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# Flame interaction identification in turbulent premixed flames

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## Abstract

An efficient formulation of the method of Griffiths et al. [1] is used to identify premixed flame interactions. This method identifies flame interactions by finding critical points in the progress variable field, and is applied to a DNS dataset featuring sound generation by a premixed jet flame. The results show that different types of flame interaction events occur, including tunnel formation, tunnel closure and pocket burn-out. A large number of these events occur close to the flame tip. The developed method, optimised for parallel processing, will be used to gain a detailed understanding of sound generation in turbulent premixed flames in future studies.

**Keywords:** *Flame interaction events, Turbulent premixed flame, Combustion noise, Optimization method.*

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## Nomenclature

$\delta_{th}$ : Flame thickness  
 $S_L$ : Flame laminar speed  
 $u$ : Velocity field

## 1. Introduction

Lean premixed combustion is a promising method of decreasing greenhouse emissions in modern gas turbines. However, the combustors operating under lean conditions are susceptible to so called ‘thermo-acoustic instability’ [2]. This phenomenon involves a strong coupling between the flame dynamics and acoustic waves and results in large pressure fluctuations leading to the combustor failure in extreme cases [3-8]. As a result, achieving an improved understanding of how flames produce sound is of great importance for environmental and safety reasons.

One of the first theoretical studies of combustion noise was performed by Strahle [9]. He used Lighthill’s acoustic analogy [10] to describe sound generation in turbulent combusting flows as a function of flame key parameters. The time derivative of the heat release rate ( $\partial\dot{Q}/\partial t$ ) was found to be the main source term of Lighthill’s equation. Much of the subsequent work used this theoretical framework and showed reasonable agreement with experimental results (See Ref. [11] for a review of these studies). One phenomenon that can result in large fluctuations of heat release rate, and therefore large  $\partial\dot{Q}/\partial t$ , is flame annihilation [6,7,12-14]. When two flame surfaces approach each other, the unburned gas trapped between them is rapidly consumed, resulting in large fluctuations of the heat release rate.

Several investigations by the group have highlighted the importance of flame annihilation in the sound generation process using one-dimensional (1D) and two-dimensional (2D) numerical simulations of laminar

premixed flames [6,7,15,16]. However, the contribution of flame annihilation events to the noise generation by turbulent premixed flames has not been examined closely. In a recent study, Haghir et al. [17] performed a three-dimensional (3D) DNS of sound generation by a turbulent premixed flame. They showed that annihilation events were strong monopolar sources of sound. However, the annihilation events have not been examined in detail in this work.

Studies are also now emerging that identify flame interaction events. For instance, Dunstan et al. [18] investigated flame interactions in turbulent, premixed, twin V-flames. They used an automatic feature extraction (AFE) technique to identify flame interactions through topological changes of a progress variable iso-surface. The effects of the different types of interactions on the turbulent flame brush, and especially on the flame stretch rate, were discussed in this work. Griffiths et al. [1] used a different approach to identify flame interactions in a temporally evolving premixed flame. They identified flame interactions by finding the critical points in the progress variable field. They classified different types of flame interactions into four groups: product pocket, tunnel formation, tunnel closure and pocket burn-out events. They then performed some statistical analysis of those interactions in two flames with different Damköhler numbers.

The present paper applies the method proposed by Griffiths et al. [1] to DNS data of a turbulent jet, premixed flame [17]. The ultimate goal is a detailed examination of the annihilation events and their contribution to the overall radiated sound from turbulent premixed flames.

The structure of this paper is as follows. First the DNS dataset is briefly presented. Then, the numerical method developed to identify the flame interactions is outlined. Next, the importance of flame interactions in the sound generation process is discussed, and finally the identified critical points with different types of annihilation events are visualised.

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## 2. DNS Dataset and Numerical Method

A direct numerical simulation (DNS) database of sound generation by a turbulent premixed flame was used in this study [17]. The DNS were performed using a modified version of S3D [19], referred to as S3D-SC [20-22]. S3D-SC uses an 8<sup>th</sup> order central differencing scheme for spatial derivatives, combined with a 6-stage, 4<sup>th</sup> order explicit Runge-Kutta time integrator. The simulation was performed on a 3D structured Cartesian mesh. The boundary conditions were based on 3D Navier-Stokes Characteristic Boundary Conditions (3DNSCBC) [23]. All non-reflecting outflow boundaries were carefully treated to avoid spurious noise reflections.

The DNS data features a round jet of unburned premixed mixture (reactant) issuing into an open environment of combustion products at the adiabatic flame temperature. The jet Reynolds number was equal to 4000 and a homogeneous turbulence field with a turbulence intensity of 10% was fed into the mean velocity field using the Taylor hypothesis. A single step chemistry model was used to reduce the computational cost. The fuel mass fraction  $Y_f$  was used as the progress variable.

Table 1 summarises the DNS parameters. A representation of the flame, with 2 iso-surface values of the progress variable, can be seen in Fig. 1.

Table 1: DNS parameters

|                                               |                  |
|-----------------------------------------------|------------------|
| Jet diameter                                  | D                |
| Domain size                                   | 15D × 16D × 16D  |
| Grid resolution                               | 1800 × 800 × 800 |
| Mean inlet Mach number                        | 0.4              |
| Co-flow Mach number                           | 0.004            |
| Non-dim. Fresh mixture temperature            | 2.5              |
| Heat release parameter ( $\alpha$ )           | 3                |
| Jet Reynolds number (Re)                      | 4000             |
| Inlet turbulence intensity ( $u'/\bar{U}_j$ ) | 0.1              |
| $\delta_{th}/D$                               | 0.07             |
| $S_L/a_{ref}$                                 | 0.007            |
| Zeldovich number ( $\beta$ )                  | 8.0              |
| Damköhler number (Da)                         | 19.44            |
| Prandtl number (Pr)                           | 0.75             |
| Lewis number (Le)                             | 1.0              |

The flame annihilation events were identified by finding the critical points in the progress variable field, i.e. points where the progress variable gradients in all directions is zero [1]. An optimised form of Newton's algorithm was used to find these critical points. At first, a linear interpolation of the three components of the gradient vector was computed for the entire domain. Then, the cells which were likely to include a critical point were found using a linear interpolation of the gradient vector. If a cell passed this test, the cell's centre was given as a first estimate for Newton's method. Before commencing the iterative process to find the critical point, a tri-cubic convolution algorithm was used to calculate the progress variable field inside a given cell. This method reduces the computational cost as the spatial derivatives can be calculated analytically anywhere inside the cell. The next step is then to obtain

the next guess for the critical point position  $\mathbf{v}_{i+1}$  as follows:

$$\mathbf{v}_{i+1} = \mathbf{v}_i - [Hf(\mathbf{v}_i)]^{-1} * \nabla f(\mathbf{v}_i), \quad (1)$$

where  $\nabla f(\mathbf{v}_i)$  and  $[Hf(\mathbf{v}_i)]^{-1}$  are respectively the gradient vector and the inverse of the Hessian matrix of the progress variable at the current estimate point. This iterative process is continued until convergence is reached based on a given position tolerance.

The critical points of interest were those located in the region with a non-zero reaction rate. From a calculation of a 1D laminar flame with the same chemical model as the 3D simulation, the progress variable  $Y_f$  between 0.02 and 0.5 was found to satisfy the non-zero reaction rate condition, as per the two iso-surfaces shown in Fig. 1.

This routine was implemented in S3D-SC, to post-process the data on parallel processors. A large number of tests on 2D and 3D data were performed to ensure that the proposed algorithm works effectively.

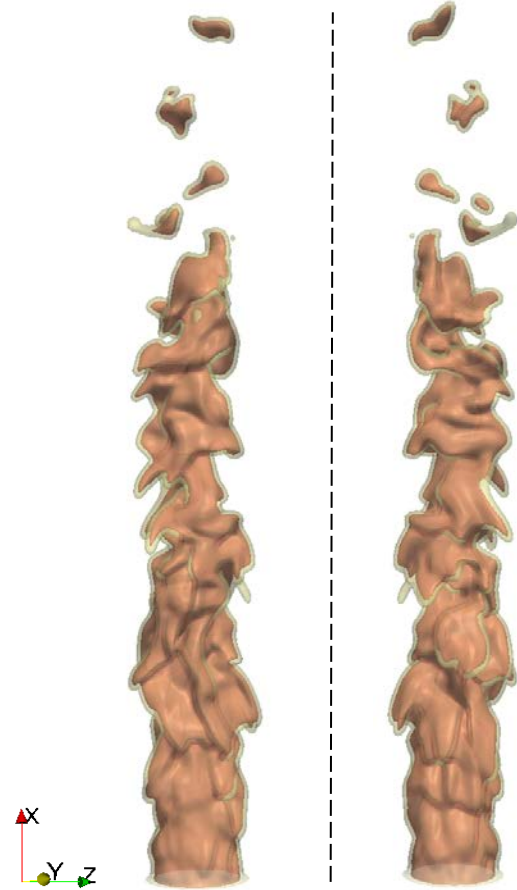


Figure 1: Back and front views of the computed turbulent premixed flame [17] represented by 2 progress variable iso-surfaces (yellow:  $Y_f=0.02$  and orange:  $Y_f=0.5$ )

## 3. Results and Discussions

Figure 2 shows the dilatation field at two different time steps in an X-Y plane cutting through a flame interaction event. (It can be readily shown that the dilatation  $\nabla \cdot \vec{u}$

and pressure are related in the far field [25].) It can be seen that annihilation events produce strong sound waves, motivating our study of flame interactions.

There are four different types of flame interactions, defined by Griffiths et al [1]. First, a ‘product pocket’ is a pocket of burnt gases, propagating outwards. This type of event did not appear in the premixed flame studied here. In flames with a moderate level of turbulence product pocket will only appear during an auto-ignition event, which does not occur in a stable premixed flame. This explains why no ‘product pockets’ were found in the flame. Second, a ‘tunnel formation’ (Fig. 3.a) occurs when a hole appears in the  $Y_f$  iso-surface. Third, a ‘tunnel closure’ (Fig 3.b) appears when a pocket of unburnt gases pinches off from part the flame surface. Finally, a ‘pocket burn-out’ is a pocket of unburnt gases propagating inwards until all the fuel is burnt (Fig 3.c). Mathematically, it is the signs of the eigenvalues of the progress variable Hessian matrix by which the event type is specified (Table 2). For a product pocket, all eigenvalues are positive whereas for a pocket burn-out,

Table 2: Relation between the types of interactions and the eigenvalues signs

| Flame interaction type | Eigenvalues’ signs |
|------------------------|--------------------|
| Product pocket         | + + +              |
| Tunnel formation       | + + -              |
| Tunnel closure         | + - -              |
| Pocket burn-out        | - - -              |

the eigenvalues are all negative. A tunnel formation is found when there is only one negative eigenvalue whereas the tunnel closure corresponds to only one positive eigenvalue.

Figure 4 shows the location and types of these events at a given time step in one simulation studied. Similar to other studies in the literature [1,18], the majority of flame interactions were found close to the flame tip. Several pocket burn-outs (shown with red points) events are observed in Fig. 4. A tunnel formation (shown with blue point) can also be seen.

To examine the significance of annihilation events in the sound generation process in a later study, this method will be applied to the large dataset introduced in this paper. Identifying different types of flame interactions and their relation to important acoustic properties at the critical points will shed light on the contribution of those events to the overall noise generated by the turbulent premixed flame.

#### 4. Conclusion

An efficient formulation of the method of Griffiths et al. [1] was used to identify premixed flame interactions. This method identified flame interactions by finding critical points in the progress variable field, and was applied to a DNS dataset featuring sound generation by a premixed jet flame. The dilatation field of the DNS

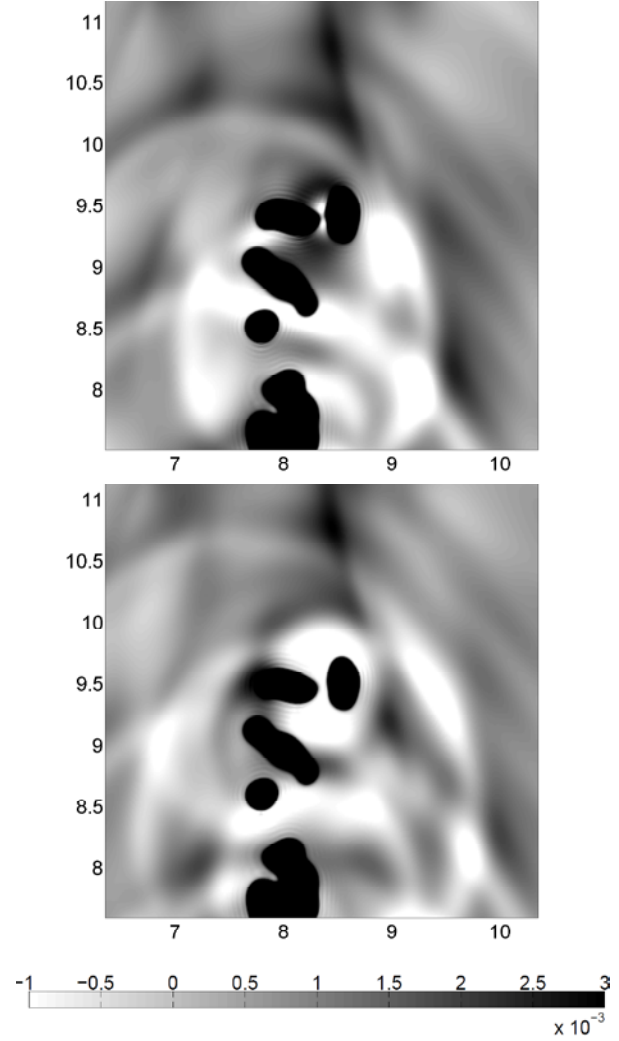


Figure 2: Dilatation field close to a flame interaction event

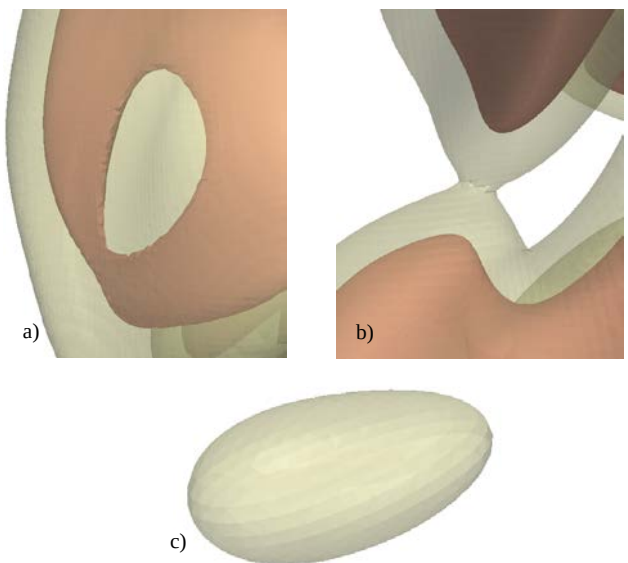


Figure 3: Three different types of flame interactions: a) Tunnel formation, b) Tunnel closure, c) Pocket burn-out

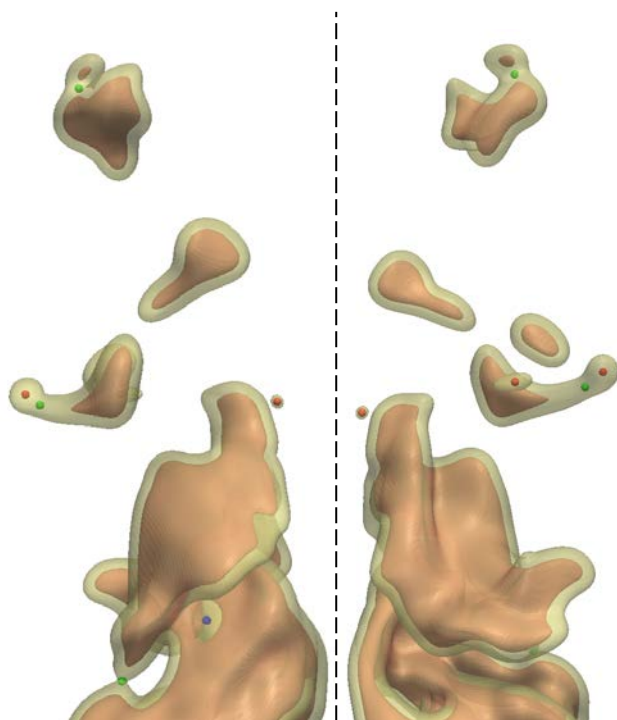


Figure 4: Back and front view of flame interactions at the flame tip (blue: tunnel formation, green: tunnel closure, red: pocket burn-out)

dataset was also used to examine the sound generation process.

The results showed that different types of flame interaction events occurred, including tunnel formation, tunnel closure and pocket burn-out. A large number of these events occurred close to the flame tip. Visual inspection suggested reasonable identification of the critical points within the progress variable field. Preliminary analysis also suggested that these identified events played a significant role in sound generation, although this requires further research to be definitive.

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