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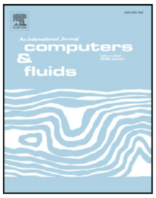

A Direct Numerical Simulation analysis of pressure variation in turbulent premixed Bunsen burner flames-part 2: Surface Density Function transport statistics

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ABSTRACT

The effects of pressure variation on the transport statistics of the magnitude of the reaction progress gradient (i.e. Surface Density Function (SDF)) have been investigated based on three-dimensional simple chemistry Direct Numerical Simulations (DNS) of Bunsen burner flames representing the flamelet regime of combustion. The large length scale separation between the nozzle diameter and flame thickness for high pressure flames makes the Darrieus–Landau (DL) instability highly likely, which in turn affects the curvature stretch. It has been found that the effective normal strain rate remains insensitive to the pressure variation for the parameter range considered here, which makes the flamelet thickness in turbulent flames comparable to the laminar flame thickness. The influences of the DL instability on the positive mean tangential strain rate counter the effects of instability on the negative mean curvature stretch and thus the effective tangential strain rate (or net flame stretch rate) remains mostly unaffected by the pressure variation within the strict flamelet regime (i.e. wrinkled flamelets and corrugated flamelets regimes) of combustion. The similarities in the SDF and the effective strain rate statistics for different values of pressure suggest that the models for the Flame Surface Density and Scalar Dissipation Rate, which were originally proposed and validated for atmospheric combustion, might remain valid also for elevated pressures.

1. Introduction

The magnitude of the reaction progress variable gradient $|\nabla c|$, which is often referred to as the Surface Density Function (SDF) [1], is a quantity of pivotal importance in turbulent premixed combustion analysis. The transport characteristics of SDF have been utilised for the analysis of pocket formation by Kollmann and Chen [1]. The SDF transport is also important from the point of view of the Flame Surface Density (FSD) [2] and Scalar Dissipation Rate (SDR) [3] transports because of the close relations between the SDF $|\nabla c|$ [2], the generalised FSD $\Sigma_{gen} = \overline{|\nabla c|}$ [2] and SDR $N_c = D_c|\nabla c|^2$ [3] where the overbar refers to either Reynolds Averaging or LES filtering, c is the reaction progress variable, and D_c is the progress variable diffusivity. The influences of turbulence intensity, mean flame curvature, global Lewis number have been analysed by Chakraborty and co-workers [4–6] using simple chemistry DNS data for a canonical configuration representing decaying turbulence in a box. The SDF transport characteristics in methane–air and hydrogen–air flames have been compared by Chakraborty et al. [7] using two-dimensional detailed chemistry DNS data. Sankaran et al. [8] analysed the SDF statistics from the point of view of characterising the flamelet thickness using three-dimensional detailed chemistry DNS data for Bunsen burner flames. The alignment statistics of ∇c with local principal strain rates in premixed turbulent flames have been investigated in Refs. [9–12], which revealed that ∇c aligns with the most extensive principal strain rate when the strain rate induced by flame normal acceleration dominates over turbulent straining and vice versa. Recently, Dopazo and co-workers [13–17] linked the evolution of the normal distance between two adjacent reaction progress variable c-isosurfaces with the SDF transport equation [4–8] and demonstrated the influences of normal and tangential strain rates arising from flame propagation on the SDF transport. Wang et al. [18] and Chaudhury et al. [19] analysed $|\nabla c|$ statistics for high-Karlovitz number jet flames and temporally-evolving slot jet flames respectively, and the scalar gradient statistics have been found to be qualitatively consistent with previous findings in canonical configurations [4–8]. It is worth noting that all the aforementioned analyses have been conducted

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for atmospheric pressures but in many engineering applications (e.g. automotive engines and gas turbines) combustion takes place at elevated pressures. Thus, it is essential to assess if the statistical behaviours of strain rates and their influences on the SDF in turbulent premixed flames at elevated pressure remain qualitatively similar to the corresponding statistics for atmospheric flames. This motivated the current analysis which focuses on the analysis of the SDF transport statistics in turbulent premixed flames for a Bunsen-burner configuration at different pressure values. For hydrocarbon–air flames both laminar burning velocity and flame thickness decrease with increasing pressure and thus the flame resolution for a fixed geometry becomes increasingly demanding. Further, the turbulent Reynolds number increases with increasing pressure. Focusing on the fluid-dynamical aspects and following earlier work [3–7] the chemical process is described by a single-step irreversible reaction in this work.

The focus of this paper is (i) to analyse and explain the statistics of the SDF transport and (ii) to discuss implications for modelling turbulent premixed combustion at elevated pressures.

The same DNS database that was used in Ref. [20] has been used for this analysis. Although detailed discussion on this database and numerical implementation was provided in [20], some of that information is repeated here for ensuring the self-contained nature of this paper.

The database considered in this work consists of 5 Bunsen flames with identical geometry. As a consequence, in contrast to generic planar flame studies of turbulent premixed combustion reported in the literature, the scale separation between turbulent scales and flame thickness increases with increasing pressure. Hence, the turbulent Reynolds number for cases A, B, C which have been simulated at three increasing pressure levels, increases from case A to case C. It is important to note that the velocity fluctuation normalised by laminar burning velocity has been kept constant for cases A–C. In order to isolate the effects of turbulent Reynolds number from the effects of pressure variation two additional cases are considered: Bunsen Flames D and E have the same pressure as that of case A but the same turbulent Reynolds number as the highest pressure flame, case C. This is achieved by increasing the velocity fluctuation (the turbulent length scale) for case D (case E). Instantaneous views of $c = 0.8$ isosurface for cases A–E are shown in Fig. 1.

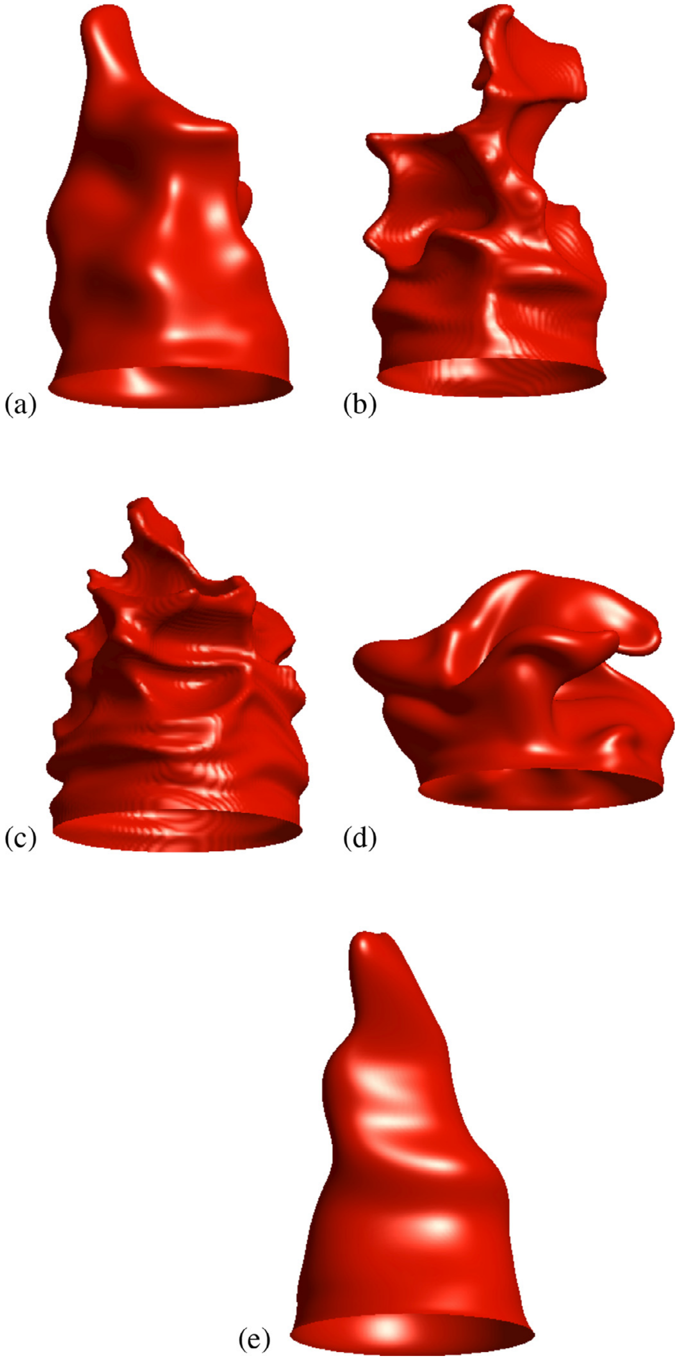

Fig. 1. Instantaneous view of $c = 0.8$ isosurface for cases (a–e) A–E.

2. Mathematical background

Increasing the pressure for a fixed Bunsen burner geometry is computationally expensive as the flame resolution becomes increasingly demanding and a parametric study using detailed chemistry DNS becomes prohibitively expensive [21]. Hence, a generic single-step Arrhenius type irreversible chemical mechanism is used for the current analysis. For methane–air combustion, the variation of the unstrained laminar burning velocity S_L with pressure P can be expressed as: $S_L \sim P^{-0.5}$ [22], whereas dynamic viscosity μ does not change with pressure but gas density ρ increases with pressure. This implies that the thermal flame thickness $\delta_{th} = (T_{ad} - T_0)/\max|\nabla T|_L$ (where T, T_0 and T_{ad} are the instantaneous dimensional, unburned gas and adiabatic flame temperatures respectively) scales as: $\delta_{th} \sim \mu/(\rho S_L) \sim P^{-0.5}$. In this analysis, the pre-exponential factor and kinematic viscosity have been modified to analyse the fluid-dynamical aspects of the pressure dependence in accordance with the aforementioned scalings.

The SDF $|\nabla c|$ and the flame surface area $A = \int_V |\nabla c| dV$ are related quantities and their transport equations are given as [13–17]:

$$\frac{1}{|\nabla c|}\frac{d|\nabla c|}{dt} = -a_N^{eff} = -\left(a_N + N_j\frac{\partial S_d}{\partial x_j}\right) \tag{1}$$

$$\frac{1}{A}\frac{dA}{dt} = a_T^{eff} = (a_T + 2S_d\kappa_m) \tag{2}$$

where the derivative d/dt has been defined as

$$d(\ldots)/dt = \partial(\ldots)/\partial t + v_j\partial(\ldots)/\partial x_j \tag{3}$$

with u_j and $v_j = u_j + S_d N_j$ being the jth component of the fluid velocity and flame propagation velocity respectively. In Eqs. (1) and (2), S_d denotes the displacement speed defined in Eq. (5). Using the flame normal vector whose jth component is given by $N_j = -(\partial c/\partial x_j)/|\nabla c|$ fluid-dynamic strain rate can be decomposed into flame normal a_N and tangential a_T components, given by

$$a_N = N_i N_j \partial u_i/\partial x_j \quad ; \quad a_T = \left(\delta_{ij} - N_i N_j\right)\partial u_i/\partial x_j \tag{4}$$

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