Combustion and Flame 158 (2011) 401–415

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

A numerical study of vortex interactions with flames developing from ignition kernels in lean methane/air mixtures

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ARTICLE INFO

Article history:
Received 23 February 2010
Received in revised form 13 April 2010
Accepted 9 September 2010

Keywords:
Ignition kernel
Flame–vortex interactions
Lean natural-gas engines
Developing flames
Flame surface area

ABSTRACT

In this work, the outcomes of interactions of counter-rotating vortex pairs with developing ignition kernels are studied. The conditions are selected to represent those in a lean-burn natural-gas engine with hot-jet ignition. The evolution of flame surface area during kernel–vortex interaction is quantitatively and qualitatively examined. It is observed that flame development is accelerated and the net flame surface area growth rate, *i.e.* heat release rate, increased with increasing vortex velocity. In general, increasing the vortex length scale increases the surface growth rate, *i.e.* increases heat release rates, but for small length scales, *i.e.* when the ratio of vortex length scale to kernel diameter is small, high flame curvature induced during the interaction leads to flame weakening and slower growth rates. When the vortex velocity is high relative to the flame speed and the length scale is comparable to the kernel diameter, the vortex breaks through the ignition kernel carrying with it hot products of combustion. This accelerates growth of the flame surface area and heat release rates compared to a kernel with no vortex interaction. On decreasing the vortex velocity and increasing the length scale, the wrinkling of the kernel becomes important. This also results in increased surface growth rates and higher heat release rates.

1. Introduction

Premixed natural gas combustion is employed as a means of power generation in reciprocating engines, for both stationary and transportation applications [1–3]. In these engines, the mixture is typically burned lean to lower flame temperature and, hence, reduce nitric oxide emissions. Making the mixture lean also increases thermal efficiency, up to a point [4]. When the mixture is too lean, igniting the mixture can be a challenge, and misfire and slow combustion rates in the engine can result in a drastic reduction in thermal efficiency. One means of enhancing ignition in lean premixed mixtures is to use a hot-jet of burned products discharged from a pre-chamber [5]. The hot-jet generates turbulence and increases the ignition surface area. The turbulent eddies generated by the jet can act as individual ignition kernels. As the premixed flame develops from the kernel, interaction of the flame with the local turbulence field can have a significant influence on flame development and flame propagation. This study focuses on this interaction. A simplified configuration of a counter-rotating vortex pair interacting with a flame developing from a kernel of hot combustion products will be employed for the studies. Such simple flow configurations are more amenable to analysis, and comparisons with equally simple experimental setups can be carried out to provide useful insight into the processes, as opposed to studies in engines. We will employ methane as a surrogate for natural gas as its chemistry has been extensively studied.

Premixed methane flame–vortex interactions have been the subject of prior studies [6–9]. A detailed review of the effect of flame–vortex interactions on flame structure, ignition and extinction is provided by Renard et al. [10]. Since the focus of this study lies in interactions of vortices with developing ignition kernel, a discussion of the relevant kernel–vortex studies is provided below. In an experimental study, conducted at 1 atm, Eichenberger and Roberts [11] explored the influence of vortices of different length and velocity scales on a spark-ignited kernel. They showed that the weaker vortices modified the local structure of the kernel flame. Increasing either velocity or length scale of the vortex leads progressively to global wrinkling, distributed combustion, and then global quenching where there is no longer combustion. Local extinction can be observed during wrinkling and distributed combustion. They concluded that larger vortices are more effective in causing global quenching at lower vortex velocities. They observed global quenching for values of the ratio of vortex length scale (d_v) to kernel diameter (d_k) greater than about 4.

Xiong et al. [12] provide quantitative analysis of these results focusing primarily on the regimes where flame propagation is enhanced. They showed that vortex interactions with kernels during the early stages of flame development had maximum impact on enhancement of heat release rates. Xiong and Roberts [13] have carried out kernel–vortex interaction studies in stratified mixtures

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doi:10.1016/j.combustflame.2010.09.008

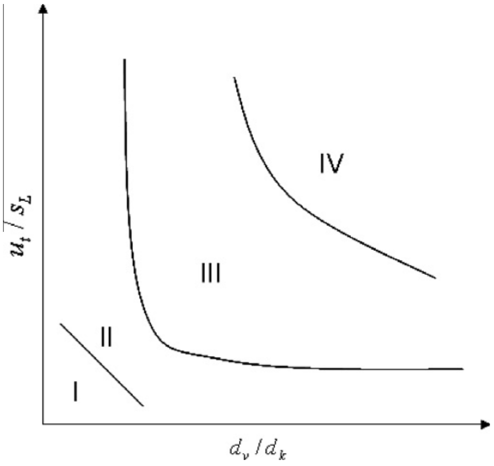

Fig. 1. Regime map for kernel–vortex interactions: (I) laminar kernel regime; (II) wrinkled kernel regime; (III) breakthrough regime; and (IV) global extinction regime [13].

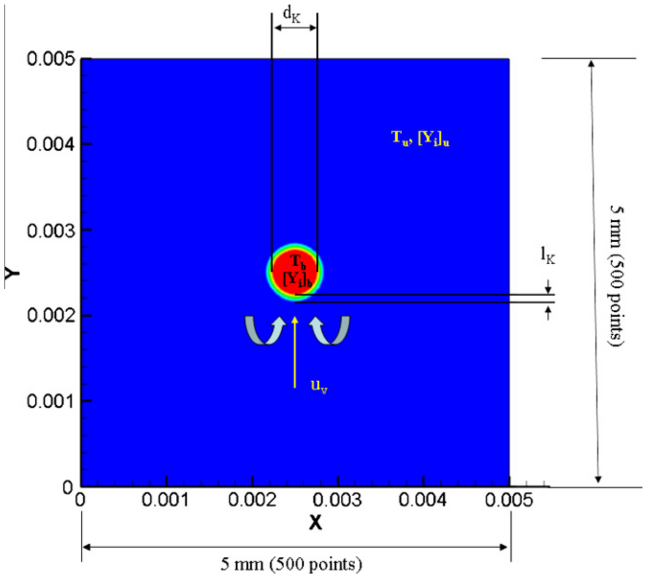

Fig. 2. Schematic of the problem setup.

where the equivalence ratio of the mixture was fixed at $\Phi = 0.6$ and that of the vortex was varied from zero (air alone) to infinity (fuel alone). Richer vortices were observed to have a higher burning rate than stoichiometric or lean vortices. A possible reason suggested is that the rich vortex attains a near stoichiometric equivalence ratio while it is propagating through the ambient mixture. It should be noted that the final equivalence ratio is dependent on the distance propagated and hence different ignition kernel placement can possibly influence the observations. The rich vortex is observed to be consumed as a single pocket. On the other hand, the leaner vortices break down into smaller pockets before being consumed.

Echekki and Kolera-Gokula [14] conducted numerical studies of kernel–vortex interactions in an axisymmetric configuration using a two-step global mechanism whose constants were adjusted to simulate hydrocarbon flame propagation. The work was not specific to methane, and mixture equivalence ratio was not directly specified. Vortex velocity, size, and kernel size were varied in their study. They represented the kernel–vortex interactions on a spectral regime diagram. A schematic of the regime map showing the trends is shown in Fig. 1. The characteristic scales that can be used to form this regime map are the ratio of the vortex translational velocity u_t to the laminar flame speed s_L and the ratio of the kernel size d_k (diameter) to the vortex size d_v (distance between centers of counter-rotating vortex pair). The laminar kernel regime was observed for weak vortices or small vortices dissipating into the kernel ($d_v/d_k \ll 1$). The wrinkling regime was observed for vortices which were comparable in size with the ignition kernel ($d_v/d_k \sim 1$) or for very small vortices with large vortex strengths ($u_t/s_L > 20$). Global extinction was observed for vortices that were typically larger than the ignition kernel ($d_v/d_k > 1$) and had very high vortex strengths ($u_t/s_L > 40$). For the rest of vortex length and velocity scales, the breakthrough regime was observed. It is not possible to conclude if the study is directly applicable to lean-burn engines because the specific temperature and pressure conditions of their work, and equivalence ratio, were not provided. Nevertheless, the work is interesting and relevant to our study.

None of the studies above are under engine conditions. High pressure and high unburned gas temperature in the engine can influence the outcomes of kernel–vortex interactions. Furthermore, in the case of hot-jet ignition with products discharged from a pre-chamber, the ignition kernel conditions are established by the conditions of the hot-jet as opposed to a spark-ignited kernel. In our work, the conditions employed are representative of

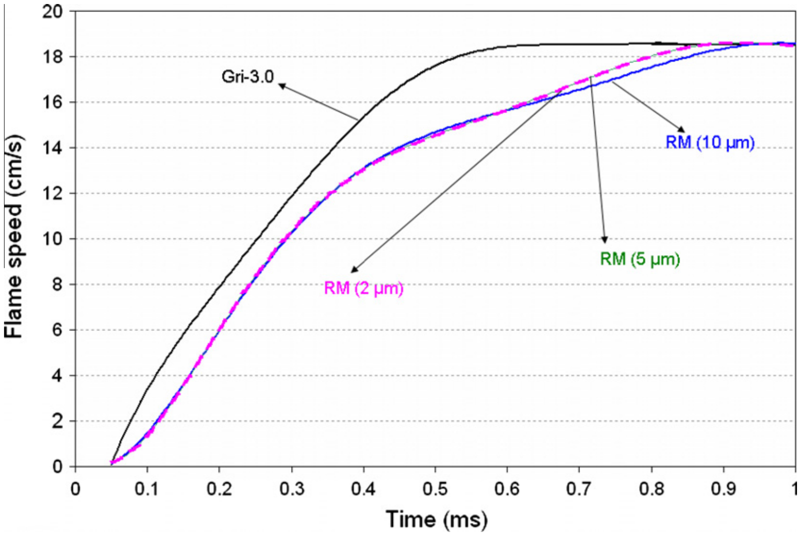

Fig. 3. Time evolution of flame propagation speed with different chemical mechanisms and grid resolutions for the baseline case with $T_b = 1700$ K and $d_K = 500$ μm.