Transient Response of Premixed Hydrogen and Methane Flames

Christina M. Vagelopoulos[†], Jonathan H, Frank and Habib N. Najm

Combustion Research Facility

Sandia National Laboratories

Livermore, CA 94551, USA

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Flame-vortex interactions are a basic component of turbulent combustion and influence operational characteristics of many practical combustion devices. On a fundamental level, these interactions provide a well-controlled means to study the response of laminar flames to unsteady strain and curvature. Previous experimental and computational investigations of vortex-flame interactions have included nonpremixed [1-2] and premixed flames [3-15] using two-dimensional vortex pairs and axisymmetric vortex rings.

For premixed flames, a range of configurations have been considered, including the head-on interaction of a toroidal vortex with a freely propagating flame [4,5,9], a line vortex-pair interaction with a V-flame [7, 10, 11] and the interaction of an axisymmetric vortex ring with twin flames in a counterflow [12,15]. The flow field has generally been mapped by particle image velocimetry (PIV). The response of flame chemistry to a vortex has been measured using line-of-sight chemiluminescence as well as spatially resolved 2-D laser-induced fluorescence (LIF) of OH, CH, CO, HCO, and CH_2O profiles. These studies have provided important insight into the complex response of flames to flow transients.

However, significant gaps in the current understanding of flame-vortex interactions remain. An important example is the existing contrast between experimental and numerical results concerning the

[†] Corresponding author: cmvagel@ca.sandia.gov

interaction between a N_2-diluted rich premixed CH_4/air V-flame and a counter-rotating line-vortex pair. Previous experimental studies revealed a phenomenon that has yet to be predicted by numerical computations. In the initial stages of the interaction, the detailed structure of the distorted flame front was nearly unchanged from that of the steady undisturbed flame. A dramatic change was observed, though, further into the interaction. In particular, the OH level abruptly increased by two to four fold [6, 11], and the CH significantly decreased, indicating a breakage in the CH front [6]. While the latter might suggest that the flame extinguished, reaction-rate and heat-release rate measurements indicated that the reaction zone remained intact [7, 13]. Simultaneous CO/OH measurements showed an abrupt depletion of CO that was spatially and temporally coincident with the OH burst [11]. The failure of two-dimensional numerical simulations [7,8] to reproduce this transient response has raised questions regarding deficiencies in current models of C_1-C_2 chemistry and transport.

The recent incorporation [14], however, of more detailed transport models did not significantly improve the discrepancy between numerical and experimental findings in a 2-D geometry. Furthermore, experiments performed in an axisymmetric geometry [15], demonstrated a fourfold *drop* instead of a twofold increase in OH along the flow field centerline, for rich diluted methane flames with very comparable chemistry and for similar vortex strength and size.

This somewhat surprising result raises further questions as to whether the contrast between numerical and experimental results can be explained solely on the basis of an inadequate C_1-C_2 chemical model and suggests the importance of better understanding the vortex/flow field characteristics as well.

Motivated by the gaps in understanding highlighted above, we aim to address a few important questions in the present study. First of all, we investigate whether the OH 'burst' can be observed in the V-flame configuration in the *absence* of C_1-C_2 chemistry. To this end we perform a series of experiments for highly diluted premixed H_2 flames. The results demonstrate that the OH 'burst' phenomenon is *not* dependent on C1-C2 chemistry. Similar to what was previously observed in highly diluted rich methane flames, the OH 'burst' for rich hydrogen flames increases with equivalence ratio. However, hydrogen

flames respond more dramatically than methane flames during vortex-flame interactions in the V-flame configuration.

Secondly, we explore the structural sensitivity of highly diluted hydrogen and methane flames to a number of parameters, such as equivalence ratio, flame stretch and reactant temperature. A wide range of diluted methane and hydrogen flames are investigated experimentally and studied numerically using 1-D codes. Part of the reason for this undertaking is the fact that although it has been reported [6] that lean premixed methane flames do not exhibit the so-called OH 'burst', it has yet to be explained why. More importantly, since this phenomenon is *not* observed in the axisymmetric geometry during toroidal vortex/counterflow-flame interaction, even seemingly unimportant system-specific characteristics of the V-flame apparatus need to be better understood and systematically studied.

From our study of this, it was found experimentally that modification of the local mixture composition in the vortex core is quite significant. More specifically, it was discovered that air is entrained into the vortex during the formation process, in the V-flame apparatus. Furthermore, 1-D numerical calculations demonstrated that flames for which the OH 'burst' has been observed experimentally are sensitive to small changes in mixture composition. Experiments followed that verified that the OH 'burst', owing to air entrainment in the vortex core, is a system-specific phenomenon, rather than due to a transient chemical response. It was also shown numerically and verified experimentally that the same reasoning explains the 'disappearance' of CH observed concurrently with the OH 'burst' in previous experiments. Moreover, the 1-D simulations demonstrated that small changes in the mixture composition significantly modify levels of CH, even for undiluted methane flames. As a result, we discuss the adequacy of CH as a flame marker.

Finally, we investigate whether implementing findings from the previous two steps will suffice for the reconciliation between state-of-the-art numerical models and experimental results, or, whether the suggestion that kinetics are largely responsible for the discrepancy still holds true. For that purpose we perform 2-D simulations for the interaction of a counter-rotating hot vortex pair impinging on a highly diluted rich hydrogen flame, utilizing detailed chemistry and detailed transport properties. The 2-D

numerical simulations for a hydrogen flame further confirmed the hypothesis for the sensitivity of OH response to the vortex core composition. The OH 'burst' was captured for the first time during the interaction of a line vortex at elevated with modified composition with a 2-D flame. Interestingly, the prediction of increase in peak OH along the vortex centerline is almost identical to the one from 1-D steady simulations.

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