Numerical study of one swirling flame

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Numerical study and validation of one swirling flame

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Abstract

This paper presents numerical study of one of Sydney swirl flames. Good agreements gained between numerical results and the experimental data. Reynolds-averaged Navier-Stokes (RANS) and large eddy simulation (LES) methods show different flow patterns in isothermal and reacting case. The influence of heat release is considered by comparing cold flow structure with same boundary conditions and reaction flow structure using RANS results. The research built the framework for the following reacting flow studies using LES.

Introduction

Swirling flows are widely used in stabilized burners. By generating central recirculation zone, swirl flow could enhance mixing, reduce flame length and improve flame stability. Sydney swirl burner is a well-defined experimental set-up to study reacting swirling flows. Corresponding flow and flame measurements have been made in University of Sydney (Australia) and Sandia National Laboratories (USA) [1-7]. The reliable experimental data are used as model database in TNF and reference for modelling studies.

Large eddy simulation (LES) is an adopted choice for such reacting flows [8-14]. In combustion, all reacting processes are in dissipative scales, which are under the filter size of LES and should be modelled. So, LES could not provide improvements in modelling, but it could predict accuracy flow field in mixing process. This is of great importance in simulating swirling non-premixed combustion. As widely using in industry, unsteady Reynolds-averaged Navier-Stokes (u-RANS) simulation gives time-averaged flame structure and needs turbulence model for closure term. Eddy viscosity models are the first group and simplest turbulence models. The assumption of this kind of model transforms stress originating from convective transport into diffusion-like transport terms, which might cause poor results when predicting recirculation zone in swirling flames.

The objective of present research is to build a frame applying LES in combustion simulation. Here, LES and u-RANS simulation are used together to calculate one middle swirling case (SM1) in Sydney swirl burner. This paper starts with a description of experiment configuration and case settings in the next section. Numerical methods are presented as follows. The following sections provide validations of the LES and RANS in terms of velocity fields and flame parameters, isothermal flow and flame structures with same momentum boundary settings are discussed. Over-all conclusions are provided in final.

Experimental set-up

Figure 1 shows the schematic structure of Sydney swirling burner [15]. The swirling burner is built based on a bluff-body burner. Central jet tube is 3.6 mm in diameter, surrounded by a ceramic faced bluff-body with 50 mm in diameter. Swirling flow comes out of the annulus with 5 mm in width. It is generated aerodynamically from three tangential acclivitous ports with 7 mm diameter, located 300 mm upstream. The whole device sits in a secondary co-flow wind tunnel with 130×130 mm square cross-section sides.

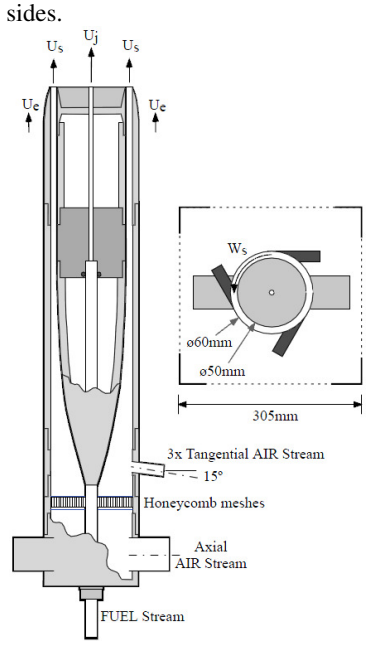

Figure 1 Schematic of the swirl generator

Four bulk velocities affect the flow field: centre jet velocity U_j, annular axial velocity U_s, annular tangential velocity W_s, and external ambient co-flow velocity U_e. Geometric swirl number S_g ($S_g = W_s/U_s$) is used to quantify the swirl strength, which is linearly proportional to the momentum swirl number S, $S = 0.9\,S_g$. The flow parameters used in this methane-air combustion case are listed below.

Table 1 Operating conditions

Case	U_s (m/s)	W_s (m/s)	U_j (m/s)	U_e (m/s)	S_g
SM1	38.2	19.1	32.7	20	0.54

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Numerical methods

In this study, case SM1 is simulated by using unsteady RANS and LES, both of which are based on the same mesh. There are 3.74M hexahedral cells applied in cylindrical domain with 200mm diameter and 270mm length. Spatial, temporal and mixture fraction discretization used second order schemes in both RANS and LES. Especially, central differential scheme is used for spatial discretization in LES. In order to enclose combustion simulation, there are three types' models: RNG k-ε model is used for u-RANS simulation and Smagorinsky-Lilly model is used in LES. Both numerical methods used 16 species reduced reactions, and RFL with presume-PDF is used for turbulence/chemistry interaction. As a primary study, this paper set inlet boundary from the burner exit directly. Power law is used for velocity inlet setting. For LES simulation, statistic steady RANS inlet turbulence is set for turbulence profile and spectral synthesizer is set for inlet fluctuation. For lateral boundary, free-slip is used for momentum boundary. Since the simulation domain is large enough, the heat transfer is neglect there.

Results and discussion

Validation study

The accuracy of the RANS simulation is presented by this validation. Good agreement is achieved between experimental measurements and simulation results. Figure 2 shows the comparisons of the time averaged mean axial and tangential velocity at x/D = 0.136, 0.8, 1.4 and 2.5 locations, where D = 50 mm is the diameter of the bluff body and R = 25 mm is the radius of that.

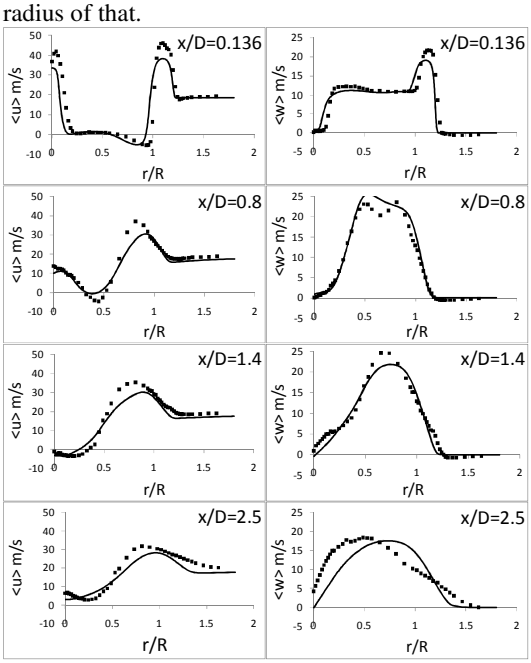

Figure 2 radial profiles of mean axial and tangential velocity component. Lines indicate RANS results, solid points indicate experimental measurements

Figure 3 shows the comparisons of the time averaged temperature and mixture fraction at x/D = 0.2, 0.8 and 1.5 locations. The momentum results successfully predict two recirculation zones in mean axial velocity plots and two shear layers in tangential velocity plots. The thermal results successfully predict stable flame in the second recirculation zone. But it failed in predicting the swirling flow in the first recirculation zone near bluff-body. It shows that the flame mainly locates in the outer layer of the first reverse zone; the mixture fraction there shows almost 1 at central line and lower value surroundings. Temperature is over-predicted, which is a direct result of the under-prediction of the mixture fraction, since there is strong non-linear coupling between them. The plots also indicate that, RANS could not predict swirling flow accurately in the first recirculation zone.

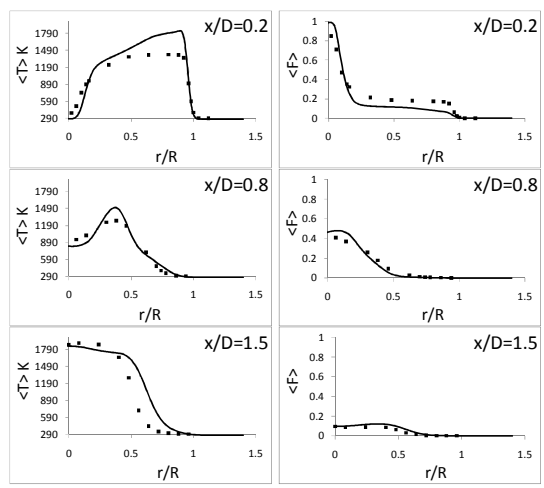

Figure 3 radial profiles of mean temperature and mixture fraction. Lines indicate RANS results, solid points indicate experimental measurements

Flow pattern in isothermal case using LES and RANS

Here presents isothermal case study with same momentum boundary settings as in SM1. The flow field is three-dimensional time dependent. LES and RANS both predict two recirculation zones and collar-like structures. Contour plots (Fig. 4) show the mean axial velocity. There are two recirculation zones in the isothermal flow field. The first one locates after the bluff-body and has a bowl shape. The second one is generated by swirling flow and is recognized as a bubble-type vortex breakdown. The collar-like structures have relative high tangential velocity. It locates at the neck region between two recirculation zones. The second recirculation zone shows 140 mm length in RANS but 83 mm length in LES result. The LES result predicts shorter recirculation zones compared with RANS result. The flow velocities in RANS results keep high value downstream.

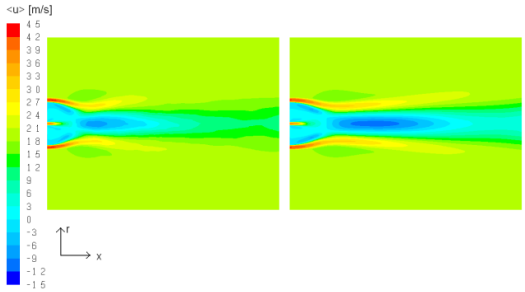

Figure 4 contour plots of mean axial velocity, LES result (left) and RANS result (right)

Flow pattern in isothermal and reacting case (RANS)

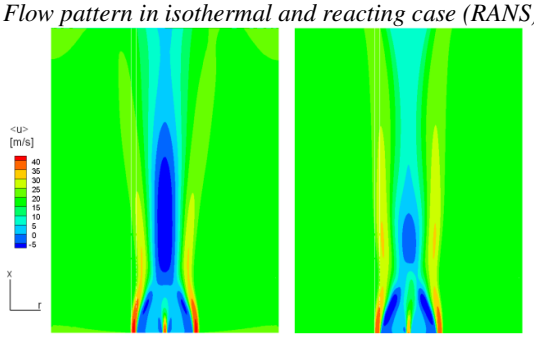

Figure 5 contour plot of mean axial velocity in isothermal case (left) and reacting case (right)

The reacting flow was predicted by using RANS and LES. Here shows (Fig. 5) the flame pattern obtained from RANS. There are also two recirculation zones with similar configuration as in isothermal case. Compared with the corresponding isothermal case, the first recirculation zone has a much lower mean axial velocity value in reacting case, the length of the reverse flow region lengthen. This axial length last till 34mm in isothermal case, but in reacting case, it extends to 40 mm. The second recirculation zone, however, has a reduced length and a higher value. In isothermal case, it starts from 40 mm and lasts to 180 mm; in reacting case, it starts from 60 mm and lasts to 100 mm. And the width reduces from 17 mm to 12 mm in reacting case. The azimuthal velocity keeps high value, and the neck region shrinks in reacting case with 16mm in radial direction.

Flame pattern in reacting case by LES and RANS

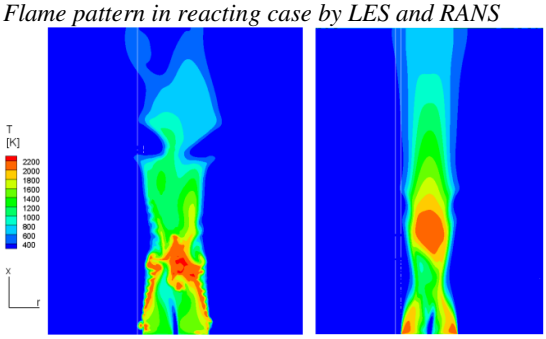

Figure 6 instantaneous plot of temperature in reacting case by using LES (left) and RANS (right)

Figure 6 shows the instantaneous flame pattern. The high temperature region predicted by using LES locates in the outer layer of the first recirculation zone, the high swirling flow region and the second recirculation zone, the region has a zigzag boundary. However, in RANS results, the high temperature region locates in the first recirculation zone just behind the bluff body and the second recirculation zone. The structures have an orbicular shape.

Conclusions

This paper presents results of one swirling flame with isothermal and reacting conditions. Validation study shows that this is could be considered as a base-frame in the following simulation. Two recirculation zones and collar like structure are found in all flow fields. The flow patterns have been compared by large flow structures between isothermal case and reacting case, LES results and RANS results. LES shows its potential in swirling flame simulation, but there is still much to improve.

Acknowledgements

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