Numerical Study of a Opposed-jet H_2/air Diffusion Flame - Vortex Interactions

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Abstract

We consider the interactions between vortices of different sizes and stength and a H_2/air diffusion flame stabilized on an opposed-jet burner. In our direct numerical simulations, we demonstrate the opposite effects produced by flame curvature of opposite orientations by placing a vortex on either the air or the fuel side of the diffusion flame. When the flame curvature is convex towards the fuel stream, the flame burns more intensely and can withstand a scalar dissipation rate almost three times the critical value calculated by a steady-state one-dimensional code. On the other hand, if the flame curvature is convex towards the air stream, the flame weakens and in some cases extinguishes locally. The effects of flame curvature indicated in our transient simulations are in agreement with steady-state results of Takagi [1], but reveal an inconsistency with recent results of Katta *et al.*[2].

1 Introduction

Prompted by the interest in improving our understanding of the micro-structure and the modeling techniques of turbulent flames, direct numerical simulation (DNS) of flame-vortex interactions have received considerable interest in fundamental combustion research for both premixed (*e.g.,* [3, 4, 5]) and diffusion flames (*e.g.,* [6, 7, 1, 2, 8, 9]). Particularly, both experimental and numerical work focus upon simple experimental setups such as the opposed-jet or the co-flow burners (*e.g.,* [6]).

A review of the past three Combustion Symposia (*e.g.,* [7, 1, 2, 10]) clearly shows the recent trend in utilizing advanced laser diagnostics to probe the response of the flame structure interacting with a vortex. Both methane/air and H_2/O_2 system are popular, with the H_2/O_2 system offering the additional richness in its flame response mainly due to preferential diffusion. Katta *et al.*[2] performed experiments and DNS on the interaction of a vortex generated by impulsively injecting air through a small nozzle imbedded in the air nozzle of an H_2/air opposed-jet burner, thereby producing a diffusion flame which is convex towards the fuel stream. An annular-quenching pattern was observed in a region where the local strain rate is below the extinction strain rate. It was concluded that the annular shaped extinction was caused by preferential diffusion and flame curvature.

The work of Takagi *et al.*[1] differs from that of Katta *et al.*[2] in that the flame is perturbed by a steady micro-jet on either the air or the fuel side of the flame, thereby creating a steady-state, locally curved flame which exhibits strong preferential diffusion effects. It demonstrated that curvature of opposite orientation produces opposite effects: when the diffusion flame is convex towards the fuel stream, the flame intensifies, when it is concave towards the fuel, the opposite effect is observed. Their results indicate the possible effects of curvature and preferential diffusion when a vortex interacts with a H_2/O_2 diffusion flame. Since the structure of the flame reported by Katta *et al.*[2] which exhibited the annular extinction pattern is convex towards the fuel, following Takagi's reasonings, the flame should instead burn more intensely. Our work closely follows the reasonings derived from Takagi's work; we simulate the interaction of a H_2/O_2 diffusion flame with a vortex coming either from the fuel or the oxidizer side of the flame, thereby reversing orientation of the flame curvature and thus, the effects of preferential diffusion.

We analyze the transient interaction of a vortex described by an analytic solution (Hill's vortex), and a H_2/O_2 diffusion flame stabilized on an opposed-jet burner. The underlying steady diffusion flame is obtained on the two-dimensional domain. The size and strength of the vortex as well as the boundary conditions used to specify the underlying diffusion flame are chosen to be comparable to the experiments of [7, 8]. Note that the boundary conditions found in [7, 8], and [2] differ slightly from each other. Furthermore, we perform simulations starting from the introduction of the vortex and continue until the diffusion flame reestablishes its steady-state structure. This way, we obtain the relaxation time scale of this problem which can be useful in validating transient flamelet models (*e.g.,* Peters [11])

We solve the transient two-dimensional conservation equations of mass, momentum, energy, and species in the cylindrical coordinate system (axi-symmetric) with the axis of the opposed-jet nozzles lying on the axis of coordinate system. More details on the numerical method, its convergence characteristics, and error control can be found in [12], and previous applications in [13, 14]. We have recently implemented matrix-free stiff ode solvers (ROWMAP [15] and VODEPK [16]) which greatly improved the code's efficiency. The computational domain used here is $4.0cm \times 2.5cm$, corresponding to nozzle of $2.5cm$ diameter separated by the distance of 4.0cm. A Hill's vortex (with a corresponding stream function $\Psi = -\frac{3}{4}\frac{U_{Hill}r^2}{a^2}(a^2 - z^2 - r^2)$ [17]), is utilized in our simulations. We chose not to simulate the formation process of the vortex (injection of an imbedded nozzle) not only to reduce computational cost, but more importantly, because we can specify clearly the size and strength of the vortex Lastly, detailed chemical kinetics and realistic transport are utilized.

2 Results

Two cases of the same boundary conditions but with the vortex placed on different sides of the flame will be shown. The velocity of the fuel stream (2.3% H_2 and 97.7% N_2 by mass) at $300K$ and oxidizer stream (air) at 300K are 56 and 42 cm/s ("top-hat" profiles), respectively. Grid resolution is 0.06 mm in the flame region, and spectral convergence is ensured by increasing the order of the interpolant until solution (and up to 2^{nd} order derivatives) are grid independent. The diameter of the Hill's vortex is 0.5 cm and its maximum rotational speed is 3.0 m/s ($a = 0.25cm$ and $U_{Hill} = 200cm/s$). The vortex is placed initially away from the flame, and its induced velocity field is superimposed onto the steady-state solution obtained on the two-dimensional grid.

Observations made from Fig. 1 can be summarized as follows: (a) The diffusion flame extinguishes in a region centered on the axis of symmetry when the vortex is placed on the oxidizer side; temperature there dropped to *ca.* $400K$. (b) The same vortex placed on the fuel size does not extinguish the flame, insteady it burns more intensely. (c) In both cases, it took approximately 120 ms for the flame to return to the steady-state. (d) During relaxation, in the case of the vortex placed on the air side, the flame thickens considerably, and the temperature rises above the steady-state value $1640K$ by *ca.* $400K$.

3 Discussions and Conclusions

We demonstrated the effects of preferential diffusion and curvature on the transient response of the H_2/O_2 diffusion flame. Similar effects are observed for both the steady-state results of [1] and our transient simulations. The results of [2] indicate that when a vortex impinges the flame from the air side, thereby making the flame convex towards the fuel stream, it produces an annular extinction pattern even though the local strain rate does not exceed the extinction value. They concluded that this was caused by preferential diffusion and flame curvature. Ours and the steady-state results (both numerical and experimental) of Takagi *et al.*[1], however, indicate the opposite trend: when the flame curvature is

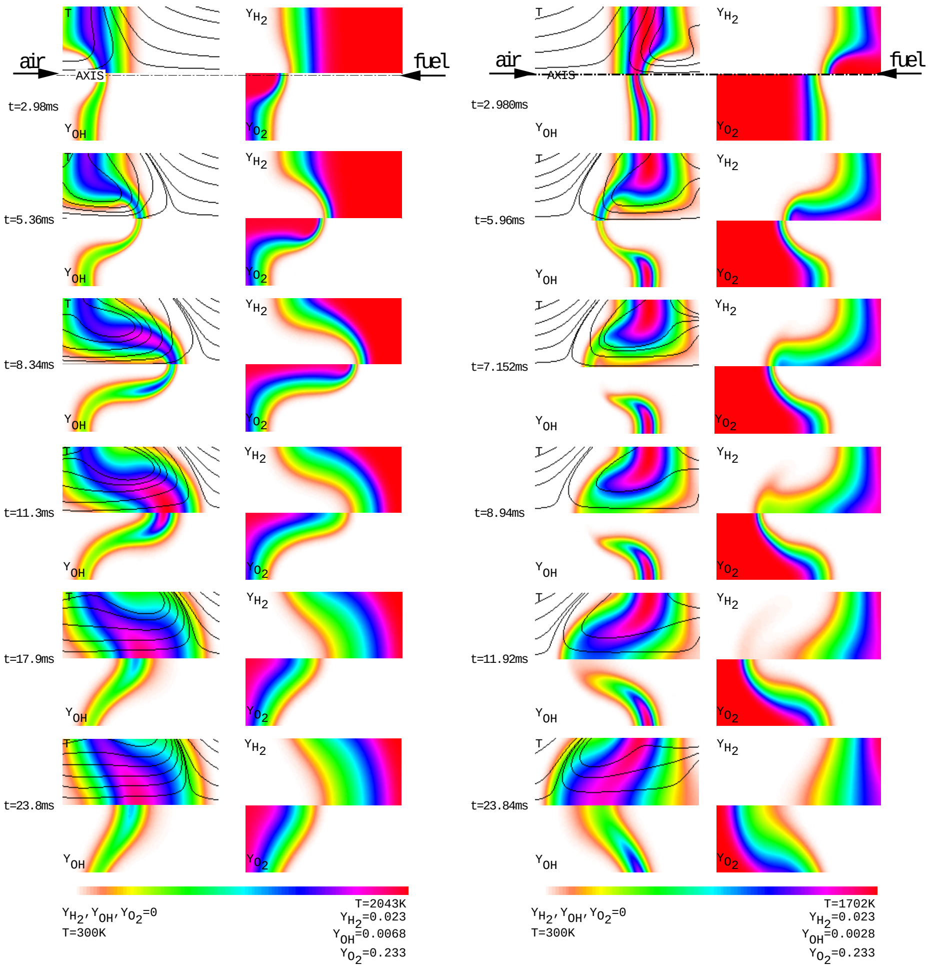

Figure 1: Time sequence of temperature and the OH, O_2, and H_2 mass fraction isocontours and streamlines of diffusion flame-vortex interactions. Left two columns: Hills vortex placed on the left side of the flame. Right two columns: vortex of opposite sign placed on the right side of the flame.

convex towards the fuel stream, preferential diffusion and flame curvature make it burn more intensely. In fact, the local scalar dissipation rate, χ at $t = 5.96ms$ (right two columns in Fig. 1) is twice the critical value of 115 s^{-1} which is predicted by a steady one-dimensional code [18]. Here, we define the mixture fraction, $Z = (\gamma * Y_{H_2} - Y_{O_2})/(\gamma * Y_{H_2,fuel} + Y_{O_2,air})$, where $\gamma = \frac{1}{2}\frac{WT_{O_2}}{WT_{H_2}}$, and the scalar dissipation rate, $\chi = (\lambda/(\rho \cdot C_p))(dZ/dx)^2$. The effect of the increased local strain rate in this case is opposite to the effect of curvature and preferential diffusion, the first tends to weaken the flame, the latter to intensify it. Thus, it is probable that extinction occurs in the annular region away from the axis where the strengthening effect of preferential diffusion and curvature is less prominent and is overcome by the high local strain rate. This explanation of Katta's observation, however, requires that the local strain rate greatly exceeds the critical value. The role of preferential diffusion and curvature is further demonstrated by the second simulation which shows that when the vortex is placed on the fuel side, thereby producing a flame curvature of opposite orientation, the flame is extinguished locally.

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