LES of Combustion Flow Field in a Practical Aeroengine Combustor with Two-Stage Counter-Rotating Swirler

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Abstract: To improve knowledge of the reacting flow in real aeroengines, large eddy simulation (LES) with dynamic Smagorinsky subgrid model is used to explore the complex unsteady flowfield in a single burner of a typical aeroengine combustor with radial two-stage counter-rotating swirler. Three combustion models namely fast chemistry model (FC), flamelet model (FLM) and progress–variable model (FPV) are applied. The complex geometric configuration including all film cooling holes is fully simulated without any conventional simplification in order to essentially reduce the modeling errors. Based on the non-reacting flowfield which has been advanced to the statistically stationary state in early work, unsteady process of fuel injection is first simulated without reaction. It cost about 2.6ms for adequate fuel reaching the real ignition location, then pseudo ignition is numerically conducted using FPV model in the given sphere region with a radius of 3mm. The process that initial flame propagates along the isoline of stoichiometric mixture and fills the whole chamber under the effect of transverse flow is simulated. It costs about 6~7ms for the flame arriving at the outlet. Compared to coherent anti-Stokes Raman scattering (CARS) measurement of mean temperature on central profile, mean error of LES–FPV, RANS–FPV, LES–FLM and RANS–FLM in the reference are 3.47%, 4.17%, 7.76% and 11.22% respectively, indicating that LES improves the accuracy and FPV performs better than FLM. Due to the severe hot spot at the outlet, RANS–FPV gives the poorest outlet temperature distribution factor (OTDF) and maximum radial temperature distribution factor (RTDF) as 0.593 and 0.313 respectively. Corresponding values predicted by LES–FPV are 0.284 and 0.193, presenting the best uniformity among all cases.

Key words: Aeroengine combustor; Counter–rotating swirler; Large eddy simulation; Dynamic Smagorinsky model; Fast chemistry model; Flamelet model; Progress variable model

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航空发动机两级反向旋流燃烧室燃烧流场大涡模拟研究

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摘要：为深入了解真实航空发动机内燃烧流场，采用动态亚网格模型结合单步快速化学反应(FC)、火焰面(FLM)及反应进度变量(FPV)等三种燃烧模型对径向两级反向旋流燃烧室单头部构型进行了大涡模拟。为避免模型简化误差，对燃烧室包括全部气膜冷却孔在内的精细结构进行了完全仿
1 Introduction

Combustor plays an important role in the aeroengine. In past years, it was investigated numerically and experimentally in many aspects like flow structures and transient processes. Due to the expensive consumption and long period, experiments and tests have been gradually superseded by CFD methodology in recent years. Especially, with the rapid growth of computer performance, large eddy simulation has been widely used to explore the complex flowfield in practical industrial facilities because of its capability of resolving micro structures and affordable computation cost.

A lot of research works have been done to acquire flow characteristics in the combustor. However, the extremely complex components contained in a real aeroengine combustor bring great difficulties to numerical simulations. Most of the current LES investigations have been carried out on simple configuration, such as mechanism research of small industrial gasturbine combustor with only one-stage swirler. For more complex combustors with two-stage swirler, a hybrid URANS/LES model and Laser Doppler Anemometry (LDA) were applied to the study of the non-reacting flowfield, and the existence of PVC in inner shear layer at 1514 Hz was verified. The same hybrid method to study a highly swirling turbulent flow generated by rotor–stator interaction was also applied and captured the helical vortex rope. Yee Chee See investigated the influence of grid resolution and mesh type on the distribution of velocity in LES of a two-stage swirller combustor and found the inconclusive grid sensitivity. As a practical industrial model, GE LM6000 lean–premixed combustor has been investigated by LES in aspects of vortex breakdown and central&corner recirculation zones, propagation of acoustic waves and flow differences between the single burner and modeled annular 18–burner combustor. Tachibana Shigeru et al. paid close attention to the thermo–acoustic instability in a single sector of an aeroengine combustor at elevated pressure and validated LES result of spray combustion by OH–PLIF experiment.

More studies such as analysis of different stable combustion state in swirl–stabilized gas turbine burner, the use of reduced / detailed chemical reaction mechanisms of aviation fuels, flame structure and instability, were also carried out. As a critical problem for aeroengine combustors, ignition behavior and flame propagation have been concerned and studied in recent years. As early as 2006, Brankovic et al. investigated the ignition, piloting and flame stability in a simple gasturbine burner using URANS and LES, suggesting that modeling the full geometry could produce better agreement with experimental data than assuming an axisymmetric geometry. For more realistic configurations, Neophytou et al. applied LES to the ignition and flame propagation in a trisector combustor, with dynamic thickened flamelet combustion model and two-step mechanism for decane. Similar LES studies about various configurations, such as a linear array of 5 laboratory–scale burners using flamelet model in ANSYS Fluent, 2 ~ 5 aeronautical swirled burners designed in the context of European project KIAI (Knowledge for Ignition, Acoustics and Instabilities–7th framework program–2009 / 2013), DLR model combustor, CESAR multi–burner annular combustor and modeled...
annular aeroengine combustor$^{[23]}$, have been wildly carried out, with two main categories of combustion models namely flamelet series$^{[24]}$ and finite rate chemistry$^{[25]}$.

However, as Yee Chee See$^{[26]}$ pointed out, one important reason that LES in realistic gasturbine combustor have so far not been fully utilized is the geometric complexity and construction of geometry-conform mesh-es with related computational complexity. As a result of this limitation, LES of aeroengine combustors have so far been performed under drastically simplified conditions apart from very few exceptions. For example, secondary geometric structure is not considered and amount of film cooling holes may be reduced to channels or approached by multi-hole boundary conditions. Difficulties of numerical simulation can be significantly reduced by the treatment mentioned above, but at the same time, error introduced by the simplification is hard to be quantified and thereby may degrade the reliability of computation.

The objective of the present work is first to study the process of fuel injection and mixing in a practical aeroengine combustor with two-stage counter-rotating swirler, and then the reacting flow in the chamber including processes of ignition and flame propagation. Great efforts have been made in generating a high quality body-fitted mesh with high fidelity to essentially reduce the error of simplification as far as possible. Most details of the geometric configuration in the combustor are simulated, including all tiny film cooling holes.

2 Numerical procedure

The governing equations of LES can be obtained by a filtering operation on $N$–$S$ equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \mathbf{u})}{\partial x_j} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \left( \frac{\partial (\rho \mathbf{u} \mathbf{u})}{\partial x_j} \right) = \frac{\partial (\rho \mathbf{u} \mathbf{S})}{\partial x_j} - \frac{\partial P}{\partial x_j} - \frac{\partial \tau}{\partial x_j}$$

where the subgrid stress $\tau = \rho (\mathbf{u} \mathbf{u} - \mathbf{u} \mathbf{u})$ can be modeled by eddy viscosity hypothesis

$$\tau = -2 \mu_S \mathbf{S} + \frac{1}{3} \mathbf{S} \mathbf{S}$$

where $\mathbf{S} = \frac{1}{2} \left( \frac{\partial \mathbf{u}}{\partial x_j} + \frac{\partial \mathbf{u}}{\partial x_j} \right)$ and $\mathbf{S}$ denotes the strain rate tensor of the resolved field. The viscosity $\mu_S$ is obtained from a subgrid model such as the standard Smagorinsky closure

$$\mu_S = \mu (C, \Delta)^{\frac{2}{3}} \sqrt{2 \mathbf{S} \mathbf{S}}$$

where $C$ denotes the Smagorinsky constant, $\Delta = 2 ||\Omega||^{1/3}$, where $\Omega$ denotes the filtering scale and $||\Omega||$ is the volume of the grid cell. The dynamic Smagorinsky model is utilized in the present work, with $C$, calculated dynamically by filtering equations twice. According to the Germano equation

$$L_\eta = \left( \left( \left( \mathbf{u} \right) \right) \right) = \left( \left( \left( \mathbf{u} \right) \right) \right)$$

it can be acquired that

$$L_\eta - \frac{1}{3} L_\eta = \mathbf{M} = \frac{\mathbf{M}}{\mathbf{M}}$$

where

$$\mathbf{M} = 2 \left( \left( \Delta_1 \mathbf{S} \mathbf{S} \right) - \left( \Delta_2 \mathbf{S} \mathbf{S} \right) \right)$$

where the superscript ‘$\cdot$’ and ‘$\cdot$’ denote the filtering scale $\Delta_1$ and $\Delta_2$ respectively. $\Delta_1$ is equal to $\Delta$ and $\Delta_2 = \frac{3}{2} \Delta$. Finally the coefficient $C$ can be computed as

$$C = \frac{\mathbf{M} \mathbf{L}}{\mathbf{M} \mathbf{M}}$$

In addition, FPY model used for reacting flow requires extra equations for mixture fraction $Z$ and progress variable $C$

$$\frac{\partial \rho \mathbf{Z}}{\partial t} + \frac{\partial (\rho \mathbf{Z} \mathbf{u})}{\partial x_j} = \frac{\partial (\mathbf{u} \mathbf{Z})}{\partial x_j} = \frac{\partial (\rho \mathbf{D}_Z \mathbf{Z})}{\partial x_j} + \frac{\partial q_z}{\partial x_j}$$

$$\frac{\partial \rho \mathbf{C}}{\partial t} + \frac{\partial (\rho \mathbf{C} \mathbf{u})}{\partial x_j} = \frac{\partial (\mathbf{u} \mathbf{C})}{\partial x_j} = \frac{\partial (\rho \mathbf{D}_C \mathbf{C})}{\partial x_j} + \frac{\partial q_c}{\partial x_j}$$

where $C$ is defined as the summation of the product gases ($Y_{CO} + Y_{CO_2} + Y_{H_2O} + Y_{H_2}$), and subgrid terms are written as $q_z = (\rho \mathbf{Z} \mathbf{Z} - \mathbf{Z} \rho \mathbf{Z})$, $q_c = (\rho \mathbf{C} \mathbf{C} - \mathbf{C} \rho \mathbf{C})$. They are also dynamically modeled. Implementation details and formulations of the model along with one-step fast chemistry model (FC) and flamelet model (FLM) can be found in the reference$^{[27]}$. Simulations of preliminary non-reacting flow and sequential reacting flow are both carried out using the LES code developed by our work- group. The code is a finite-volume, low-Mach package for unstructured grid, based on the SIMPLE algorithm.
technique with second order scheme both in space and time.

3 Computational setup

The study object in our present work is a single rectangular burner of a practical aeroengine combustor with counter-rotating swirler and 6 rows of film cooling holes located on both upper and lower wall of the chamber. There is a rectangular diffuser before the test section with a length of 250mm. The whole length, height, and width of the model are 570mm, 43mm (inlet)/130mm (outlet) and 90mm respectively. Some LES investigations with similar configuration have been performed in early works\textsuperscript{28-30} with only 1.34 million grid cells. To improve the quality and fidelity of the mesh, several structural layers of prismatic or hexahedral grids are extruded along the normal direction of surface grid in near-wall region. Holes are discretized of full hexahedral grids, while the unconfined space are discretized with tetrahedral elements. The mesh is alternately checked and adjusted by several times of pre-calculation to ensure that the first layer grid is located under the viscous sub-layer, and the variation of flow variables on monitor points tends to be grid-independent. There are 17 million cells in the finally generated mesh (Fig.1), which contains about 500 elements in each film cooling hole and 6 million elements in the chamber.

LES is then carried out based on the high fidelity mesh. The flow condition can be seen in Table 1, where \( p, T, \rho \) and \( U \) denote the operating pressure, inflow temperature, fluid density and mean inlet velocity respectively. Velocity components in the three directions are set as \( u=U \) and \( v=w=0 \). Under the circumstance that there is a long diffuser in front of the swirler, only the average value of normal velocity is given for the inlet, which indicates a developed flow with possible natural transition for the chamber. No slip boundary condition is applied on the wall while the normal gradient of all variables is prescribed as zero at the outlet.

As the distance between inlet and outlet is about 570mm, the flow-through time estimated by \( U \) is about 11ms. Calculations are performed in parallel, distributed on 40 Intel Xeon X5670 CPUs with a total number of 480 cores. 2.0\times 10^5 steps are first advanced for the non-reacting flow with a physical time of 159ms and a cost of about 20 days. Afterwards simulation of the reacting flow is subsequently conducted with uniform time step of 0.4\mu s.

![Fig. 1 Schematic of the high fidelity mesh](image)

<table>
<thead>
<tr>
<th>Table 1 Flow condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p/\text{kPa} )</td>
</tr>
<tr>
<td>550</td>
</tr>
</tbody>
</table>

4 Validation

Validation of spatial and temporal resolution was conducted first to find out whether the grid resolution is enough for the current LES. Coordinates origin is set at the center of the outlet plane of the swirler cup as point \((0, 0, 0)\). The Taylor length scale \( \lambda = (10\nu k/e)^{1/2} \), the Taylor time scale \( \tau = (15\nu /e)^{1/2} \), the Kolmogorov length scale \( \eta = (\nu /\varepsilon)^{1/4} \), and the Kolmogorov time scale \( \tau_\eta = (\nu /\varepsilon)^{1/2} \), are calculated at different streamwise locations (Fig.2) and compared with the cube root of the cell volume \( l = (\Delta x \Delta y \Delta z)^{1/3} \) in Fig.3. It shows that almost all grids lie under the two length scales. On the other hand, due to the intense interaction between the two-stage counter-rotating high speed swirling flows, minimum \( \eta \),
can reach the level close to $10^{-5}$s in the shear layer at the location $x=-10$mm. So the chosen time step size for the present simulations should be small enough to capture small scales in the flow field.

**Fig. 2** Schematic of the coordinate system

5 Result and comparison

In this section we begin to explore the unsteady flow processes and analyse the result of LES, in the sequence of information about preconditioned non-reacting flow, fuel injection, ignition, flame propagation and comparison.

LES of non-reacting flow in the combustor has been carried out in early work in order to provide a fully developed, statistically stationary flow field. Fig. 4 exhibits the turbulence kinetic energy spectrum of $u$ at point $(0, 0, 0)$ and $(35, 0, 0)$, which shows good agreement with the $-5/3$ law in the inertial subrange and suggests that the turbulent fluctuation is well resolved by present calculation based on the high fidelity mesh. Fig. 5 provides a 3-D view on the iso-surface of instantaneous vorticity at $t=55$ms, showing a fully developed turbulent swirling flowfield in the chamber, which is especially complex in central region due to the coupling of main swirl and transverse flow from primary and dilution holes. More details about the LES investigation of non-reacting flow in this combustor can be found in reference [31].

5.1 Fuel injection

Based on the precursor simulation of non-reacting flow, subsequent reacting case is to be studied by LES with different models. The fuel is gaseous kerosene, with detailed chemical mechanism involving 203 species and 1592 reactions. The mass flow rate of fuel is 11.5g/s with bulk velocity of about 80m/s and temperature of 300K, while other computational conditions and parame-
FPV model is first used to study fuel injection and ignition. Fig. 6 shows the transient process of fuel injection in the form of mixture fraction on central profile \( z = 0 \) mm. To observe the contour more conveniently and confirm the ignition opportunity more appropriately, extremely lean regions that \( Z < 0.01 \) are clipped. As the fuel being injected from the nozzle, it mixes with air under the effect of two-stage swirling flow, impacts and interacts with the wall of the swirler cup, transports into the chamber along the expanded configuration. At \( t = 161.6 \) ms, the fuel has reached the location close to the virtual igniter near the primary hole upstream, with local mixture approaching the stoichiometric ratio. Then an initial value of 0.2 is assigned to progress variable \( C \) in a sphere region around point \((10, -30, 0)\) with a radius of 3 mm and consequently the chemical reactions are activated.

### 5.2 Flame propagation

As the manner of pseudo ignition in the present work differs from conventional ways which usually take account of energy deposition and finite rate chemistry, it provides another perspective to regard the problem. Fig. 7 illustrates the development of temperature on central profile \( z = 0 \) mm. As the ignition region is just located on the isoline of \( Z = 0.063 \) corresponding to the stoichiometric ratio, intense chemical reactions are activated with fast increment of \( T \). The initial flame expands around the ignition region and propagates roughly along the isoline. Since \( t = 162.7 \) ms, flame front tends to spread to the central recirculation zone (CRZ) under the influence of transverse flow from the lower primary hole. It ultimately fills the whole primary zone at \( t = 167 \) ms and propagates downstream. Fig. 8 shows the iso-surface series of instantaneous temperature. Regions with high temperature can be roughly divided into two major zones located upstream and downstream from primary holes respectively. Fig. 9 shows the time-series of instantaneous temperature at point \((35, 0, 0)\) and \((180, 0, 0)\). For the former, it cost about 2.1 ms \((161.6 \sim 163.7)\) ms for initial flame front propagating to the center of the chamber. Peak value of 2564 K appears at \( t = 168.8 \) ms, after which temperature fluctuates with relatively stable peak and valley values, indicating a statistically stationary state. It also can be concluded from the latter point that the

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Fig. 4  Energy spectrum of streamwise velocity fluctuations at two points

Fig. 5  Instantaneous vorticity field at \( t = 55 \) ms (iso-surface: \( 3.5 \times 10^4 \) s\(^{-1} \) & \( 5.0 \times 10^4 \) s\(^{-1} \))

Fig. 6  Distribution of instantaneous mixture fraction on central profile \( z = 0 \) mm (isoline: \( Z = 0.063 \))
characteristic time of flame passing through the chamber is about $6 \sim 7$ ms.

5.3 Mean flowfield

Instantaneous results predicted by LES have revealed the unsteady processes of fuel injection, pseudo ignition and flame propagation in the combustor. According to the time scale evaluated above, flow statistics are collected since $t=180$ ms to assure that the reacting flowfield has fully developed.

Fig. 10 provides a 3-D view of the mean flowfield in the chamber, where the symbol ' $<>$ ' denotes a time-averaged quantity. Swirling flow passing through the swirler cup eventually generates an expanded iso-surface of $<u>=0$ representing the CRZ. Meanwhile, transverse flow from primary holes with speed up to 110 m/s plays an important role in supplying fresh air and facilitating the flame stabilization in primary combustion zone. Located at $x=95$ mm, downstream dilution holes
further supplement air for secondary afterburning with unreacted fuel, producing new regions with high temperature (Fig.11).

Fig.12 shows the 2-D distribution of mean temperature on central profile $z=0$mm combined with specific isolines. For comparing, other results obtained under the identical inflow conditions from FC and FLM models under the LES framework, and a RANS simulation with standard $k-\varepsilon$ model for turbulence and FPV model for combustion are also exhibited.

![Fig. 10 Distribution of $\phi$ on profile $x=35 \text{ & } 95$mm, and iso-surface of $\phi=0$ colored by temperature (isoline: $Z=0.063$)](image1)

Differences among the four cases mainly lie in the distribution of high temperature regions. In general, temperature predicted in the CRZ is lower in all LES cases than in RANS case. On the contrary, LES results show higher temperature in the afterburning areas downstream from primary holes. It’s also notable that in RANS–FPV result, extra high temperature appears along isoline of $Z$ in near–wall regions upstream from primary holes. Overall, this phenomenon can be attributed to the over-estimation of chemical reactions in primary combustion zone, and accordingly underestimation of combustion intensity downstream by RANS simulation. Besides, it can be found from the isoline of $\phi=0$ that transverse flow predicted by LES shows greater penetration depth, which consequently provides better conditions for secondary stagnation combustion downstream. Thus it can also be explained that LES predicts the afterburning areas with better symmetry.

To quantify the differences among these cases, 1–D distribution of mean mixture fraction and temperature at different locations is shown in Fig.13 and Fig.14. At the first position $x=-10$mm where fuel mixes and reacts with air under the effect by the coupling of swirling flow from the two stages, conspicuous differences can be observed in Fig.13(a). Due to the fast chemistry assumption, FC model significantly overestimates the reaction intensity in the mixing layer with corresponding peak temperature. As the heat release is unreasonably high, burnt gas expands at unexpected high level. Thus the fuel and air on both sides of the mixing layer are prevented from further mixing. Therefore a large amount of unreacted fuel still stays inside the swirler cup, presenting a high mixture fraction in the range of $-10\text{mm}<y<10$mm. For FLM model which has taken into account multi–species and multi–step reactions in kerosene combustion, it predicts a lower reaction intensity and consequent lower temperature than FC model. Essentially different from that in LES–FC and LES–FLM cases, temperature in LES–FPV case shows that there is no combustion occurred at this location. However, RANS–FPV result is quite the contrary, which can be ascribed to the usage of different turbulence models. In Fig.13(b), Distribution features at $x=0$mm show qualitative agreement with that at $x=-10$mm, except that LES–FPV also predicts the occurrence of combustion as others.

At $x=10$mm (Fig.13(c)), it can be concluded from the distribution of mixture fraction that fuel has nearly been mixed uniformly in primary zone. FPV results still exhibit higher mixing level with the mixture fraction closer to 0.063. Thus temperature in the two FPV cases both reaches high. It is notable that RANS–FPV shows a thin flame sheet in the near–wall region $y=\pm 40$mm, with extra higher temperature peak up to 2200K, which also can be observed in Fig.12. This is somewhat unreasonable, indicating that in spite of the use of FPV model
with outstanding performance, essentially the defects of simulating complex flow field under the RANS framework can’t be remedied.

Fig. 13 (d) shows the distribution along the line through primary holes. Benefiting from the fresh air provided by the transverse flow, fuel in central region is diluted and mixture fraction consequently approaches to 0.063, leading to intense combustion with temperature up to 2000 K in a wide range. What calls for special attention is that temperature predicted by LES–FLM is distinctly lower than others.

Fig. 13 (e) exhibits corresponding distribution along the center line from inlet to outlet. It clearly reveals that for the prediction about mixing, differences mainly lie in primary zone where \( x < 40 \text{mm} \). Mixture fraction predicted in either FPV case presents more closely to the value corresponding to stoichiometric ratio, indicating better mixing. Consequently the high temperature region predicted by RANS–FPV has the widest range. But on the other hand, premature consumption of fuel also leads to a underestimation of combustion intensity downstream. On the contrary, LES–FC and LES–FLM both predict higher temperature in afterburning areas than in primary zone.

As dilution holes also play important role in the chamber and especially affect the outlet temperature, distribution of temperature and mixture fraction along the line through a couple of dilution holes is also inspected in Fig. 14. Due to the supplementary air from dilution holes, mixture fraction predicted in different cases all approaches to the level of stoichiometric ratio and inducing intense combustion. However, RANS–FPV result presents significant asymmetry which is distinct from the others.

To evaluate the eventual influence of different numerical models on the simulation results, time-averaged temperature predicted in the four cases are compared with the experimental data from CARS measurement and the reference results\(^{[32]}\) from a RANS simulation with flamelet model. Table 2 shows the values and corresponding errors at 12 discrete points located around the primary zone on the central profile.

Overall, all simulation results show relatively significant discrepancy with CARS data at point (35, 0) located in the center of primary zone, with errors above average. This problem principally depends on the complex local flow environment. The point lies near the border of the CRZ with low speed, and is significantly affected by the collision of transverse flow with intense chemical reactions. As a result, a small numerical disturbance may...
induce relatively big changes of flow variables, which makes it rather hard to precisely simulate the local field. By contrast, best predictions appear at the same point (35, 30), where the impact of above factors are weaker.

For cases using the identical model, LES performs better than RANS as expected, especially when compar-

Fig. 13  1-D distribution of mean mixture fraction and temperature on central profile z=0mm

Fig. 14  1-D distribution of mean mixture fraction and temperature along the intersection line of profile x=95mm & z=15mm
ing LES–FLM to the reference. More specifically, there are 7 points with errors greater than 10% in the reference result and only 2 in LES–FLM. The former shows rather poor accuracy at point 9 ~ 12 in the area downstream from the CRZ. Besides, although it seems that RANS–FPV nearly reaches the same level of LES–FPV in the sense of mean error, it performs not so well on aspect of symmetry in afterburning areas downstream.

For model performance, prediction by FPV model reaches better agreement with CARS measurement than FLM model, which almost underestimates the temperature at all locations under both LES and RANS framework. It’s worth pointing out that in spite of the least error, FC model should not be considered to be suitable for combustor simulation, as it’s well-known that there are essential defects in the simple mechanism of the model. When comparing to the flow fields in other areas, unreasonable phenomena emerge. The best accuracy can only be regarded as a coincidence for the specified locations.

In addition, as the outlet plane is mostly concerned in practice, 2–D flow fields on it are extracted and compared in the present work. Fig. 15 shows the distribution of mean temperature on the outlet plane and Table 3 shows the outlet temperature distribution factor (OTDF). In RANS–FPV case, a significant hot spot lies in the upper right with maximum and average temperature at 2145.0K and 1666.9K, respectively. Corresponding OTDF is 0.593 which far exceeds the normal range 0.25 ~ 0.35 desired in general combustors, indicating a poor uniformity. By contrast, maximum and mean temperature predicted by LES–FPV is 1995.4K and 1744.2K respectively, with a much better OTDF of 0.284 which is more reasonable. Distribution feature in LES–FC result distinctly reflects the influence of transverse flow from dilution holes. Due to the essential defects in the mechanism, FC model underestimates the degree of mixing in downstream areas and cause poor uniformity. Consequently, it’s not unexpected that LES–FC predicts a high OTDF up to 0.487. LES–FLM exhibits a nice uniformity, second only to LES–FPV. This can be attributed to the high value of $T_{\infty}$ up to 1881.3K predicted by it. However, in view of the poor model performance in primary zone upstream, the greatest average temperature predicted by LES–FLM at the outlet is somewhat doubtful. Considering that the chemical mechanism used in FLM is identical to that in FPV, the unreasonable high temperature may be partly attributed to the lack of unstable branch in the flamlet database (Fig. 16). The unstable branch introduced in FPV model can help predict unsteady combustion and local extinction, avoiding the overestimation of temperature.

Further comparison of radial temperature distribution factor (RTDF) is shown in Fig. 17. Due to the hot

Table 2  Temperature at specified locations on profile z=0mm

<table>
<thead>
<tr>
<th>No.</th>
<th>(x,y)/mm</th>
<th>CARS/K</th>
<th>LES–FC/K</th>
<th>Error%</th>
<th>LES–FLM/K</th>
<th>Error%</th>
<th>RANS–FPV/K</th>
<th>Error%</th>
<th>LES–FPV/K</th>
<th>Error%</th>
<th>Ref.[32]/K</th>
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<td>−7.93</td>
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<td>−2.53</td>
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<td>0.17</td>
<td>2152.37</td>
<td>2.49</td>
</tr>
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<td>6</td>
<td>(34,20)</td>
<td>2087</td>
<td>2016.0</td>
<td>−3.40</td>
<td>1915.6</td>
<td>−8.21</td>
<td>2026.9</td>
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<td>2098.9</td>
<td>0.57</td>
<td>2202.20</td>
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<tr>
<td>7</td>
<td>(35,30)</td>
<td>1915</td>
<td>1930.5</td>
<td>0.80</td>
<td>1821.2</td>
<td>−4.90</td>
<td>1889.6</td>
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<td>1.29</td>
<td>1717.50</td>
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<td>8</td>
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<td>1895</td>
<td>1923.3</td>
<td>1.47</td>
<td>1809.2</td>
<td>−4.53</td>
<td>1982.4</td>
<td>4.41</td>
<td>1980.1</td>
<td>4.30</td>
<td>1877.55</td>
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<td>9</td>
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<td>2160</td>
<td>2097.1</td>
<td>−2.91</td>
<td>1991.7</td>
<td>−7.79</td>
<td>1914.0</td>
<td>−11.39</td>
<td>1991.7</td>
<td>−7.79</td>
<td>1658.99</td>
<td>−23.19</td>
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<tr>
<td>10</td>
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<td>2190</td>
<td>2129.9</td>
<td>−2.74</td>
<td>2001.8</td>
<td>−8.59</td>
<td>1964.7</td>
<td>−10.29</td>
<td>2026.7</td>
<td>−7.46</td>
<td>1678.34</td>
<td>−23.36</td>
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<td>11</td>
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<td>1870</td>
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<td>−5.56</td>
<td>1976.7</td>
<td>5.40</td>
<td>1874.3</td>
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<td>1849.7</td>
<td>−1.09</td>
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<td>−13.12</td>
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<td>12</td>
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<td>1905</td>
<td>1964.7</td>
<td>3.04</td>
<td>2010.5</td>
<td>5.25</td>
<td>1939.1</td>
<td>1.76</td>
<td>1933.3</td>
<td>1.46</td>
<td>1663.33</td>
<td>−12.69</td>
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</table>

Absolute mean error% 3.36 7.76 4.17 3.47 11.22
spot introducing severe nonuniformity, maximum RTDF in RANS–FPV case reaches up to 0.313, which is much larger than 0.193 in LES–FPV. In spite of the high OTDF, LES–FC exhibits nice uniformity along the radial direction in the sense of RTDF. The curve in LES–FLM case presents similarly to that in LES–FPV, except that the maximum value is slightly higher.

However, the maximum RTDF in mainstream combustors usually does not exceed 0.15. One dominant factor inducing the higher-than-desirable nonuniformity may be attributed to the shape of combustor which is transformed from a sector to a rectangle to facilitate measurement in this work. The change of configuration brings certain influence on the flowfield, especially the distribution of flow variables near the geometric boundary.

<table>
<thead>
<tr>
<th>Item</th>
<th>$T_{\infty}/K$</th>
<th>$T_{\text{avg}}/K$</th>
<th>OTDF</th>
</tr>
</thead>
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<tr>
<td>LES–FC</td>
<td>2269.2</td>
<td>1807.7</td>
<td>0.487</td>
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<tr>
<td>LES–FLM</td>
<td>2201.2</td>
<td>1881.3</td>
<td>0.313</td>
</tr>
<tr>
<td>RANS–FPV</td>
<td>2145.0</td>
<td>1666.9</td>
<td>0.593</td>
</tr>
<tr>
<td>LES–FPV</td>
<td>1995.4</td>
<td>1744.2</td>
<td>0.284</td>
</tr>
</tbody>
</table>

Fig. 15  Distribution of mean temperature on the outlet plane

Fig. 16  S-shape relation of maximum temperature and stoichiometric scalar dissipation rate

Fig. 17  Radial temperature distribution factor
6 Conclusions

In this work the feasibility of LES on the prediction of complex reacting flow in a practical aeroengine combustor with two-stage counter-rotating swirler without any conventional simplification is validated. From the simulation results some conclusions can be acquired.

1. Unsteady evolution process of fuel injection shows that it costs about 2.6 ms for the fuel moving to the virtual ignition location and about 6 ~ 7 ms for the initial flame passing through the whole chamber.

2. In early stage, initial flame generated by the pseudo ignition using FPV model is dominated and transported by the main swirling flow. Then under the effect of transverse flow, it principally spreads into the CRZ, filling primary combustion zone and partly propagates downstream. Due to the supplementary fresh air from primary holes, downstream fuel-air mixture mostly approaches the stoichiometric ratio, inducing intense combustion and consequent new areas with high temperature.

3. In general, time-averaged temperature on central profile predicted by LES shows a more reasonable distribution with better symmetry than RANS. To be more specific, compared with the CARS measurement and reference data, LES-FLM significantly improves the poor prediction accuracy in the reference, with the mean error reduced from 11.22% to 7.76%. LES-FPV result also reaches better agreement than RANS-FPV.

4. As a result of the unexpected severe hot spot at the outlet, RANS-FPV result exhibits the poorest uniformity with OTDF and maximum RTDF up to 0.593 and 0.313 respectively. Limited by the essential defects in the mechanism, FC model also predicts unreasonable distribution uniformity with OTDF far exceeding the normal range in mainstream combustors, in spite that it performs as well as FPV model at the 12 measure points on central profile. Corresponding values obtained by LES-FPV are 0.284 and 0.193 respectively, presenting the best uniformity among all cases.

5. Compared to RANS, LES with the growth of computing power and proper combustion models can be widely used to explore complex flow in various kinds of practical combustors due to the remarkable improvement in accuracy.

References:

[14] Ruggles A, Kelman J. A Gas Turbine Combustor for In-


