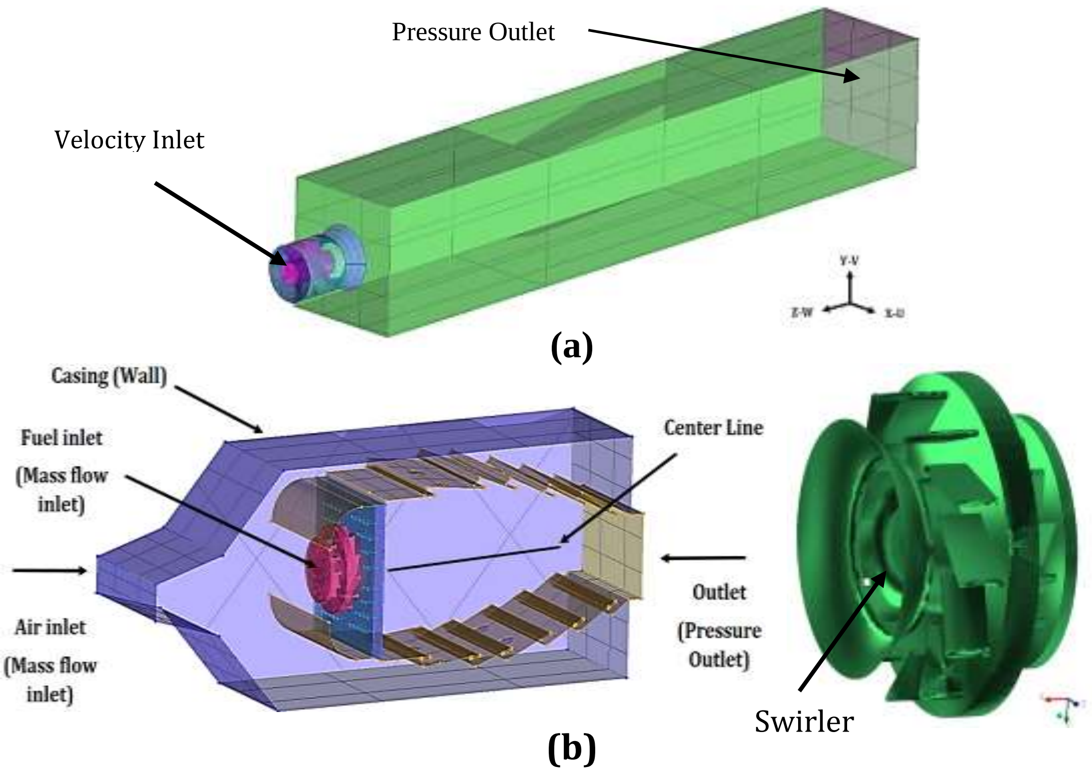

Figure 3 Geometry of Validation (a) and main (b) combustion chamber

Table 1 dimensions of main and validation combustion chambers

Parameter	Symbol	Validation combustion chamber	Main combustion chamber (first blade)	Main combustion chamber (second blade)
Blade angle (Degree)	θ_v	60	64	70
Swirl number	S_N	1.3	1.09	1.25
Blade number	N	6	12	12
Effective area (mm^2)	A_e	870	146.7	190.7
Vane height (mm)	B	8	5.1	7
Outer radius of swirler (mm)	R_0	11	12.5	15
Inner radius of swirler (mm)	R_i	4.65	8	13.5
Vanes thickness (mm)	δ	1.2	1.2	1.2
Liner Length (mm)	---------	300	215	
Liner width (mm)	---------	50	100	
Primary liner holes	----------	-------	R 6.25×1, R 5.5×2	

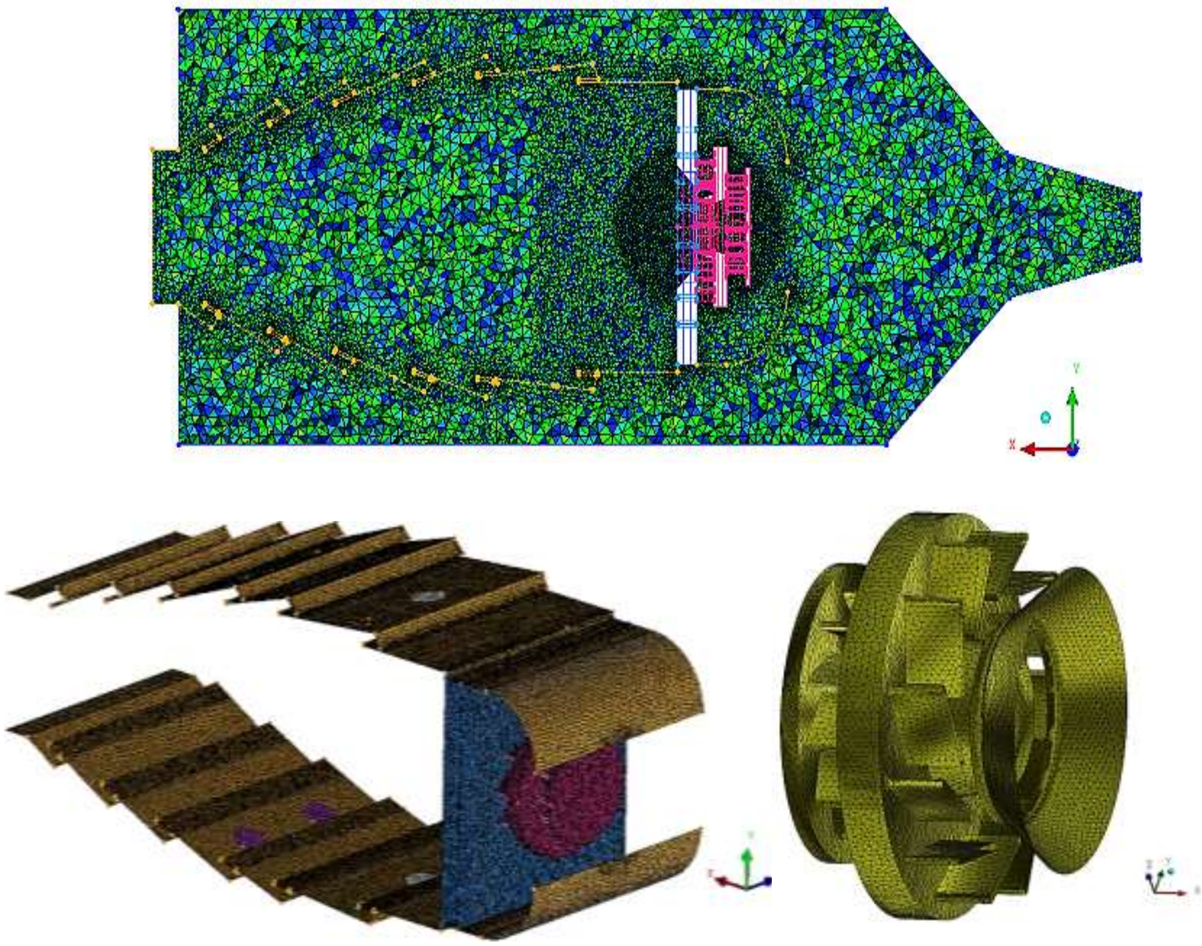

Figure 4 combustion chamber volume and surface mesh

combustion chamber. In addition, three grids (i.e. 3390000, 3997000 and 4499786) were used for the geometry of the main combustion chamber. Various views of Computational grids for main combustion chamber is represented in Fig. (4).

5 Numerical Simulation

In this study, $k-\varepsilon$ Realizable the model was used. Because of containing more terms in ε-equation, analysis of flows with significant deviations has improved significantly and swirl effects on flow turbulence were included in calculations. Accordingly, $k-\varepsilon$ Realizable model was used for simulation in the present study and it offers desirable solutions in comparison with empirical results [18-19]. In this study, apart from turbulence models for analysis of cold flow field the fuel species transport models and liquid phase spray modelling (i.e. atomization and fuel evaporation) in Fluent Software were used. The software enables simulation of secondary phase from Lagrangian viewpoint [20]. In regard to fuel species transport, a gaseous mixture of air-fuel was used instead of air. Also, liquid Fuel spray was modeled by using Specifications listed in Table (2).

Numerical simulation is intended to calculate the two parameters of α and $V_{f,N}$ and include them in Eq. (3) and (4). In addition, it should calculate the parameter $(m_r.V_f)$ and include it in Eq. (2). The results of q_{LBO}obtained through the two methods will be compared with q_{LBO} of Lefebvre's original model and empirical test of a combustion chamber. First, the parameters were solely analyzed based on fuel species transport. Then, the obtained results were improved by including atomization and evaporation in the calculation of the above-mentioned parameters. Finally, prediction of LBO for a combustion chamber is done through cheapest calculation method. In this study, flow simulation is done through Fluent Software. To do so, specifications of numerical solution represented in Table 3 were used. The obtained results were compared with empirical testing data and results of Lefebvre's original model.

As empirical tests detailed in ref. [3] and [7] suggest, real combustion zone during the lean blowout is not as big as the chamber or even dilution zone but limited to a zone close to the atomizer. In addition, the studies suggest that during lean blowout all of the fuel-air mixture (with different fuel concentration) does not burn but flame spreads in certain zones.

Table 2 Injection characteristics

Spray half angle (Degree)	30
Fuel mass flow rate (kg/s)	0.0032
Injector up stream temperature (K)	400
Injector up stream pressure (MPa)	0.8
Break-up model	TAB
Injector type	Pressure swirl atomizer

Table 3 Specification of numerical simulation for the main combustion chamber

Parameter	Numerical Simulation
Boundary condition	Mass flow inlet-pressure outlet
Model	$k-\varepsilon$ Realizable
Near wall treatment	Standard wall function
Mixture	Air-Kerosene
Equations	Implicit
Air mass flow	0.589 (kg/s)
Fuel mass flow	0.0032 (kg/s)
Pressure inlet-outlet	321325-331325 (Pa)
Hydraulic diameter inlet-outlet	64.78-36.33 (mm)
Turbulence intensity	7 %
Wall treatment	Adiabatic

In this study, the combustion zone is initially determined through the lean-rich limit. The limit is calculated based on fuel accumulation and cold flow numerical simulation (i.e. fuel species transport solely). The combustion zone is called flammable zone (V_f). Comparison of results of the numerical simulation with empirical results suggested that flame volume obtained through numerical simulation is less than the flame volume obtained through empirical testing. In order to modify the results of ref [3], the inclusion of fuel species transport in cold flow numerical simulation is accompanied by modeling of atomization and evaporation of fuel. The empirical tests [3] also suggested that apart from flame volume, the parameter of the percent of airflow through dome holes α is highly influential upon LBO prediction. In order to develop a better model than Lefebvre's one, this parameter should also be calculated. α Is highly influenced by number and diameter of dome holes, the velocity of inlet airflow, and the upstream component of the holes in combustion chamber. In this study, the combustion chamber has 52 holes and the diameter of each hole is 8mm. The parameter was calculated under the two conditions mentioned above.

Finally, the two parameters were included in Eq. (3) and the value of q_{LBO} was calculated. Based on results of ref. [3] and [7] and Eq. (2), if two parameters of flame volume and reverse flow, as well as loading parameter (resulting from these two parameters), was determined, one could calculate the value of q_{LBO} for combustion chamber used in this study. First, it is necessary to analyze the air used for combustion. Theoretically, most of the air in the combustion zone (m_c) includes swirler air and primary holes of the liner. In regard to flow field without combustion, the parameter could be calculated difficulty because some of the inlet air into ignition volume is due to the reversible flow of swirler and it should be computed continuously. Therefore, one could suggest that (m_c) is correlated with reverse flow(m_r). The recirculation zone includes high-temperature burned gases which provide the necessary heat for combustion of new mixture. If the mass flow rate of fuel reduces, the temperature of recirculation zone reduces too and amount of air in the main zone will rise. The empirical test of ref [1] suggests that the increase of air-flow ratio during the lean blowout is followed by the exponential increase of mass flow rate of reverse flow which enters the combustion zone. Therefore, the variation of flow of reverse fuel and air mixture which enters flammable zone due to recirculation (m_r) is highly critical when the lean blowout is concerned. The significance of this parameter is schematically represented in Fig. (5).

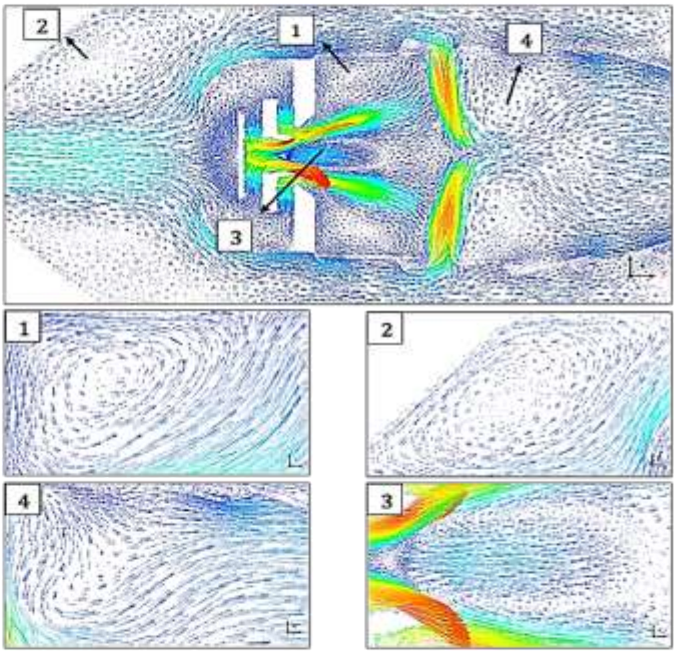

Figure 5 schematic of velocity reverse flow vectors in combustion chamber mid plane

For numerical simulation, the parameter $V_{f,N}$ which is related to Eq. (4) (i.e. identical with V_f in Eq. (2)) should be calculated. The parameter is highly affected by temperature. Therefore, determination of real combustion zone requires determination of temperature distribution around the zone. Determination of temperatures through empirical methods is difficult. Therefore, mean temperature, calculable through energy conservation law (Eq. (5)), is used in the primary zone (T_{pz}).

$$0.5\left[0.5\left(m_{ph}+m_{co}\right)+m_{sec}+m_{pri}\right](T_{PZ}-T_3)\left(C_{P,T_{PZ}}+C_{P,T_{PZ}}\right)=0.5m_A(T_4-T_3)\left(C_{P,T_{PZ}}+C_{P,T_{PZ}}\right) \quad (5)$$

In ref. [19], Eq.6 is used for determination of lean-rich range based on temperature.

$$\text{For lean:}\quad L_T=L_{298.15}-\frac{25285.71}{\Delta H_r}(T_{PZ}-298.15)$$
$$\text{For Rich:}\quad U_T=U_{298.15}+\frac{25285.71}{\Delta H_r}(T_{PZ}-298.15) \quad (6)$$

In Eq. (5), T_{pz} refers to the mean temperature of the primary zone of the chamber (K) and H_r is Low heat value (J/kg). L_T and U_T refer to rich and lean limit (measured based on the volumetric percent of fuel) respectively. Conversion of the volumetric percent to mass percent through Eq. (7) enables determination of the lean-rich weight limit of fuel based on Table 4. In Eq. (11), M refers to the molecular mass of fuel and it is equal with 170.33 kg/J [20].

$$L\left(\frac{mg}{l}\right)\approx 0.45\times M\times L\ (\text{vol pct}) \quad (7)$$

Fig. (6) Represents the flammable zone close to the atomizer which is similar in shape to a horn. The Figure shows four cases of the empirical test based on ref [3], numerical simulation based on ref [1], numerical simulation with fuel species transport solely, and numerical simulation with fuel species transport, atomization and evaporation.

Fig. (7) Shows the way of calculating the parameter of flame volume. To do so, a volume is determined based on the mass of the fuel in a definite rich-lean range (i.e. 0.046 to 0.338). This enables calculation of flame volume. The results of numerical simulation of non-reacting fluid zone suggest that the volume in the vicinity of fuel concentration, moving in a definite point of the combustion chamber, is solely influenced by the structure of chamber and location of the point and it is not associated with the mass flow rate of the fuel. Variation of the fuel mass flow rate only changes the amount and contour of the fuel which moves along the point [3].

In simulation without atomization and evaporation, the flammable zone of numerical simulation is smaller than the zone obtained through the empirical test. When the numerical simulation is accompanied with atomization and evaporation, flame volume increased and the obtained results got closer to the results of the empirical test. Based on empirical tests detailed in ref [3] and [7], the increase of flame volume is followed by the increase of fuel to air ratio during the lean blowout and an easier mixture of fuel and air in the combustion chamber.

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. (6). the parameter α is calculable from the mass flow rate of dome holes. Finally, results of q_{LBO} for the main combustion chamber of the present study (i.e. two models based on Eq. (2) and Eq. (3) and Lefebvre's original model) are compared with results of empirical test and error of each method was determined.

Table 4 Lean-Rich limit

Lean limits (by weight)	Rich limit (by weight)	T_{PZ} (K)	T_4 (K)
0.046	0.339	604.9	445.28

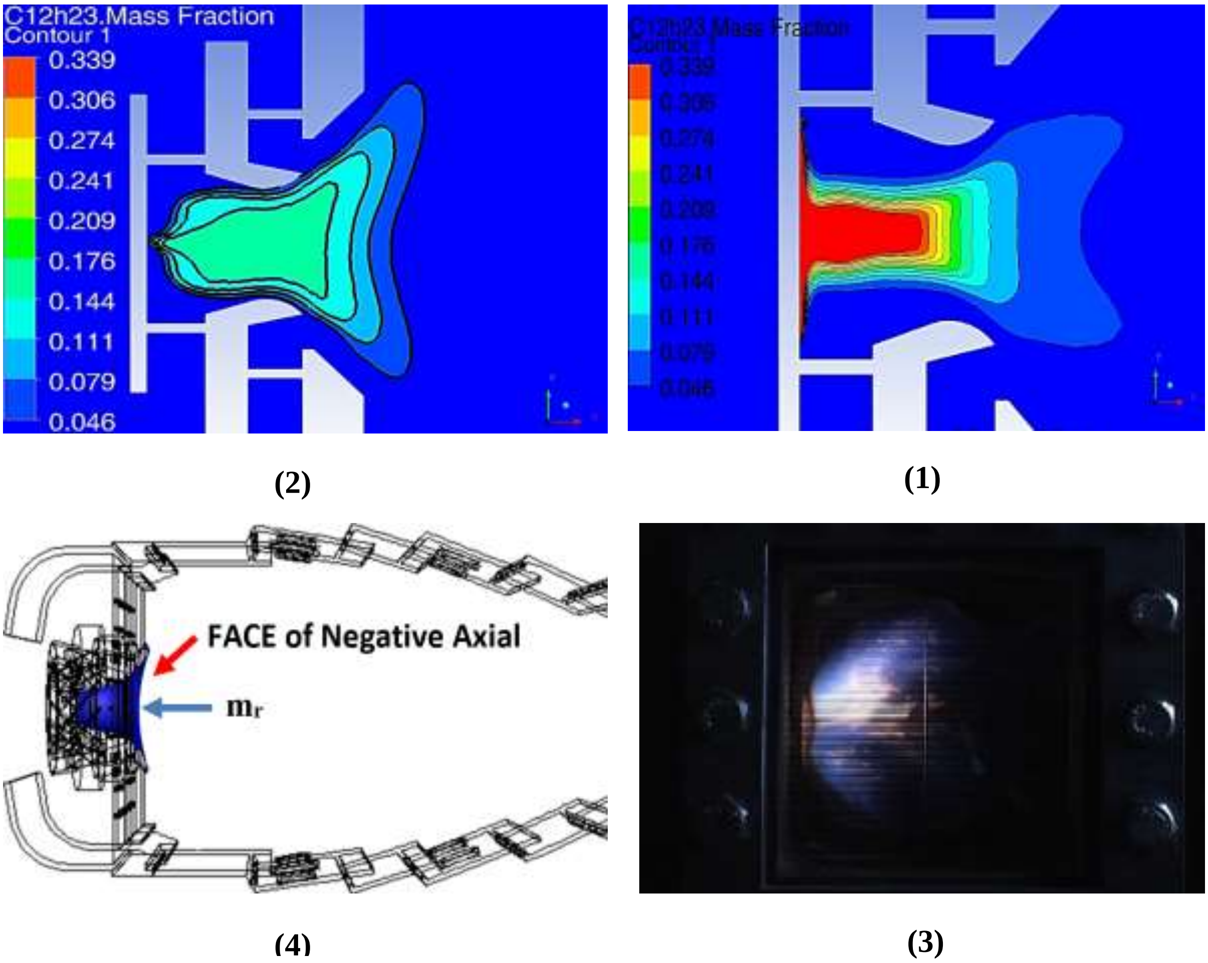

Figure 6 Flame volume comparison in different methods
1) Present study (only fuel species transport)
2) Present study (fuel species transport, atomization and evaporation.)
3) Test result-Ref (3)
4) Numerical simulation-Ref (1)

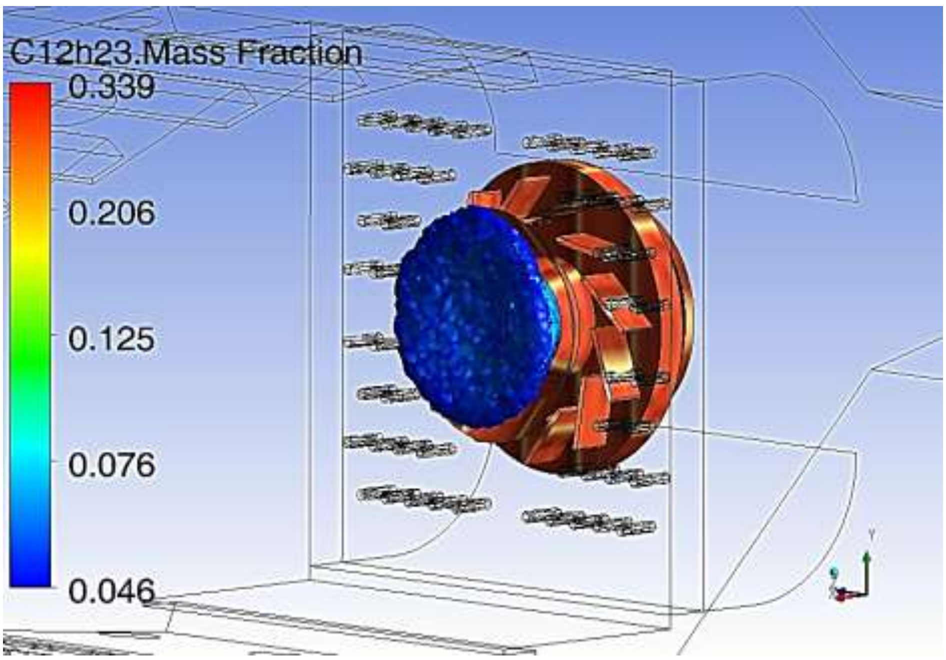

Figure 7 Calculation of flame volume in CFD-POST software

6 Validation

In order to find confidence in results of numerical simulation for prediction of LBO of the main combustion chamber and to conduct grid dependence study, results of the empirical test were compared with results of the numerical analysis in terms of the parameter of velocity at the central line and three different grids (Fig. (8)). As the Figure suggests, there are two points with negative axial velocity at flow field inside the combustion chamber. This is due to swirler and its reverse pressure gradient. The point with the negative axial velocity which closer to the inlet of combustion chamber is mostly affected by vanes of primary swirler. The second point with negative axial velocity at downstream of flow is mainly developed by the airflow of primary zone holes. Lower diameter of holes of the primary zone is correlated with lower negative axial velocity at the second point.

Test results of ref [1] suggested that the first point with negative axial velocity affects fuel-air ratio during lean blowout significantly. The Increase of negative axial velocity is followed by the significant increase of air-flow ratio during the lean blowout. Based on the insignificant difference, the mean grid results (i.e. 3997000) will be used in numerical analysis. In order to validate numerical simulation conditions (e.g. boundary conditions and turbulence model used in this study), a lean direct injector combustion chamber with axial swirler (Fig. (3)) was used. In this chamber, cold flow (without any chemical reaction) was modeled based on boundary conditions suggested in Table 5.

The contour of velocity in the present study, numerical simulation of ref [22] and proper contour of swirler-caused recirculation zones are compared schematically in Fig. (9). Fig. (10) Shows a comparison between results of empirical test and results of numerical simulation in ref [14]. In Fig. (10), the distribution of axial velocity along the central line of combustion chamber and profile of axial velocity in different locations downstream of the flare of swirl cup has been shown. The obtained results point to the desirability of the validation process.

Another noteworthy point is related to the verification of results obtained around the walls and calculation of y^+. The values of y^+ for the main combustion chamber and validation chamber are 124 and 36 respectively which are within a desirable range when $K-\varepsilon$ Realizable model is concerned. For this turbulence model, the desirable range of y^+ is from 30 to 300 [20].

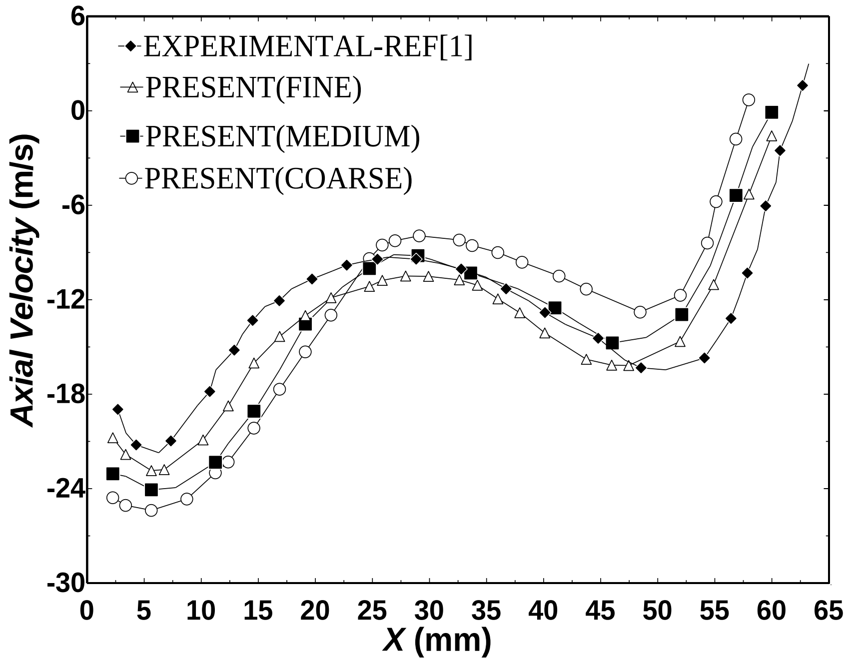

Figure 8 Comparison between test and numerical simulation results in center line velocity for three different mesh

Table 5 Specification of numerical simulation for validation combustion chamber

Parameter	Numerical Simulation
Boundary condition	Velocity inlet-Pressure outlet
Model	$k - \epsilon$ *Realizable*
Near wall treatment	Standard wall function
Fluid Type	Ideal gas
Inlet velocity	20.14 (m/s)
Pressure outlet	0 (Pa)
Turbulence intensity	5 %

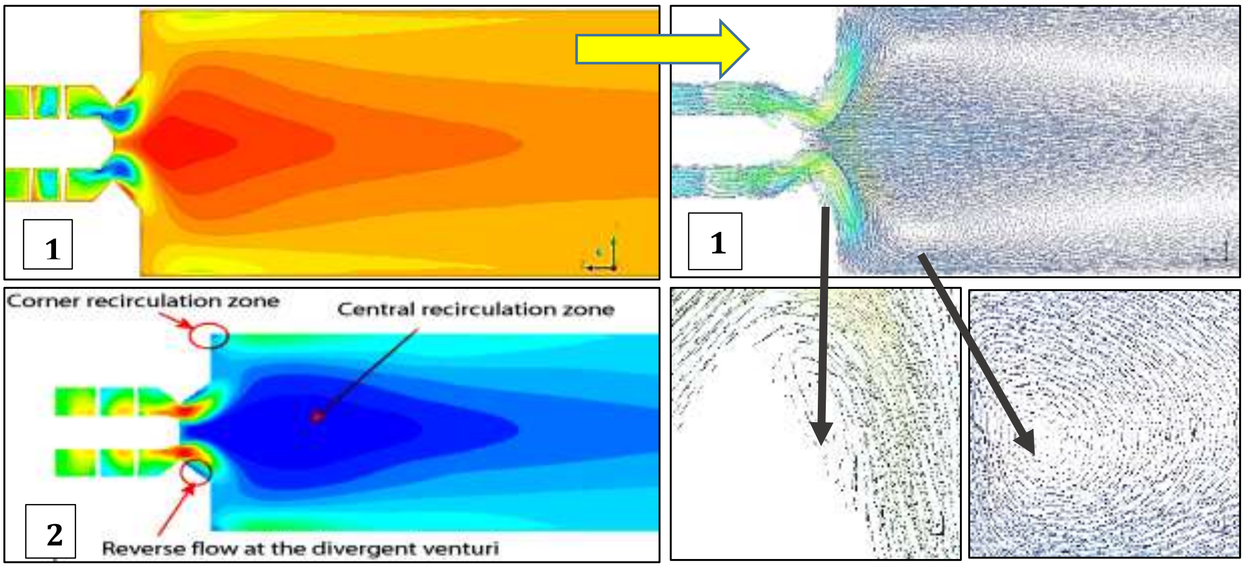

Figure 9 comparison between velocity contours and recirculation zones
(1) Present research (2) Ref [20]

7 Results and Discussion

In this study, three models of HST, LSC, and HSS were used for prediction of LBO of a definite combustion chamber. In the HST model, values of V_f and m_r were obtained through numerical simulation under two scenarios of fuel species transport (HST-FM) and taking atomization and evaporation (HST-SM) into account. The Modifications of these two parameters versus changes in loading parameter are shown in Table 6 and Table 7.

Table 8 shows the association between loading parameter and q_{LBO}. Values of q_{LBO} in both HST-SM and HST-FM methods are determined through Eq. (2).

In ref [7] method, q_{LBO} is determined through Eq. (1) (Lefebvre's model (LSC)). The parameters used in this method are shown in Table 6.

In the other method (i.e. HSS), calculation of q_{LBO} based on Eq. (3) (i.e. Lefebvre's improved semi-empirical correlation) requires referring to Table 9, calculating the parameters $V_{f,N}$ and α through numerical simulation and adding two parameters β_N and β to this equation. In this method, parameters obtained through numerical simulation were analyzed in two cases of fuel species transport (HSS-FM) and atomization and evaporation (HSS-SM). The mentioned parameters are obtained as shown in Table 10 and have been compared with ref [7] results. Regard to this method, values of q_{LBO} obtained through hybrid semi empirical-numerical simulation as shown in Table 11.

Finally, error percent of all methods used in this study as well as empirical results are shown in Fig. (11). In Fig. (11), the first method (FM) signifies fuel species transport while the second method (SM) includes fuel species transport accompanied by atomization and fuel evaluation.

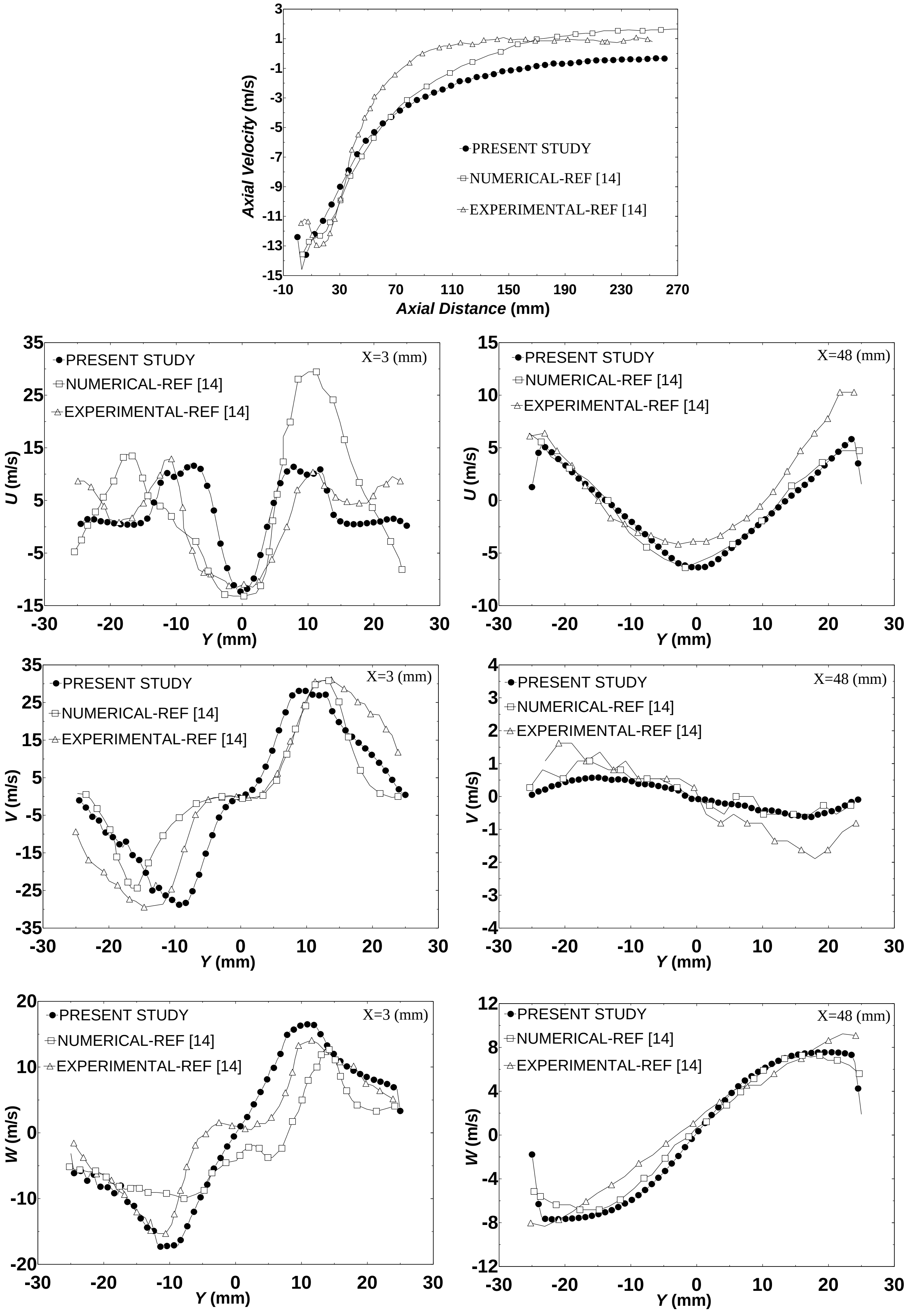

Figure 10 Compare velocity in different sections

Table 6 Values of Loading Parameter and Reverse Flow in Different Methods

Reverse flow (m_r)	*Loading parameter* ($m_r.v_f$)	Method of LBO Prediction
0,0073	0,0042	(HST-FM)
0,0076	0,0053	(HST-SM)
0,0089	0,0049	Ref [7]

Table 7 Values of Loading Parameter and Flame Volume in Different Methods

Flame volume (v_f) (cm^3)	*Loading parameter* ($m_r.v_f$)	Method of LBO Prediction
5.95	0,0042	(HST-FM)
6.99	0,0053	(HST-SM)
5.51	0,0049	Ref [7]

Table 8 Values of Loading Parameter and q_{LBO} in Different Methods

q_{LBO}	*Loading parameter* ($m_r.v_f$)	Method of LBO Prediction
0.0032	0,0042	(HST-FM)
0.0036	0,0053	(HST-SM)
0.0035	0,0049	Ref [7]

Table 9 Values of Lefebvre's model parameters (LSC)

λ	D_r (μm)	V_c (m^3)	H_r (j/kg)	$\acute{A}f_{PZ}$	q_{LBO}
1	50	0.0012	43.5	32.84	0.0068

Table 10 Values of α ,β ، β_N and Flame Volume in Different Methods

Flame volume (v_f) (cm^3)	β_N	β	α	Method of LBO Prediction
6.99	0.0054	0.087	0.123	(HSS-SM)
5.95	0.0046	0.073	0.114	(HSS-FM)
5.51	0.0042	0.067	0.115	Ref [7]

Table 11 Values of q_{LBO} Obtained from different Methods

q_{LBO}	Method of LBO Prediction
0.003399	(HSS-FM)
0.003542	(HSS-SM)
0.003507	Ref [7]
0.003622	Test Results

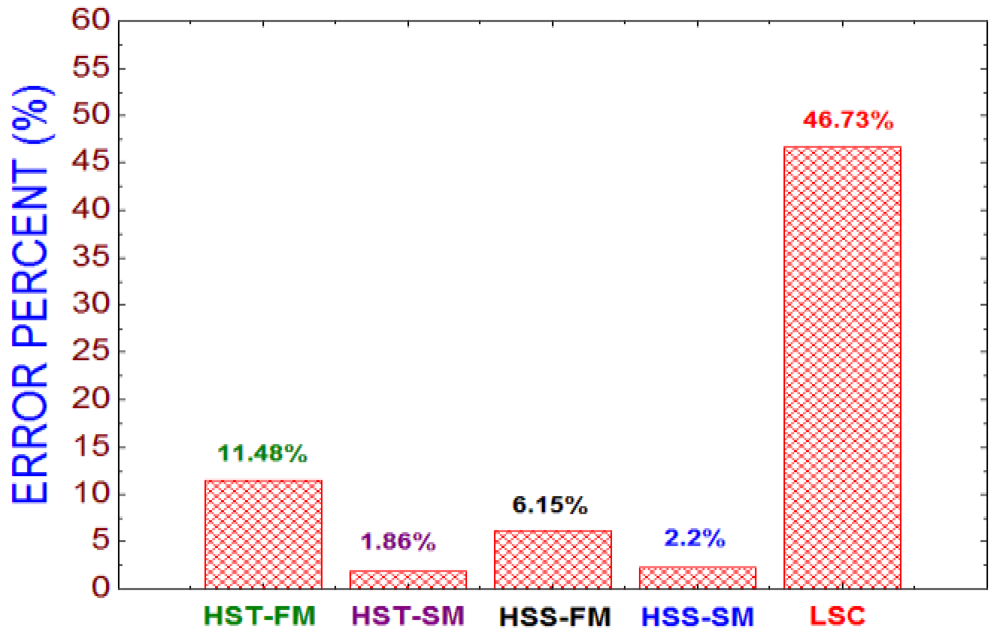

Figure 11 Error percent of different Methods for lean blow out prediction Compared with test results

8 Conclusion

In this study, the prediction of LBO of a combustion chamber is done through three methods. First, q_{LBO} is determined through the HST method which is based on the loading parameter and it is a combination of test-numerical simulation. The second method uses a combination of numerical simulation and Lefebvre's improved semi-empirical correlation (i.e. HSS). In this case, calculation of q_{LBO} is done through Lefebvre's final correlation (i.e. LSC). In the first case, numerical simulation is solely done by taking fuel species transport into account and errors of HST and HSS were 11.48 and 6.15 percent respectively. In the second case, atomization and fuel evaporation were also taken into account and obtained error percent of HST and HSS methods were 1.86 and 2.2 percent respectively. It should be noted that the error of Lefebvre's original correlation for calculation of q_{LBO} is 46.73 percent. The obtained results suggest that taking atomization and evaporation into account adds to calculation accuracy of parameters used in prediction of LBO in comparison with first case (mere consideration of fuel species transport) while error percent reduces significantly. In addition, the time and cost of adopting the method are significantly lower than semi-empirical methods which are based on expensive tests such as Lefebvre's model. This is while accuracies of the two hybrid methods adopted in this study are significantly higher than semi-empirical models. Therefore, analysis of LBO through these two hybrid methods could be regarded as the desirable substitution for semi-empirical methods or empirical tests. This method could be used in different steps of the design of combustion chamber.

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Nomenclature

A'	Model constant defined in Lefebvre's model for LBO
D_{hub}	Hub diameter of swirler vane (mm)
D_r	Mean drop size relative to JP4 (μm)
D_{sw}	Tip diameter of swirler vane (mm)
f_{PZ}	Air fraction in primary zone
H_r	Lower calorific value relative to (j/kg)
m_A	Total mass flow rate of combustor inlet (kg/s)
m_{co}	Mass flow rate through dome holes(kg/s)
m_{ph}	Mass flow rate through liner primary holes (kg/s)
m_{pri}	Mass flow rate through primary swirler (kg/s)
m_r	Reversed mass flow rate due to swirler(kg/s)
$m_r \cdot v_f$	Loading parameter (kg.m^3/s)
m_{sec}	Mass flow rate through secondary swirler (kg/s)
q_{LBO}	Overall fuel/air ratio at LBO (g/kg)
T_{pz}	Average temperature of primary zone(K)
T_4	Outlet temperature of combustor(K)
V_c	Combustor volume ahead of dilution holes (m^3)
V_f	Flame volume (m^3)
τ_{sl}	

Greek symbols

	Shear layer residence time
τ_{hc}	Characteristic time for fuel ignition delay
τ_{eb}	Characteristic time for fuel evaporation
λ_r	Effective evaporation relative to that for JP4
α	Fraction of dome air