Abstract

Dissipation element analysis is a method for analyzing scalar fields in turbulent flows. Dissipation elements are defined as a coherent region, in which all gradient trajectories of a scalar field reach the same extremal points. Therefore, the scalar field can be compartmentalized in monotonous space filling regions. The dissipation element analysis is applied to a set of spatial evolving premixed jet flames at different Reynolds numbers. The simulations feature finite rate chemistry with 16 species and 73 reactions. The jet consists of a methane/air mixture with an equivalence ratio $\phi = 0.7$. Marginal statistics of dissipation element parameters are shown and compared to those of a DNS of a non-reacting spatial jet. In addition, the correlation between the local flame structure and dissipation elements is investigated.

Introduction

In turbulent combustion, various regimes exist which pose different implications to the accompanying modeling procedure. For premixed combustion, the so-called “regime-diagram” exists [1], where turbulent scales, such as the Kolmogorov length are compared to different scales of the flame. To test the underlying theory of the combustion diagram by means of direct numerical simulations (DNS), a set of simulations of spatially evolving jet flames situated in the thin reaction zone regime was conducted by Luca et al. [2]. To achieve a meaningful comparison between the local turbulent and chemical scales, a procedure is required that employs a space-filling decomposition to assure that all interactions are being considered.

A method for obtaining the local turbulent scales in a turbulent scalar field is the dissipation element (DE) analysis [3,4]. DEs are constructed by tracing gradient trajectories in a scalar field in the ascending direction until a maximum is reached and in the descending direction, until the gradient trajectory terminates at a local minimum. All grid points whose gradient trajectories reach the same extremal points are grouped into a single DE. DEs can be statistically described by two parameters, namely the Euclidean distance between their extremal points $\ell$ and
their scalar difference in these points $\Delta \psi$. The joint probability density function of these two parameters is expected to suffice for a statistical reconstruction of the scalar field.

DE analysis was originally applied to scalar fields in isotropic turbulence [3,4,5], later to free shear flows [6] and verified in experiments [7]. More recently, the DE analysis was applied to a non-premixed jet flame [8].

In the scope of this work, the DE analysis is applied to the temperature fields of two DNS whose details will be outlined in the section below. Since the temperature can be interpreted as a progress variable in the context of premixed combustion, the gradient trajectories used in forming a DE can be interpreted as a grouping of flamelets, which share the same start and end points in space.

**Configurations**

The DE analysis was applied to two DNS of spatially evolving methane jet flames of the Bunsen burner configuration. This configuration is illustrated in Fig. 1, where the atomic oxygen mass fraction in the x-y center plane of the two DNS is shown.

![Figure 1. Atomic oxygen mass fraction in the x-y center-plane of the two DNS cases investigated here. The yellow colored regions correspond to high values of the mass fraction, and brown colored regions to low values [2].](image)

The jet Reynolds number is set to 5,600 and 11,200 for the low Re case and the high Re case, respectively. The jet Reynolds number is varied by changing the slot width $H$ while keeping the jet bulk velocity constant. In this fashion, the turbulent small scales remain approximately constant while the integral scales are changed. The DNS feature lean premixed methane/air flames with an equivalence ratio of $\phi = 0.7$ and a temperature of $T = 800K$, as it is commonly found in stationary gas turbines. The temperature and species concentrations in the co-flow correspond to the equilibrium state of the burned mixture.

The laminar burning velocity is $s_L = 1.01$ ms$^{-1}$ and the temperature gradient based flame thickness is $\delta_L = 110 \, \mu\text{m}$. This places the cases in the regime of the thin
reaction zone.
The DNS are performed in the low Mach number limit using finite rate chemistry with a skeletal mechanism with 16 species and 73 elementary reactions [9]. Additional details regarding the DNS are summarized in Tab. 1.

<table>
<thead>
<tr>
<th>Table 1. Summary of the details of the DNS investigated with the DE analysis.</th>
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<tbody>
<tr>
<td>Low $Re$ case</td>
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<tr>
<td>Jet Reynolds number $Re$</td>
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<tr>
<td>Jet bulk velocity $U$</td>
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<tr>
<td>Slot with $H$</td>
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<tr>
<td>Grid size ($n_x \times n_y \times n_z$)</td>
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**Dissipation Element Parameter Statistics**
The DE analysis is applied to the temperature fields of the previously outlined DNS approximately $4H - 10H$ downstream from the nozzle, where the turbulence is already sufficiently evolved, but the flame front has not begun to close in on itself.

The corresponding DE analysis is shown in Fig. 2 for the $x$-$y$ center plane of the temperature fields. On the top part of the figure, the temperature fields are shown as well as a black contour indicating the iso line of the temperature where the heat release peaks as an indicator for the position of the turbulent flame front. On the bottom part of Fig. 1, the DE analysis is shown in a mirrored fashion. The DE are colored individually and encompassed in a black contour. For the sake of orientation, the iso-line of the temperature of the maximum heat release is again shown in white. One observes that, compared to the jet thickness in cross-stream direction, the DEs of the high $Re$ flame are a lot smaller in scale than in the low $Re$ flame. Another observation to be pointed out are the various shapes and sizes of the DEs intersecting the flame front, which indicates a wide range of local turbulent scales interacting with the flame.

**Figure 2.** Top part: $x$-$y$ center plane of the temperature fields in two DNS of spatially evolving methane jet flames. Red colored regions correspond to high temperatures, blue color to low temperature regions. The black contour indicates the iso-surface of the maximum heat release. Bottom: corresponding DE analysis of the temperature, mirrored. The DE are colored individually and encompassed in
A black contour. Left: low Re case, right: high Re case.

Figure 3. PDFs of normalized separation length $\ell$. Left: normalization with the mean length $\ell_m$. Right: normalization with flame thickness $\delta_L$.

An important characteristic of DE statistics of the separation length $\ell$ is its invariance towards changes in Reynolds numbers when normalized with the mean length $\ell_m$. The probability density functions (PDF) of the normalized separation length $P(\ell / \ell_m)$ are shown on the left of Fig 3. The solid blue and the red line correspond to the PDF of the low and high Re case, respectively. As a reference, the DE analysis of the passive scalar field in a non-reacting jet with a jet Reynolds number of $Re = 10,000$ is shown by the dashed line. For all three cases, for the short elements, a linear increase of the PDFs is observed. This linear increase is caused by the diffusive drift of the extremal points [2]. After a maximum, an exponential decrease of the PDF for longer DEs is observed, which is attributed to the Poisson process of random cutting and connecting of the DEs by turbulent eddies. Here, the PDF of the low Re case differs. A second, local maximum of the PDF is situated at $\ell / \ell_m \approx 1.6$. This second maximum is a signature of a length scale induced at the nozzle that has not been sufficiently mixed out at this streamwise location due to the low level of turbulence in this case.

On the right hand side of Fig. 3, the normalization of $\ell$ is performed with the flame thickness $\delta_L$ to achieve the originally proposed comparison of turbulent and chemical scales. The PDFs display good agreement for the short DEs. For the longer elements, the PDF of the high Re displays a higher probability density than that of the low Re case, which is a result of the larger scale separation induced by the difference in the Reynolds number. In addition, this validates the original intent of the numerical experiments of keeping the small scales constant while changing the large scales. The assumption of the regime of the “thin reaction zone” is reflected by the PDFs as well. While being larger than the flame thickness $\delta_L$, the
vast majority of the DEs are of a comparable length.

**Influence of Dissipation Elements Parameters on the Flame Structure**

To gain insight into the flame structure, the mean temperature conditioned on the distance to the flame front \(\langle T|s\rangle\) is shown on the left of Fig. 4.

The flame front is defined as the iso-surface of the maximum heat release of \(T = 1800\) K. The distance \(s\) is obtained by using gradient trajectories in the temperature field to assure the shortest possible path from the unburned to the burned side. The unstretched 1D flamelet solution for the simulated conditions is indicated as the black dashed line. The conditional temperatures for the jet flames are indicated by the solid lines, which show a perfect collapse for all distances. For negative values of \(s\), the jet flames show distinctly higher temperatures than the flamelet solution. This is due to turbulent mixing in the preheating zone. Close to the reaction zone all three lines collapse, indicating an unbroken inner reaction zone. In the oxidation zone, for positive values of \(s\), the jet flames display slightly lower values of the temperature. All these findings are highly consistent with the expected flame structure in the “thin reaction zone” regime.

To achieve a more local comparison of scales as well as investigate the correlation between the DE parameters and the flame structure, the temperature is additionally conditioned on the DE temperature difference \(\langle T|s, \Delta T\rangle\). This is shown on the right of Fig. 4. The solid lines and the dashed lines correspond to the low \(Re\) case, respectively, and the colors indicate different \(\Delta T\). For decreasing values of \(\Delta T\) and therefore smaller indicated turbulent scales, the temperature in the preheating zone increases, which is caused by more intense turbulent transport.
from the inner reaction zone. For very small values of $\Delta T$, a significant influence on the oxidation zone can be observed as well.

**Conclusions**

DE analysis was performed on the temperature fields of the DNS of two spatially evolving methane jet flames. The invariance of the normalized statistics of $\ell$ towards changes in $Re$ observed in scalar fields in non-reacting flows was retained in the reacting cases. The marginal statistics showed a high consistency with the assumptions regarding the general setup of the DNS and the regime of the thin reaction zones. Additionally the correlation between the DE parameter $\Delta T$ and the flame structure was demonstrated.

**References**


