Combustion and Flame 158 (2011) 2465–2481

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Measurements and LES calculations of turbulent premixed flame propagation past repeated obstacles

Sreenivasa Rao Gubba [a,*], Salah S Ibrahim [b], Weertunge Malalasekera [a], Assaad R Masri [c]

[a] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK
[b] Aeronautical and Automotive Engineering, Loughborough University, Loughborough LE11 3TU, UK
[c] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 24 February 2010
Received in revised form 20 July 2010
Accepted 8 May 2011
Available online 12 June 2011

Keywords:
LES
Dynamic flame surface density
Turbulent premixed flames
Influence of the obstacles
Propane/air mixture

ABSTRACT

Measurements and Large Eddy Simulations (LES) have been carried out for a turbulent premixed flame propagating past solid obstacles in a laboratory scale combustion chamber. The mixture used is a stoichiometric propane/air mixture, ignited from rest. A wide range of flow configurations are studied. The configurations vary in terms of the number and position of the built-in solid obstructions. The main aim of the present study is two folded. First, to validate a newly developed dynamic flame surface density (DFSD) model over a wide range of flow conditions. Second, to provide repeatable measurements of the flow and combustion in a well-controlled combustion chamber. A total of four groups are derived for qualitative and quantitative comparisons between predicted results and experimental measurements. The concept of groups offers better understanding of the flame–flow interactions and the impact of number and position of the solid baffle plates with respect to the ignition source. Results are presented and discussed for the flame structure, position, speed and accelerations at different times after ignitions. The pressure–time histories are also presented together with the regimes of combustion for all flow configurations during the course of flame propagation.

1. Introduction

Large Eddy Simulation (LES) is gradually replacing Reynolds-averaging (RANS) method of solving the Navier–Stokes equations to compute the structure of turbulent flames. Several recent works confirm the high fidelity nature of LES in predicting key characteristics of complex reacting flows including those of practical combustors [1–5]. The main attraction of LES lies in its ability to fully resolve features of the flow above a certain cut-off length scale hence, making it possible to compute transient dynamics; this being a clear advantage over RANS methods. The penalty, however, lies in the additional computational cost and the need to model the unresolved contributions, hence the issue of sub-grid-scale (SGS) modelling. This is, particularly, an important issue in LES modelling of turbulent premixed combustion given that chemical reaction occurs at the molecular level and hence needs to be modelled at the sub-grid scale.

A range of approaches to model combustion at the SGS are being pursued at varying degrees and relevance to the spectrum of turbulent combustion. The flamelet approach [6] was used by many researchers in the past in various forms [7–9] and, although limited to thin reaction zones, remains applicable to a wide range of applications. Recent developments of this approach involve flame generated manifolds (FGM) tabulated in terms of mixture fraction, reaction progress variable as well as other parameters such as a measure of flow strain [10]. Such formulations enable the application of flamelet modelling in premixed, non-premixed, as well as partially premixed flames. Two variations of the laminar flamelet approach are the flame surface density (FSD) where a transport equation for the FSD is solved [11] and the thickened flamelet model which has been applied successfully by Poinsot and co workers [12]. Recently, Di Sarli et al. [13,14] demonstrated the importance of FSD based SGS model [1] to predict explosions in a vented chamber using LES. SGS modelling approaches that are seen as alternatives to flamelets include the filtered density functions (FDF) [15], the conditional moment closure [16] and the linear eddy model (LEM) [17]. Each of these approaches suffers from different limitations that are currently the subject of intense research. It is worth pointing that the combined LES/LEM is a truly multi-scale approach that is also receiving considerable attention.

In this paper the LES approach is used together with a recently developed dynamic flame surface density (DFSD) model [18–20] to

---

[*] Corresponding author. Present address: School of Process Environment and Materials Engineering, University of Leeds, Leeds LS2 9JT, UK. Fax: +44 (0) 113 246 7310.

E-mail addresses: S.R.Gubba@Leeds.ac.uk (S.R. Gubba), S.S.Ibrahim@lboro.ac.uk (S.S Ibrahim), W.Malalasekera@lboro.ac.uk (W. Malalasekera), masri@aeromech.usyd.edu.au (A.R Masri).

0010-2180/$ - see front matter © 2011 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.combustflame.2011.05.008

compute turbulent premixed flames propagating in a laboratory scale combustion chamber containing a range of built-in solid obstructions. Earlier studies [20,21] using the same DFSD model showed promising results in computing key characteristics of the propagating turbulent premixed flames but with only three selected configurations. In the present study, the main focus is to analyse the physics associated with flame–solids interactions and extend the calculations to a wide range of configurations to explore aspects such as the effects of location and number of the solid obstacles as well as area blockage ratio. The calculated results are validated against measurements taken from a novel experimental test facility [22,23]. Eight different flow configurations are studied both experimentally and numerically. Results reported here also explore the effects of the resulting turbulence intensity on the structure of the reaction zone as well as the burning rate.

This paper is organised as follows: Section 2 briefly describes the experimental combustion chamber. Details of the newly developed SGS-DFSD model used in the LES calculations are outlined in Section 3. Numerical predictions for four groups of configurations are compared with available experimental data and reported in Section 4. Results are discussed highlighting the merits and drawbacks of the used model while discussing flame dynamics and behaviour in these groups of flow configurations. Finally general conclusions from the present investigation are summarised in Section 5.

2. Combustion chamber and test cases

The combustion chamber, shown schematically in Fig. 1a is only briefly described here and more details can be found elsewhere [22,23]. It has internal dimensions of 50 × 50 × 250 mm giving an overall volume of 0.625 L. Up to three turbulent generating grids (also referred to as baffle plates or simply obstacles) may be placed in the chamber at 20 mm, 50 mm and 80 mm from the base. Each baffle plate consists of five strips, 4 mm wide, evenly separated by six gaps, 5 mm wide, thus creating an overall blockage ratio of 0.4. Downstream of the baffle plates, a further obstruction with a square cross section may be placed such that its bottom surface is maintained at 96 mm from the base plate. Two obstruction sizes are used, a small one with a cross section of 12 × 12 mm and a large one with a 25 × 25 mm cross section. The blockage ratios of these square obstructions are 25% and 50%, respectively.

The fuel used throughout these experiments is Liquefied Petroleum Gas, LPG (88% C_3H_8, 10% C_3H_6 and 2% C_4H_{10} by vol.) at an equivalence ratio of $\varphi = 1.0$. The mixture is ignited from rest and ignition is achieved by focusing the infrared output from a Nd:YAG laser 3 mm above the base. Laser timing is controlled by the Q-switch of the Nd:YAG laser and this marks the start of each experiment or time zero. Pressure is recorded using two Keller type PR21-SR piezo-electric pressure transducers with a range of 0–1 bar and a total error <0.5% located in the base plate and in the wall of the chamber just upstream of the exit plane. Eight configurations are rendered using this test chamber as shown in Fig. 1b. These are clustered into four different "groups" as shown in Table 1 to test the following aspects:

○ The effects of increasing the number of baffle plates starting with one baffle plate farthest from the ignition source (Group 1, configurations: 5–2–1).
○ The effects of increasing the number of baffle plates starting with one baffle plate closest to the ignition source (Group 2, configurations: 7–4–1).
○ The effects of using the same number of baffles plates (two) positioned at different locations (Group 3, configurations: 2–3–4).
○ The effects of using the same number of baffles plates (one) positioned at different locations (Group 4, configurations: 5–6–7).

It should be noted here that configuration 0 with no baffle plates is not included in any of the groups discussed here but it is useful as a baseline case for rest of the cases considered here.

3. Modelling and numerical issues

The governing equations and other numerical details associated with the LES model adopted in this paper are detailed elsewhere [18–20] and only a brief description is given here. A grid resolution of 90 × 90 × 336 (2.7 million cells) is adopted in the present calculations, as further refinement to 3.6 million cells shows no significant improvement in the results [19] for the present configuration. The filter width $\bar{\Delta}$ is calculated using a box filter, which is generally related to grid resolution by 2.0 $(\delta x \delta y \delta z)^{1/3}$ and fits in with the finite volume discretisation. The SGS combustion model used is described below in detailed, considering its importance and novelty.

In LES, modelling the filtered chemical reaction rate in turbulent premixed flames is very challenging due to its non-linear relation with chemical and thermodynamic states, and is often characterised by propagating thin reaction layers which are thinner than the smallest turbulent scales. In the present simulations, the SGS chemical reaction rate, $\bar{\dot{\omega}}_c$ is the source term in the Favre filtered reaction progress variable equation (see Eq. (1)) and this is modelled using the laminar flamelet concept. The filtered conservation equation for the reaction progress variable may be written as:

$$\frac{\partial \bar{\rho}\tilde{c}}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j\tilde{c})}{\partial x_j} + \frac{\partial(\bar{\rho}(\widetilde{u_j c} - \tilde{u}_j\tilde{c}))}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{\bar{\mu}}{Sc}\frac{\partial \tilde{c}}{\partial x_j}\right] + \bar{\dot{\omega}}_c \tag{1}$$

In the above equation, ρ is the density, c is the reaction progress variable, u_j is the velocity component in x_j direction, μ is the dynamic viscosity, Sc is the Schmidt number and $\dot{\omega}_c$ is the rate of chemical reaction. An over-bar describes the application of the spatial filter, while the tilde denotes Favre filtered quantities. The reaction rate in Eq. (1) is modelled as:

$$\bar{\dot{\omega}} = \langle \rho u \rangle_s \bar{\Sigma} = \rho_u u_L \bar{\Sigma} \tag{2}$$

where ρ_u is the density of unburned mixture, u_L is the laminar burning velocity, and $\bar{\Sigma}$ is the flame surface density (FSD). The filtered FSD term in Eq. (2) ($\bar{\Sigma} = \overline{|\nabla c|}$), can be split into two terms as resolved and unresolved:

$$\bar{\Sigma} = \underbrace{\prod(\bar{c}, \bar{\Delta})}_{\text{Resolved}} + \underbrace{\lambda(\bar{c}, \bar{\Delta}, \prod(\bar{c}, \bar{\Delta}))}_{\text{Unresolved}} \tag{3}$$

The resolved term in the above equation is evaluated as [24]:

$$\prod(\bar{c}, \bar{\Delta}) = 4\sqrt{\frac{6}{\pi}}\frac{\tilde{c}(1-\tilde{c})}{\bar{\Delta}} \tag{4}$$

The unresolved term in Eq. (3) is evaluated using the following expression:

$$\lambda(\bar{c}, \bar{\Delta}, \pi(\bar{c}, \bar{\Delta})) = \bar{\Sigma} - \prod(\bar{c}, \bar{\Delta}) = \overline{|\nabla c|} - \prod(\bar{c}, \bar{\Delta}) \tag{5}$$

The ratio of test filter to grid filter, i.e. $\hat{\bar{\Delta}}/\bar{\Delta}$ is defined as γ, such that the test filter $\hat{\bar{\Delta}}$ is greater than the grid filter $\bar{\Delta}$. In this study, test filter to grid filter ratio is considered as 2.0. Applying the test filter to FSD i.e. to Eq. (3) gives:

$$\hat{\bar{\Sigma}} = \widehat{\overline{|\nabla c|}} = \underbrace{\prod(\hat{\bar{c}}, \hat{\bar{\Delta}})}_{\text{Resolved@testfilter}} + \underbrace{\left[\widehat{\overline{|\nabla c}} - \prod(\hat{\bar{c}}, \hat{\bar{\Delta}})\right]}_{\text{Unresolved@testfilter}} \tag{6}$$