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NON-PREMIXED SWIRL FLAME MODELLING USING THE OPEN SOURCE CFD PACKAGE OPENFOAM

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ABSTRACT

In this work the Sydney swirl stabilized burner for a hydrogen:methane fuel mixture is numerically modelled using the OpenFOAM C++ library package. A non-reacting high swirl test case (N29S159) and a reacting low swirl test case (SMH1) were investigated using Large Eddy Simulations and the Steady Laminar Flamelet concept. For the non-reacting case the velocity field components are in very good agreement with experimental results. For the reacting flow case the velocity components are also in excellent agreement with experimental values, however the scalar quantities exhibit some under prediction. Possible reasons for the under prediction are discussed.

KEY WORDS: OpenFOAM, flameletFOAM, LES,dynamic Smagorinsky, Swirl burner

NOMENCLATURE

S	Swirl Number	(-)
Z	Mixture Fraction	(-)
Z''	Mixture Fraction Variation	(-)
χ	Scalar Dissipation rate	(1/s)

U	Axial Velocity component	(ms^{-1})
V	Radial Velocity component	(ms^{-1})
W	Radial Velocity component	(ms^{-1})
x	Axial distance from inlet	(m)
r	Radial distance	(m)

1. INTRODUCTION

The power to gas concept, where excess power can be used to generate hydrogen, provides a feasible solution to the ever increasing demand for cleaner and reliable energy since current and future gas turbines will look to use different blends of Hydrogen based fuel mixtures. Hence from design and maintenance points of view the understanding of such fuel mixtures is vital. Combustion instabilities in modern fuel flexible gas turbine burners is an operational concern that requires computational modelling as a tool for optimization purposes. Detailed investigations of temporal and spatial variations of flow and temperature fields alongside chemical species concentrations can be accomplished using Large Eddy Simulation (LES) methods. For industrial burner applications direct numerical simulations of the detailed chemistry with turbulence modelling is computationally infeasible. Hence attention is focused towards simplified modelling of the chemistry. In this work the open-source software package OpenFOAM is used and the solver *flameletFoam* [1] is validated using detailed experimental data from the Sydney swirl burner.

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2. THE SYDNEY SWIRL BURNER

The Sydney swirl burner experiments, conducted in collaboration with Sandia National Laboratory under TNF workshops, provides data for both reacting and non-reacting swirl flows at several Swirl Numbers [2],[3],[4]. Swirling flow is characterized by Swirl Number at the inlet, $S = W/U$. In this work a high swirl, non-reacting test case (N16S159, S=1.59) and a low swirl, reacting case (SMH1, S=0.32) are investigated. For the reacting case a central jet provides a fuel mixture of equal volume fractions of Methane and Hydrogen.

3. COMPUTATIONAL METHOD

OpenFOAM provides a platform to solve the discretized Navier-Stokes and transport equations using the Finite Volume Method. Using an ensemble of Laminar 1D flame structures to model turbulent non-premixed flames forms the basis of the well established Laminar Flamelet method [5]. To model the swirling flows a locally dynamic Smagorinsky Sub-Grid Stress (SGS) model [6] for turbulence viscosity closure was used. For the reacting flow this was used in conjunction with the *flameletFoam* solver, which is based on the adiabatic Steady Laminar Flamelet Method (SLFM). 1D steady laminar flamelets for different scalar dissipation (χ) values were generated using the *Cantera* chemical kinetics software to obtain a relationship between scalars and mixture fraction $Y_k(Z, \chi)$ for a counter-flow flame configuration. According to laminar flamelet theory, it is assumed that. for turbulent reacting flows, the mean Favre averaged scalar values are distributed in a β Probability Density Function (PDF) of mixture fraction (Z) and a $Dirac - delta$ PDF of (χ). Note that χ has been parameterized by the stoichiometric scalar dissipation value (χ_{st}).

3.1 Numerical Set-up

Mesh and Numerical Schemes. The computational domain consisted of a block unstructured hexagonal grid. The reacting and non-reacting cases were simulated on 1.9×10^6 and 7×10^6 cell grids respectively. Mesh gradients were kept to a minimum to avoid numerical errors due to non-uniform grid LES filter widths. The outlet boundary was place beyond $200 \times R_{centraljet}$. The inlet boundary conditions required careful consideration. Artificially generated eddies using the random spot method [7],[8] were used with appropriate integral length scales for annular and central jet inlets. Side walls were placed far from the central axis of the domain in order to assume zero normal gradients. An implicit second-order temporal discretization scheme was used with a $vanLeer$ Total Variation Diminishing (TVD) scheme for the scalar convection terms. The momentum convection term was discretized using the low dissipation scheme $filteredlinear2V$. Once the flow had advected five times through the grid the LES results were time averaged over a period of around 60 ms. In addition the field data were spatially averaged on four orthogonal planes through the central axis.

4. RESULTS

This section presents some selected examples of the LES simulations. Fig 1 shows the velocity field of the non-reacting test case (N29S159). The negative values of axial velocity field (U) indicate the presence of a counter rotating zone. The predicted axial (U) and tangential (W) velocity component values were found to be in good agreement with the experimental results. The RMS of the axial velocity component is in close agreement with the experimental results, indicating that the LES resolved turbulent energy percentage is sufficient to assume that the SGS modelled turbulent energy is negligible. Fig 2 indicates that, for the reacting flow case (SMH1), the LES results for the velocity field components are in good agreement with the experimental profiles at both the near field and far field. The negative values of the axial velocity component for the reacting case indicates a stronger recirculation zone than in the non-reacting case despite having a lower swirl number. The tangential velocity field for the reacting flow case is in very good agreement with the experimental results, however close to the central axis the accelerating swirl motion is under predicted in the LES results. The RMS values of axial velocity are in good agreement with the experimental results, and apart from the region near the jet central

axis both mean velocity field and velocity fluctuations agree well with experimental results. Disparity between numerical simulation results and experiments are understood to be induced by the very high mean jet velocity ($140.8m/s$).

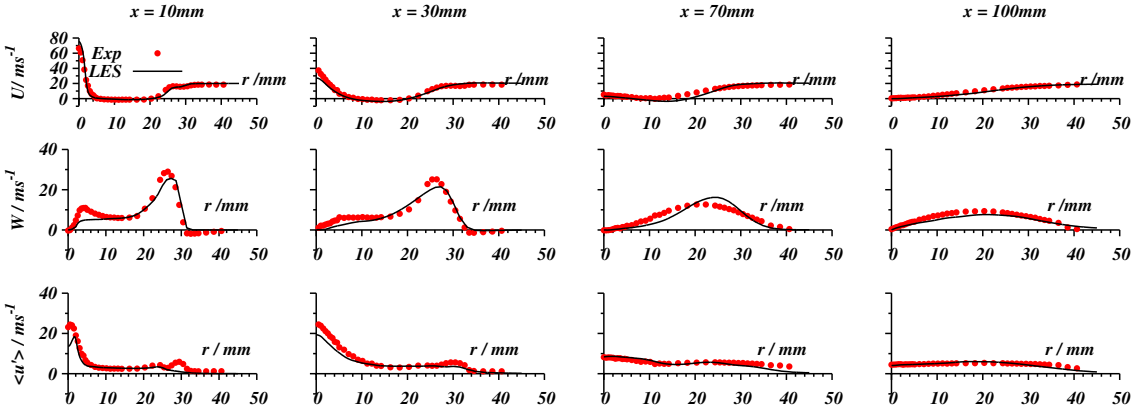

Fig. 1 Axial velocity (U), Tangential velocity (W), Axial velocity RMS ($< u' >$) against radial distance (r) for non-reacting test case (N29S159).

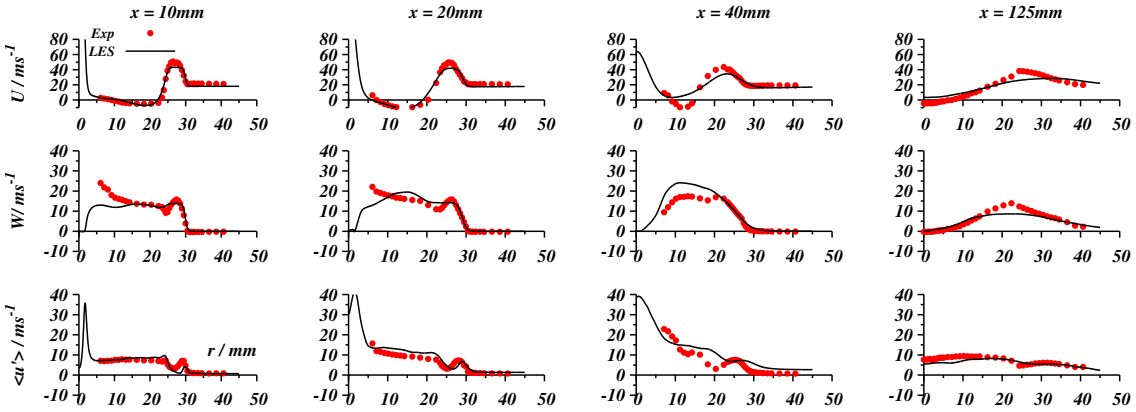

Fig. 2 Axial velocity (U), Tangential velocity (W), and Axial velocity RMS ($< u' >$) distribution for reacting test case (SMH1).

Fig 3 shows the mixture fraction and temperature variations for the reacting flow case. Both scalars are in reasonable agreement with the experimental results, however they are under predicted possibly due to two reasons: i) It was observed that in the 1D flamelet relationship (generated using GRI-3.0 mechanism) for temperature and mixture fraction, the temperature was in general under predicted when compared against recorded measurements, as shown in Fig 4. ii) The numerical diffusion associated with TVD schemes could contribute towards scalar under prediction.

5. CONCLUSIONS AND FUTURE WORK

The LES results for both reacting and non-reacting simulations were, in general, in good agreement with the experimental results. The velocity components for the reacting flow case were in very good agreement with the experimental results, however the scalar predictions (mixture fraction, temperature and other species) exhibited some numerical discrepancy. As stated above this could be due to the difference between the laminar flamelet structure obtained using GRI-3.0 and the measured turbulent flame structure. Therefore further chemical mechanisms could be investigated for modelling $CH_4 : H_2$ fuel mixtures.

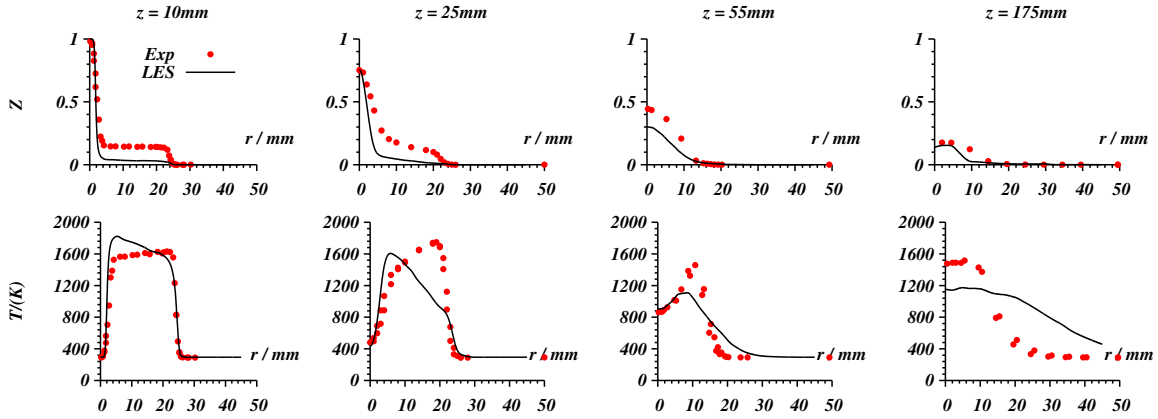

Fig. 3 Reacting test case (SMH1) mixture fraction variation and temperature variation

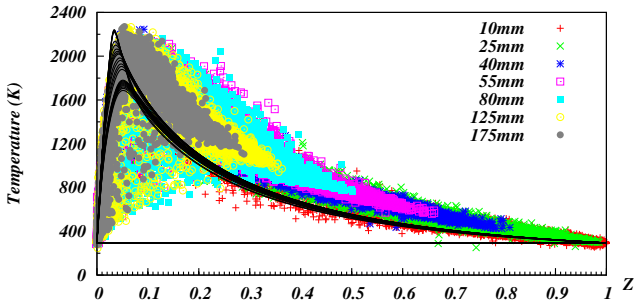

Fig. 4 1D laminar flamelet structure and measured turbulent flame structure for $CH_4 : H_2$

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