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Large eddy simulation of a premixed propane turbulent bluff body flame using the Eulerian stochastic field method

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HIGHLIGHTS

- A premixed propane–air triangle bluff body stabilizer was studied by numerical simulation.
- The LES-pdf method with Eulerian stochastic field solution method was employed.
- A 4 reaction steps and 7 species global chemistry mechanism were utilized.
- Predictions showed overall good agreement with the experimental averaged data.
- Temperature and velocity RMS, and CO prediction error were lower than 10%.

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ABSTRACT

A premixed propane/air flame stabilized on a triangular bluff body was studied by numerical simulation as a simplified model of many practical propulsion and power generation systems. The sub-grid scale (*sgs*) probability density function (*pdf*) approach in conjunction with the stochastic fields solution method is used to account for *sgs* turbulence–chemistry interactions; a skeleton chemistry mechanism with 4 reaction steps and 7 species was used to describe the propane–air reaction. Three cases, one non-reacting and two reacting were studied. The instantaneous flow pattern and CO concentration are discussed and the averaged velocity and temperature, the RMS velocity and temperature fluctuations and averaged CO mass fraction profiles are compared with the experimental data. The simulations show very good agreement with the experimental data demonstrating the capability of the LES method coupled with the *sgs-pdf* method in representing premixed combustion in complex flame configurations.

1. Introduction

In industrial combustors the turbulent flame is usually anchored by a stabiliser that gives rise to a recirculation zone. In [1], during the development of low-emission, lean-premixed gas turbine combustion systems, various injector configurations and related flow characteristics around the stabiliser were investigated. Although industrial combustor geometries are complex, the flow and combustion around a bluff body is a useful simplification for main parameter analysis. Bluff body stabilisers are also used in many practical systems, such as industrial boilers and ramjet engines, due to their stable structure, low production and running costs and light weight. Consequently the flow pattern, combustion process and the interaction with the fuel injections of the bluff body flame-holder have been extensively studied over the years.

Esquiva-Dano et al. [2] investigated experimentally the geometry of the flame holder focusing on the effect of the bluff-body shape on flame stabilization for practical burner design. Direct visualization, supported by Laser Doppler Anemometry and thermocouple measurements of the isothermal and reacting flow showed the existence of various types of flame whose form was determined by the bluff-body shape and the gas-jet to air velocity ratio. By controlling the axial fuel gas momentum in combination with the swirl number the mixing of fuel and air can be influenced, thus leading to different flame types, as also reported in [3].

In order to avoid the complexity introduced by fuel atomisation and vaporization premixed bluff body combustion systems have often been studied by previous workers. In the lean premixed

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pre-vaporized regime design, the flameholders also work in an approximately premixed regime. The development of computing technology and modeling methodology has led to numerical simulation becoming more and more attractive due to its ability to provide detailed information. The accurate prediction of the flow field in a combustion system is made difficult by the wide range of length and time-scales of the physical processes and the strong nonlinear interaction between turbulence and chemical reactions taking place.

In principle Direct Numerical Simulation (DNS) can resolve flow and reaction over all the turbulent length and time scales, but the computational cost is too high at the high Reynolds number found in practical applications. Reynolds Averaged Navier–Stokes methods (RANS) using, for example the k–ε two equation turbulence model, are used widely in industry and while of low computational cost, its predictive abilities are limited. LES represents choice midway between DNS and RANS and is a promising alternative both for fundamental studies and for industrial applications. The method has been applied by a number of workers to premixed turbulent flames over a range of bluff-body configurations using a variety of *sgs* combustion models.

The premixed propane-air flame comprising a straight rectangular cross-section channel with a triangular cross-section bluff-body and studied experimentally by Sjunnesson et al. [4–6], has been simulated by Moller et al. [7] and Fureby [8]. In the LES of [7] the performance of an eddy-dissipation-kinetic model, a presumed pdf approach and MILES are compared whereas in [8] modeled equations for a reactive coordinate, the flame wrinkling density and the laminar flame speed are solved. LES has been applied to the same configuration by Potami et al. [9], Erickson and Soteriou [10] and Park and Ko [11].

Potami et al. simulated the burner using LES with a fractal *sgs* model for the turbulence and chemical kinetics closures. The instantaneous velocity field and wake oscillations were studied and compared with experimental data. Erickson and Soteriou investigated the dynamics of the flow and combustion using the Lagrangian Transport Element Method with the flame-sheet turbulent combustion model. The impact of increased reactant temperature on the numerical simulation results was investigated. Park and Ko applied LES coupled with a dynamic G-equation model to predicted a turbulent premixed bluff body flame. The calculated results of the velocity and temperature fields showed good agreement with the experiment data.

Briones et al. [12] modeled non-reacting and reacting flows past typical square and triangular flame-holders with unsteady RANS and LES. A 2-step global or, alternatively a 44-step reduced chemical mechanism for C_3H_8-air combustion, and an eddy dissipation turbulent combustion model, were utilized. Instantaneous images of span wise vorticity magnitude contours and a time-averaged stream-wise velocity comparison are presented.

Kempf et al. [13] analyzed the LES computational error using the Sydney bluff body flame data. The Smagorinsky model and a flamelet model were used. A global optimum for $C_s = 0.13$ on the finest grid led to accurate simulations of the flow.

Sankaran et al. [14] numerically investigated the dynamics of bluff-body premixed flames using the Lagrangian Transport Element Method and a kinematical flame-sheet model. The key physics of flame blow-off were captured, in particular it was noted that holes developed in the flame sheet as the inlet flow velocity increased, which resulted in increased mixing of reactants and products leading to further destabilizing of the recirculation zone.

In practical flames and combustion chambers there may be diffusion flame burning and also regions where the flame is partially-premixed or premixed [15]. As a consequence if accurate solution are to be obtained then a methodology able to cover all these burning regimes is needed. When considering industrial applications in addition to the prediction of the velocity, temperature and concentration field, an ability to reproduce flame propagation, local ignition and blow-off, as well as combustor and/or flame-holder performance is required [16]. In addition the flow, combustion and fuel injection processes are highly dependent upon the engine operating conditions [17].

Table 1
4-Step global reaction mechanism for propane of [31].

Reaction step	Reaction
(R1)	$C_3H_8 + \frac{3}{2}O_2 \Rightarrow 3CO + 4H_2$
(R2)	$C_3H_8 + 3H_2O \Rightarrow 3CO + 7H_2$
(R3)	$H_2 + \frac{1}{2}O_2 \Longleftrightarrow H_2O$
(R4)	$CO + H_2O \Longleftrightarrow CO_2 + H_2$

Table 2
The simulation cases.

Case	Reaction	Velocity, m/s	Temperature, K	Equivalence ratio
1	Non-reacting	17.0	288	–
2	Reacting	17.0	288	0.61
3	Reacting	34.0	600	0.61

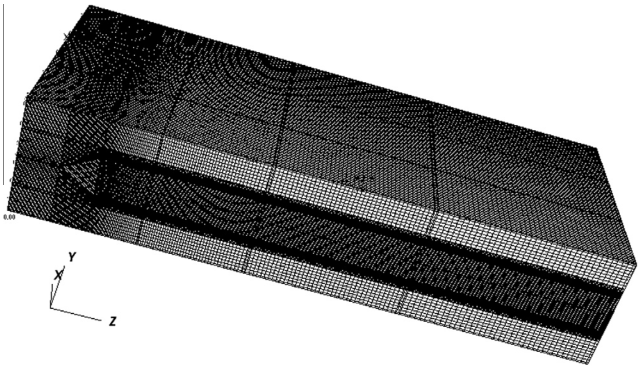

Fig. 1. The solution domain and computational mesh.

In principle approaches based on the one-point joint filtered fine grained probability density function (*sgs-pdf*) for all of the scalar quantities needed to describe reaction provide a means of devising models that are capable of reproducing a wide range of burning regimes. In this approach it is usual not to invoke assumptions related to any specific burning regime, the chemical source terms appear in closed form and further modeling for combustion, beyond specification of a chemical reaction mechanism, is not required. Because of the large number of independent variables involved in this approach stochastic methods of solution must be used. In the present work the stochastic field method [18], is adopted. The *sgs-pdf*/stochastic field solution method has been

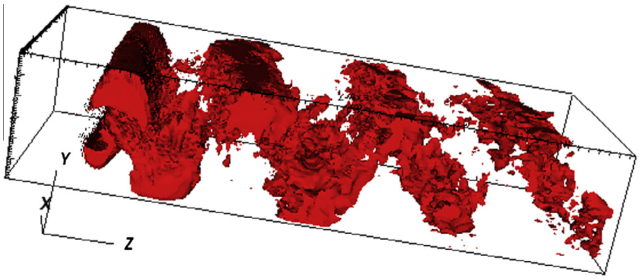

Fig. 2. A snapshot of velocity magnitude, 45 m/s iso-surface (Case 2).