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Flow topology distribution in head-on quenching of turbulent premixed flame: A Direct Numerical Simulation analysis

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ABSTRACT

The distribution of flow topologies within the flame, and their evolution with flame quenching have been analysed using a Direct Numerical Simulation (DNS) database of head-on quenching of statistically planar turbulent premixed flames by isothermal inert walls for different values of turbulence intensity and global Lewis number. It has been found that dilatation rate plays a key role in determining the flow topology distribution within the flame and this dilatation rate field is significantly affected by the flame quenching in the vicinity of the wall. The influence of the wall on the dilatation rate field in turn affects the statistical behaviour of all three invariants of the velocity gradient tensor and the distribution of flow topologies. The effects of heat release and thermal expansion strengthen with decreasing Lewis number which give rise to an increase in the probability of obtaining topologies which are specific to high positive values of dilatation rate. As the magnitude of positive dilatation rate and the likelihood of obtaining it decrease with flame quenching, the probability of finding the topologies, which are obtained only for positive values of dilatation rate, decreases close to the wall. The interrelation between the flow and flame topologies has been analysed in terms of Gaussian flame curvature and mean of principal flame curvatures. The contributions of individual flow topologies on the mean behaviour of wall heat flux magnitude, and the scalar-turbulence interaction and vortex-stretching terms in the scalar dissipation rate and enstrophy transport equations, respectively have been analysed in detail and dominant flow topologies which dictate the mean behaviours of these quantities have been identified. Detailed physical explanations have been provided for the observed flow topology distribution and its contribution to the scalar-turbulence and vortex-stretching terms. The nodal flow topologies have been found to be the significant contributors to the wall heat flux magnitude during head-on quenching of turbulent premixed flames irrespective of the value of global Lewis number.

1. Introduction

Flow topologies are often characterised in terms of a three-dimensional space made up of the three invariants (i.e. first P, second Q and third R) of the velocity gradient tensor $\partial u_i/\partial x_j$ [1,2], where u_i is the ith component of the velocity vector. The topologies are schematically shown in Fig. 1. To date, most analyses on flow topologies have been carried out for non-reacting incompressible flows. For incompressible flows the first invariant P is identically zero so the flow topology distribution is governed by Q and R. The analyses by Perry and Chong [1] and Soria et al. [3] indicated the topology $S4$ is predominantly obtained for positive values of second-invariant Q. Blackburn et al. [4] revealed that the topologies $S2$ and $S4$ remain dominant away from the wall for incompressible flows. It has been demonstrated by Chong et al. [5] and Chacin and Cantwell [6] that the joint probability density function (pdf) shows a “teardrop” structure, and subsequently Ooi et al. [7] provided the evidence regarding the universality of this “teardrop” structure in Q–R space. The physical explanations behind this “teardrop” structure of the Q–R joint pdf for incompressible flows have been provided by Elsinga and Marusic [8]. Both numerical and experimental investigations suggested that the “teardrop” structure of the Q–R joint pdf exists only in the fully turbulent region and not in the interface between turbulent and non-turbulent regions [5,6]. The qualitative arguments for predominant physical mechanisms associated with individual topologies (e.g. enstrophy production is large in $S4$ topology whereas the strain rate production is associated with $S1$ topology) were postulated by Tsinober [9]. The interaction of flow topologies with passive scalar surface topology can be quantified in terms of Gauss and mean curvatures (i.e. κ_g and κ_m) and was analysed in detail by Dopazo et al. [10]. It is worth noting that all the aforementioned analyses were

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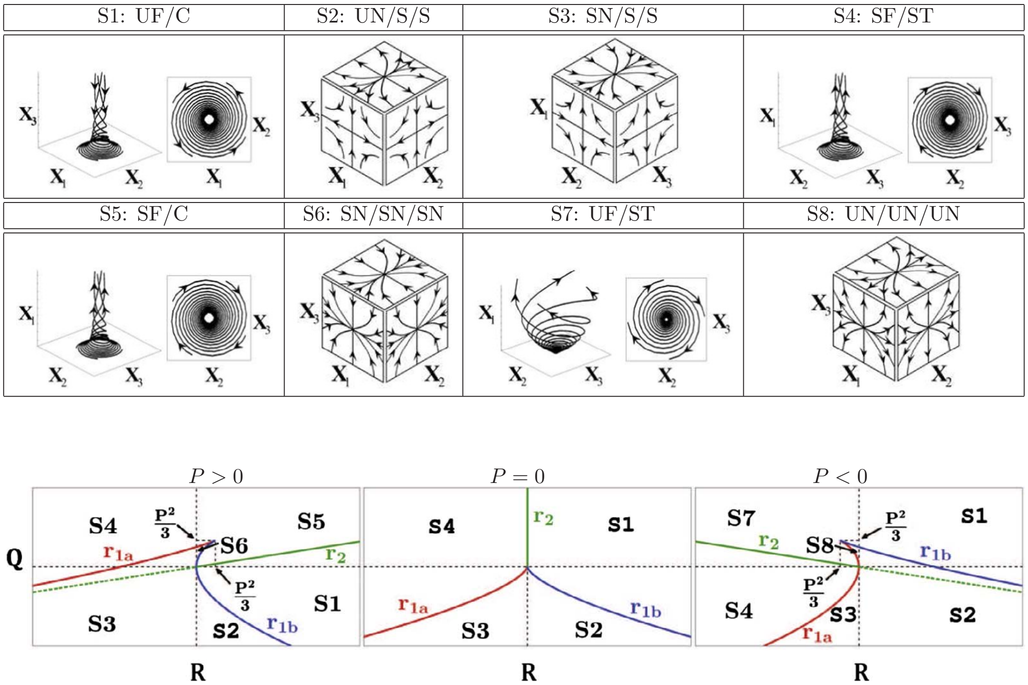

Fig. 1. Classification of $S1-S8$ topologies (UF = unstable focus, UN = unstable node, SF = stable focus, SN = stable node, S = saddle, C = compressing, ST = stretching) in the $Q-R$ plane with the lines r_{1a},r_{1b} and r_2 dividing the topologies, and black daksed lines indicates $Q = R = 0$.

conducted for incompressible fluids where the first invariant P is identically zero. However, in compressible flows the statistical behaviour of the first invariant of the velocity gradient tensor P plays an important role, and thus the co-ordinates in three-dimensional $P-Q-R$ space determine the local flow topology. The structure of a compressible wake, using the critical point theory in terms of P,Q and R, was analysed by Chen et al. [11] for the very first time. Sondergaard et al. [12] characterised small-scale local flow topologies in a compressible turbulent shear flow in terms of P,Q and R. Maekawa et al. [13] and Suman and Girimaji [14] demonstrated that $S2$ and $S4$ topologies are predominant on $Q-R$ plane for decaying isotropic compressible turbulence. The topology distributions in the inner and outer layers in turbulent compressible boundary layers were analysed using Direct Numerical Simulation (DNS) data by Wang and Lu [15]. It is worth noting that all these analyses were carried out for non-reacting flows.

Tanahashi et al. [16] was the first to analyse the flow topologies in turbulent premixed flames in order to distinguish between strain dominated and vorticity dominated regions. Grout et al. [17] analysed flow topologies using decaying turbulence DNS data of a reacting transverse fuel jet in cross-flow, and revealed that $S8$ topology is associated with the regions of high heat release. Recently, Cifuentes and his co-workers [18,19] analysed the distribution of flow topologies across the flame front using simple chemistry DNS database of premixed turbulent flames with unity Lewis number representing the flamelets regime of combustion under decaying turbulence and reported that the probabilities of finding focal (nodal) flow topologies decrease (increase) across the flame front. Flow topology distributions in turbulent spray flames were analysed by Wacks and Chakraborty [20] using DNS data, which demonstrated that the flow topology distribution within the spray flames shows some resemblance to the findings by Cifuentes et al. [18] and Grout et al. [17]. Recently, Wacks et al. [21] analysed flow topology distributions for the different regimes of turbulent premixed combustion and it has been found that the weakening of dilatation rate (in other words weakening of P) from the corrugated flamelets to the thin reaction zones to the broken reaction zones regimes of premixed turbulent combustion plays a key role in the behaviours of the invariants of the velocity gradient tensor and their components, which in turn affects the distribution of flow topologies and their contributions to the evolutions of enstrophy and scalar dissipation rate. In this respect, it is useful to note that all the flow topology analyses for turbulent reacting flows were carried out for both steady and unsteady flow conditions which are not wall-bounded. The presence of a cold wall is essential for the structural integrity of the combustor, but the heat loss through the wall gives rise to flame quenching. Thus, the presence of a wall is expected to affect the dilatation rate and thus the behaviour of the first invariant of the velocity gradient tensor P. Poinsot et al. [22] indicated that the presence of wall significantly affects the vorticity and enstrophy distributions close to the wall during head-on quenching of turbulent premixed flames. The aforementioned discussion suggests that the flow topology in the region close to the wall is likely to be affected by the presence of the flame and its quenching. To date, considerable effort has been made to analyse flame-wall interaction based on numerical investigations [22–35], but none of these analyses focussed on the flow topology distribution in the near-wall region during unsteady wall-induced flame quenching. This gap in the existing literature is addressed here by analysing the statistical behaviours of the invariants of the velocity gradient tensor $\partial u_i/\partial x_j$ and flow topology distributions at different instants of time as the flame approaches the isothermal wall in the case of head-on quenching of statistically planar turbulent flames with different values of global Lewis number Le (i.e. $Le = 0.8-1.2$). For this purpose an existing DNS database [30–35] of head-on quenching of statistically planar turbulent premixed flames for different values of turbulence intensity and global Lewis number has been considered. All the flow topologies shown in Fig. 1 are associated with particular combinations of strain rate and vorticity distributions, and they can influence the local alignment of the principal strain rate and scalar gradient and vorticity, which in turn affect the statistical behaviours of the scalar-turbulence interaction and vortex-stretching terms. Moreover, vortex-stretching mechanism is of pivotal importance to the energy cascade in turbulent flows [36] and it plays a leading order role in the enstrophy transport in turbulent premixed combustion even though some other physical mechanisms (e.g. baroclinic torque) might also play leading roles alongside the vortrex-stretching term [35]. For the above reasons, the contributions of flow topologies on the scalar-turbulence interaction and vortex-stretching terms in addition to the wall heat flux magnitude at different stages of