PDF SIMULATIONS OF NON-PREMIXED SYDNEY SWIRLING BLUFF-BODY FLAME

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Abstract The velocity-turbulent frequency-compositions JPDF method is applied to simulate the non-premixed Sydney swirling bluff-body flame (SM1). A new consistent hybrid FV/particle algorithm is developed and used to solve the PDF model equations. Present results are found to be in a good agreement with the available experimental data and with the earlier PDF simulations.

INTRODUCTION

Swirl has been used for stabilization of of high-intensity combustion. The main effects of swirl are (i) to reduce combustion length by increasing the entrainment of ambient fluid and enhance mixing, (ii) to improve flame stability due to the formation of toroidal recirculation core in strongly swirling zone, and (iii) to minimize the flame impingement on the burner and thus extend life of the unit [7].

Various models and numerical techniques have been used to simulate the swirling flames[8, 1]. However, the swirl flames are not yet fully understood due to complexity of flow field and strong turbulence-chemistry interactions. The PDF method is thus well suited for simulations of swirling flames. Compared to conventional approaches, the PDF method offers the unique advantages of being able to take into account the important processes of convection and non-linear reaction in closed form[5]. Of these advantages, the exact treatment of finite-rate non-linear chemistry makes the PDF method particularly attractive for modeling of complex turbulent flows which are dominated by strong turbulence-chemistry interactions such as swirling flames.

As for any turbulence model, an efficient numerical solution algorithm is of essential importance to apply the PDF method to flow problems of practical interest. The consistent hybrid FV/particle method has proved to be an efficient way of solving the modeled PDF transport equation[2, 3]. In the original hybrid method developed by Muradoglu et al.[2, 3], a density-based FV algorithm is used to solve the Favre-averaged mean conservation equations for mass, momentum and energy while a particle-based Monte Carlo method is used to solve the modeled PDF transport equation for the fluctuating velocity, turbulent frequency and compositions. Although the density-based FV method is suitable for solving compressible flow equations, it is found to be too dissipative and yet not very robust for incompressible or near incompressible flows mainly due to stiffness of the compressible flow equations in the low Mach number limit. Therefore, the density-based FV solver is first replaced with a pressure-based PISO solver in present study. For this purpose, the particle algorithm is combined with the OpenFOAM[4], the open source FV package that is freely available from the internet. In the new hybrid algorithm, the FV (OpenFOAM) and particle codes are coupled to form a complete solution algorithms as follows: The mean velocity and mean pressure fields are supplied to the particle code by the FV code while FV code gets all the Reynolds stresses and mean density fields from particle code. The hybrid method has been first validated for the non-swirling inert and reacting bluff-body flows. It is found that the new hybrid algorithm is very robust and the results compare well with the earlier PDF simulations of the same flows. Then the new hybrid algorithm is employed to simulate the axisymmetric swirling bluff-body flame 'SM1' studied experimentally by Sydney group[9]. Computations have been performed using the simplified Langevin model (SLM) for velocity, the modified Jayesh-Pope model (JPM) for the turbulent frequency and IEM model for mixing. The chemical reactions are treated by a simple flamelet model. Hence the main focus of the paper is on the accurate predictions of the mean flow, turbulence and mixing, which lays foundations for future work in which the chemistry is described in greater detail.

RESULTS AND DISCUSSION

A full description of swirl burner can be found in [9]. It has a 50 mm diameter bluff-body ($D_b = 50$ mm) with a 3.6 mm central fuel jet. Swirling air is provided through a 60 mm diameter annulus surrounding the bluff-body. A wide range of testing conditions have been studied experimentally [9]. These test cases are distinguished by five independent parameters: the bulk axial velocity of the central jet (U_j), the bulk axial and tangential velocities of the swirling air annulus (U_s and W_s), the bulk axial velocity of the coflow of the wind tunnel (U_e) and also with the type of fuel. We consider here the case 'SM1' for which the flow parameters are summarized in Table 1 where S_g is geometric swirl number defined as $S_g = W_s/U_s$. The computational domain is 0.5 m ($10D_b$) in the axial direction starting from the bluff-body surface

Table 1. Flow parameters of the case 'SM1'

case	fuel	$U_e(\mathrm{m/s})$	$U_j(\mathrm{m/s})$	$U_s(\mathrm{m/s})$	$W_s(\mathrm{m/s})$	S_g
SM1	CH_4	20	32.7	38.2	19.1	0.5

and 0.2 m ($4D_b$) in the radial direction. A fully developed turbulent pipe flow is assumed for the mean axial velocity in the jet region while the experimental data are used in the primary swirling air stream for axial and tangential velocities and also for axial velocity in coflow region. Figure 1 presents the radial profiles of mean and rms fluctuations of the axial velocity as well as the mean mixture fraction at various axial locations in the flame. The results are compared both with experimental data and previous PDF simulations of De Meester et al. [1]. Here R_b is the radius of bluff body. Note that De Meester et al. have not reported the rms fluctuating velocities. It is found that the flow filed is well captured by the present simulations. There are two recirculation zones, the center of first one is located at $x/D_b \simeq 0.4$ and extends to about $x/D_b \simeq 0.9$, another is located at $x/D_b \simeq 2.2$. Figure shows that the present preliminary results are in a reasonably good agreement with the experimental data and with the PDF simulations of De Meester et al. [1].

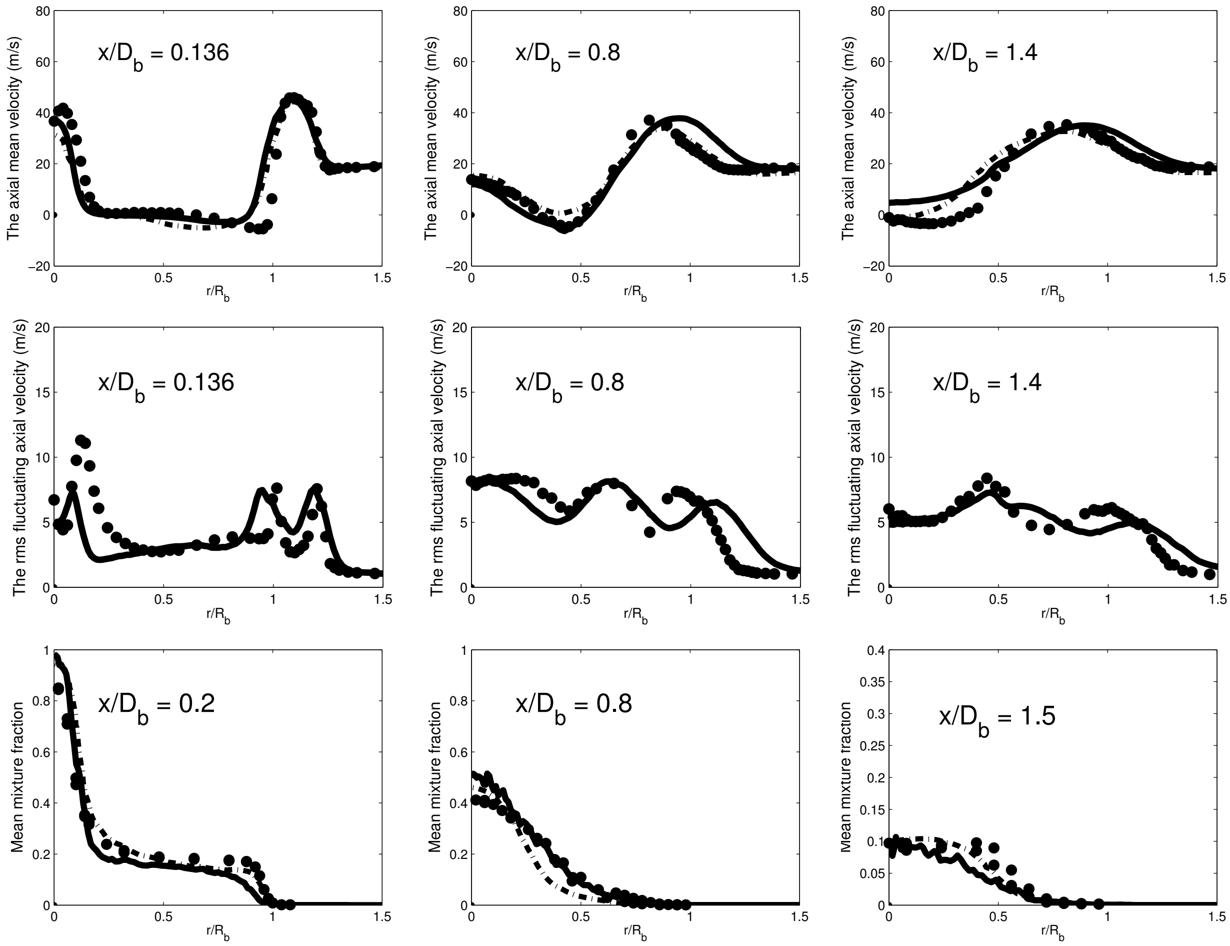

Figure 1. Profiles of mean axial velocity, rms fluctuating axial velocity and mixture fraction at various axial locations. Present results (solid line) are compared with experimental data and previous PDF simulations of De Meester et al.(dash-dot line).

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