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Identification of local extinction and prediction of reignition in a spark-ignited sparse spray flame using data mining

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A R T I C L E I N F O

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A B S T R A C T

Direct Numerical Simulations (DNS) of droplet fields which are ignited using a spark are investigated to deduce any behaviour that distinguishes between the cases where successful flame propagation occurs and where a flame ignites but subsequently extinguishes. At the instant the spark was deactivated, some of the studied cases displayed no local extinction, others showed some local extinction (one with reignition and the rest with global extinction) and the rest showed global extinction. The gaseous field at this instant was analysed using the data mining technique the Gaussian Mixture Model on each case separately; this method groups data points, enabling distinction between the various behaviours. The results from this analysis showed that in the case with local extinction–reignition, the regions of space near the flame kernel which produced local quenching were caused by evaporating droplets. These regions of local quenching were relatively small compared to the strong flame front surrounding them; the regions of local quenching were also relatively far from the centre of the flame kernel. In contrast, in cases with local then global extinction, the droplets created regions which were extensions of the relatively-small flame front, and these regions behaved in a similar manner to the flame propagation. As a consequence, these cases were unable to support a self-sustaining flame. Such distinctive behaviour promises opportunities to detect situations where global extinction is imminent and implement appropriate control strategies to prevent global extinction.

1. Introduction

The behaviour of spray flames under the influence of spark ignition is important for direct-injection engines [1] and gas turbine relight. Direct-injections engines are particularly receiving a lot of recent attention because of their potential to reduce emissions compared to port injection. An experimental study into the effects of equivalence ratio on a lean hydrous-ethanol engine [2] varied the leanness of the mixture and advanced the injection timing to compensate for the increased ignition delay as leanness increased. They observed a critical equivalence ratio which provided the maximum fuel efficiency and reduction in pollutants. Mixtures closer to stoichiometric had similar combustion phase durations, while leaner mixtures had increasing combustion phase durations. In another study [3], Rayleigh scattering was used to determine that injecting the fuel in two separate parcels improved the mixing compared to a single parcel with the same total mass, with consequential improvements in combustion. Two-parcel injections were also investigated [4] using PIV (Particle Image Velocimetry) to measure the effects on the turbulence caused by varying the injection timings. Adjusting the first injection timing produced a local minima in mean peak pressure for an intermediate timing, which also displayed the most cycle-to-cycle variability in IMEP and worst early flame development. This was likely due to the second injection interfering with the flow pattern created by the first. Advancing the second injection timing reversed the direction of the tumble flow, simultaneously strengthening it.

Two experimental investigations which are targeted at improving simulations of engines are now reviewed. One studied the fluid flow adjacent to the walls, which requires algebraic approximations in simulations in order for the computational time to obtain the solution to be tractable; some improvements were devised [5]. The other focussed on the nature of the turbulent eddies for four different fuels, providing invaluable information to enable simulations to match the conditions inside an engine [6].

Some recent investigations into the fundamental behaviour of sprays will be reviewed next. An experimental investigation studied the breakup of moderately-dense spray injections, characterising the behaviour of the various sizes of liquid structures

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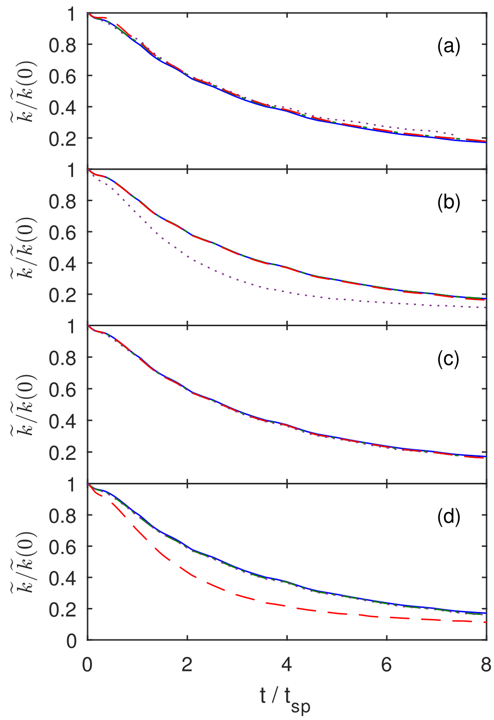

Fig. 1. Favre-mean turbulent kinetic energy, normalised by initial turbulent kinetic energy. Base case is shown in all plots: ___. Other cases: (a) B1, — ·; B2, — —; BG, ···. (b) BE, — —; KG, ···. (c) I1, — ·; I2, — —; IG, ···. (d) F1, — ·; F2, — —; FG, ···.

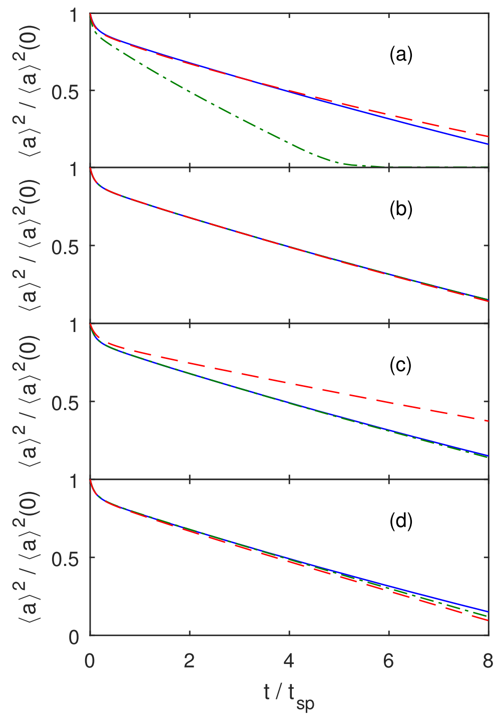

Fig. 2. Square of mean droplet diameter for droplets still in the domain, normalised by initial droplet diameter. Base case is shown in all plots: ___. Other cases: (a) B1, — ·; B2, — —. (b) BE, — —. (c) I1, — ·; I2, — —. (d) F1, — ·; F2, — —.

formed in the evaporation process and subsequent combustion [7]. Another experimental study compared the behaviour of palm biodiesel with Jet-A1 (standard jet fuel) to support the possibility of a biofuel for the aerospace industry [8]. A modelling study investigated the nature of an *n*-dodecane spray flame, reporting detailed information about the structure of the flow, behaviour of the combustion and mechanisms for flame success [9]. A Large Eddy Simulations (LES) investigation studied a series of ethanol flames, validating the results against experiments before providing information about the nature of the combustion [10]. Experimental [11] and LES [12] studies found that the location of the spark needs to be carefully chosen so that conditions are suitable for successful ignition.

Due to the complexities in the gaseous scalar field induced by the discrete nature of the droplet field and the evaporation rate [13], the large variations in gradients pose challenges for modelling [14,15]. Detailed Numerical Simulations also show that large gradients prevent ignition of single droplets in high-temperature regions [16].

While Direct Numerical Simulation (DNS) provides a powerful tool for investigating such phenomena [15], it is limited by currently-available computational resources (both memory and processing power). Two approaches are utilised: one resolves the turbulent gaseous scales (the Kolmogorov length scale for the gas, as done in single-phase DNS) and either the droplets are modelled as point sources of mass whose diameters are significantly smaller than the grid resolution, e.g., Refs. [17–25], or larger droplets and droplet structures are simulated using models such as the Volume of Fluid (VOF) method and level-set method, e.g., Refs. [26–28]. The other approach fully-resolves the liquid phase with the limitation of only simulating a few tiny droplets [29–33].

The current work uses the first approach to investigate the causes for spark-ignited spray cases extinguishing. Few papers investigate spark ignition, and those that do focus primarily on ignition behaviour, not extinction. The author has previously investigated extinction in spark-ignition cases with a qualitative measure [34] and a quantitative measure [35] to determine flame success being found. The approach taken in the current work is to use a data mining technique to analyse the gaseous fields at the instant the spark is deactivated to discriminate between regions of space that promote flame propagation and those which produce quenching. Note that droplet evaporation naturally produces local quenching, with the potential for providing a state that will support flame propagation. It has previously been suggested [35] that for cases which promote a self-sustaining flame, there is a distinction between a “burning” branch (regions which promote a self-sustaining flame front) and an “extinguishing” branch (regions which cause local extinction). For flames which ignited, but subsequently extinguished, there was no such distinction near the core of the flame kernel. The objective in this paper is to categorically determine whether the regions of local quenching are distinct from the regions of self-sustaining flame propagation and investigate the causes of this separate behaviour. If these regions are distinct, then this enables identification of regions of local extinction which will reignite in the future, as opposed to causing global extinction.

2. Theory

2.1. DNS code

A 3-D compressible DNS code called SENGA was used [36–40]. Complete details of the code and simulations investigated here can be found in Ref. [35]; a summary will be provided here. The gas-phase transport equations for continuity, momentum, total energy, fuel and oxidiser are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_i}{\partial x_i} = \dot{d}_F \tag{1}$$