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Three-dimensional topology of turbulent premixed flame interaction

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Abstract

The topology of turbulent premixed flames is analysed using data from Direct Numerical Simulation (DNS), with emphasis on the statistical geometry of flame–flame interaction. A general method for obtaining the critical points of line, surface and volume fields is outlined, and the method is applied to isosurfaces of reaction progress variable in a DNS configuration involving a pair of freely-propagating hydrogen–air flames in a field of intense shear-generated turbulence. A complete set of possible flame-interaction topologies is derived using the eigenvalues of the scalar Hessian, and the topologies are parametrised using a pair of shape factors. The frequency of occurrence of each type of topology is evaluated from the DNS dataset for two different Damköhler numbers. Different types of flame-interaction topology are found to be favoured in various regions of the turbulent flame, and the physical significance of each interaction is discussed.

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Keywords: Turbulent premixed flame; DNS; Flame structure; Flame topology

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1. Introduction

Direct Numerical Simulation (DNS) results for turbulent flames are becoming available for increasing Reynolds numbers [1–3], thus making it possible to carry out a detailed analysis of the structural properties of the flame. The dissipative range of length scales is of particular interest since combustion reactions take place at small length and time scales. This emphasises the need for highly-resolved DNS data containing the greatest possible range of scales. The structure of prime importance in combustion at high Damköhler number is the flame front itself. It can be located as an embedded surface defined as a chosen level surface of a suitable scalar field. In premixed combustion the usual scalar of choice is the reaction progress variable. The geometry and local topology of the flame surface is central to turbulent premixed combustion modelling using the flamelet concept, and especially in modelling using the Flame Surface Density (FSD) equation or the G-equation approach [4,5]. Processes related to the local flame

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topology, such as cusp formation or pocket burnout, can have a significant effect on the overall balance of flame area production and destruction and hence affect the overall burning rate. Flame topology is also highly relevant to the occurrence of intermittent events such as local extinction [6]. A good fundamental understanding of these phenomena is essential if they are to be captured accurately in modelling.

The statistical geometry of turbulent premixed flames has been addressed in previous work which has highlighted the importance of flame curvature in determining propagation behaviour [7,8]. The specific issue of pocket formation through flame pinch off has been analysed in detail using DNS data for the two-dimensional case [9,10]. Topological aspects of scalar field structure have been analysed in non-reacting turbulent flows [11,12], and aspects of flame structure have been addressed [13]. Recently, DNS data has been used to elucidate the topology of flame structure in MILD combustion [14]. The present work is aimed at analysing the topology of freely-propagating turbulent premixed flames using DNS data in three dimensions. The general principles will be outlined, and the specific DNS datasets will be described. The set of possible topologies for flame–flame interaction in three dimensions will be presented, the frequency of occurrence of each type of interaction will be evaluated, and some observations will be made concerning the local flame propagation behaviour.

2. Spatial/Eulerian structures

Spatial structures are defined as measurable subsets of the flow domain, fully specified by the relevant physical and chemical properties, and specified in the spatial/Eulerian description [15]. The notion of measure is taken as a generalisation of properties such as length, area, volume etc. [16]. The most important and elementary properties of the subsets are the measure denoted by V_0 and its dimension, the area of the boundary V_1 and its dimension, and the mean and Gaussian curvature integrated over the bounding surface, denoted by V_2 and V_3 respectively. The V_i are called the Minkowski functionals [17]. The usual definition of dimension as the number of basis vectors (coordinates) required to specify any vector is not sufficient and a more general point of view must be taken [18,19].

2.1. Line type structures

Subsets of the flow field $\mathcal{D} \subset R^3$ with Hausdorff dimension $d_H \leq 1$ are called line type structures. The vector fields defined on $\mathcal{D}$ such as velocity and vorticity generate tangential vector lines according to

$$\frac{dx_\alpha}{ds} = v_\alpha(\mathbf{x}(s), t), \quad \alpha = 1, 2, 3 \tag{1}$$

with an arbitrary initial condition $\mathbf{x}(0) = \mathbf{x}_0 \in \mathcal{D}$ where s denotes the arclength measured along the vector line. Time t is constant in the spatial description, and hence the system of ordinary differential equations is always autonomous with respect to arclength s. For a finite set of initial conditions $\mathbf{x}^i$, $i = 1, \ldots, N$, the vector lines through the set can be analysed with the aid of algebraic topology including braids, knots and linking number [20] and entanglement [21]. Dynamical systems theory [22,23] provides the critical structures of the vector lines which may include critical points, limit cycles, invariant tori and invariant sets of dimension $d_H > 2$.

2.2. Surface type structures

Subsets of the flow field $\mathcal{D} \subset R^3$ with Hausdorff dimension $1 < d_H \leq 2$ are called surface type structures. The vector fields relevant to combustion flows are velocity, vorticity and various flux vector fields. Clearly, subsets corresponding to reaction zones are of particular importance in combustion flows. These reaction zones can be approximated by propagating surfaces [24] if the chemical reactions are sufficiently fast. Propagating surfaces in both reacting and non-reacting turbulent flows may develop singularities in finite time [25] in contrast to materially invariant surfaces. In particular, cusp singularities are an identifying characteristic of propagating surfaces in the spatial description.

2.3. Volume type structures

Subsets of the flow field $\mathcal{D} \subset R^3$ with Hausdorff dimension $2 < d_H \leq 3$ are called volume type structures. These structures may have dimension less than three and hence may not fill the Euclidean space R^3, thus reflecting the intermittent properties of the flow. The Minkowski functional V_0 is interpreted as the principal measure of the structure, and hence can be computed if the volume type structure is measurable. The functionals $V_1, \cdots, V_3$ may not exist for structures with a fractal dimension. However, if the dimension of the volume type structure is equal to three and the boundary is sufficiently smooth, then the Minkowski functionals V_1 to V_3 are computable and the latter is then the Euler number of the surface.

3. DNS formulation and datasets

The analysis is applied to study topologies of flame–flame interactions in highly turbulent premixed flames using the DNS data of Hawkes

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