Extinction Behavior of either Gaseous or Spray Counterflow Diffusion Flames Interacting with a Laminar Toroidal Vortex

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Key Words: Vortex, Diffusion Flame, Counterflow, Spray

Introduction

The interaction of a laminar vortex with a flame offers a scenario that is intermediate in complexity between laminar flames and turbulent ones. Specifically, effects of time-dependence and curvature can be studied in a well-controlled environment and shed light on phenomena that are relevant to turbulent flames. In this study the interaction of a toroidal vortex and laminar counterflow diffusion flames was examined experimentally. A similar configuration was the object of recent experimental and numerical investigations in gaseous diffusion flames [1-3]. The present emphasis is on the quantitative characterization of the extinction behavior under conditions in which the fuel was admitted either as vapor or as a fine spray of droplets.

Experimental Methods

An axisymmetric counterflow diffusion flame was established in a vertical configuration, with the oxidizer being fed from one side, methanol and inert from the other, as shown in Fig. 1. The liquid was dispersed using a commercial ultrasonic nebulizer. This device can atomize modest liquid flow-rates, imparting a small velocity to the liquid drops and maintaining the relative standard to values below 0.4. Both sides of the burner terminated in a contraction, contoured following a well-established wind tunnel design practice, that optimized the uniformity of the axial velocity in the radial direction. The exit diameter of the two nozzles was 12.5 mm and the separation distance between them was kept constant at 12 mm. The steady flame was perturbed by periodically-generated laminar toroidal vortices from the oxidizer side. A suitably-synthesized voltage function was applied across the loudspeaker, causing the latter to force air through a 1.5 mm tube impulsively, similarly to [4].

The vortices were visualized using planar light scattering of submicron TiO_2 particles, produced by hydrolysis of $TiCl_4$. To monitor the flame dynamics under vortex excitation, formaldehyde planar induced fluorescence was used as a *complementary* marker of the flame. In fact, calculations under steady state conditions, using a numerical code [5] with detailed kinetics and transport, indicated that, for both gaseous and spray methanol flames, the peak of heat release corresponds to the location where the formaldehyde concentration precipitously drops. Consequently, the third harmonic of a Nd:YAG laser, 355 nm and 120 mJ/pulse of energy, was used to excite the 4_0^1 transition in the $\tilde{A}^1A_2 \leftarrow \tilde{X}^1A_1$ band of CH_2O, as in [6]. The resulting signal was detected using a gated single stage image intensifier coupled to a CCD (Santa Barbara Instrument Group ST6B). A narrow interference filter at 415 nm with a half-width of 7 nm was used to reject flame luminescence and other interference. This instantaneous diagnostic technique, when synchronized with respect to the vortex generation using a variable time delay, allowed for the monitoring of the evolution of the interaction of vortex and flame. These diagnostic techniques were complemented by single-point phase-locked LDV measurements to monitor the instantaneous strain rate on the flame centerline.

Initially, two flames, one gaseous and the other a spray flame, were studied in detail. The boundary conditions were the same for both flames, namely: the fuel mass fraction on the fuel side was Y_F=0.72; the oxygen mass fraction on the oxidizer side was Y_{O2}=1; fuel, oxygen and inert flow rates flow rates were kept at 2 g/min, 2.65 l/min and 4.7 l/min, respectively, and helium was used as inert. These two base-case flames were then perturbed by a vortex intense enough to induce local extinction. Subsequently, a wider range of either gaseous or spray flames was examined in which Y_F and the base-case strain rate were kept constant, while Y_{O2} was varied. For each flame stoichiometry, extinction was induced either under quasi-steady state conditions, by replacing part of the oxidizer with inert, or by vortex interaction, by varying the strength of the vortex generated up to the onset of local extinction.

Results and Discussion

Under vortex excitation, localized wrinkling in the vicinity of the centerline was observed, which, for sufficiently strong vortices, yielded *local* extinction, with the development of a "hole" in the middle of the flame. After passage of the vortex, the now annular flame closed in and re-established a flat and uniform diffusion flame. This behavior was observed in both gaseous and spray flames, as shown by PLIF images.

Flame strain rates were measured along the centerline of the burner using a single-point phase-locked LDV technique. A sample of the phase-averaged measurements at two axial locations is shown in Fig. 2 for the gaseous flame as a function of time measured from the generation of the voltage pulse to the loudspeaker. To evaluate the strain rate, the velocity measurements were plotted at fixed times as a function of the axial coordinate, as shown in Fig. 3 for the case of the gaseous flame, and the strain rate was calculated as the local derivative, $\partial v / \partial z$, at the flame. In Fig. 4, the evolution of the strain rate in time is reported for both flames, the maximum being defined as the extinction strain rate.

This procedure was repeated for a wider range of flames, in which Y_{O2} was varied. The results are summarized in Fig. 4. Also shown in that figure are the results for the “quasi-steady” extinction that was obtained by increasing the mass flux from both sides slowly, until extinction was observed. Two main observations emerge: first, there is a remarkable difference between the “quasi-steady” extinction strain rate and the vortex-induced one; second, strain rates at extinction are consistently larger for a gaseous flame as compared to the spray counterpart. The first observation can be partly rationalized as follows. The vortex introduces an unsteady effect in the outer diffusive-convective layer, while the inner reactive-diffusive layer behaves in a “quasi-steady” manner, since the characteristic chemical time is much smaller than the characteristic unsteady time. As a result, even though the instantaneous strain rate is much larger than the “quasi-steady” extinction strain rate, the flame is subject to a damped strain rate through the outer layer. The second observation can be partly explained because of the extra energy needed in the vaporization process of the liquid fuel, that results in a smaller reduced Damkohler number for the spray flame by a factor depending on the ratio of the heat of vaporization to the heat of combustion [7].

A noticeable difference was observed between gaseous and spray flames in the time between the onset of local extinction and the complete reconstitution of the flame, that is when the extinction hole was closed. For example, for the initially studied two flames, Δt= 26 ms for the spray flame, as compared to Δt= 11 ms for the gaseous one. This difference is attributed to droplet inertia, as estimates of the relevant Stokes number suggest. The vortex, after penetrating the flame and entering the fuel side, centrifuges the droplets away from the centerline, reducing the amount of fuel supplied locally to the reaction zone, and retarding the re-establishment of the appropriate triple flame propagation conditions as compared to the gaseous flame counterpart.

Acknowledgments

The support of NASA, under the Microgravity Science and Applications Program, Grant # NAG3- 1688 (Mr. Dennis Stocker, Grant Monitor) and NSF, through a NSF Young Investigator Award, is gratefully acknowledged.

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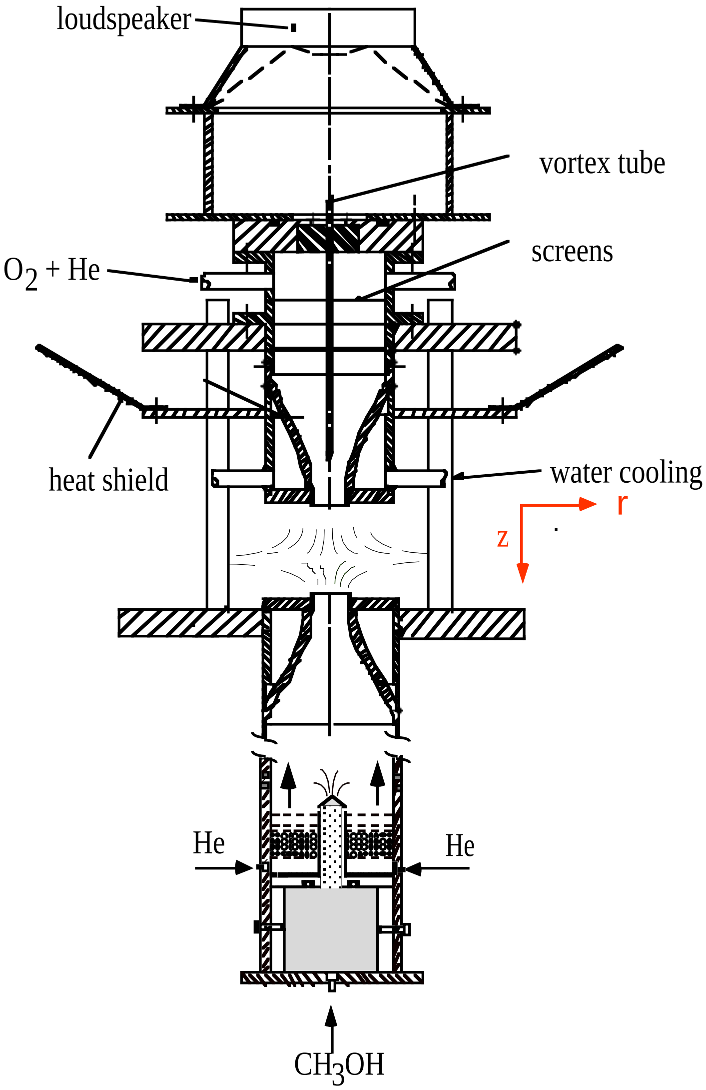

Fig. 1: Experimental apparatus

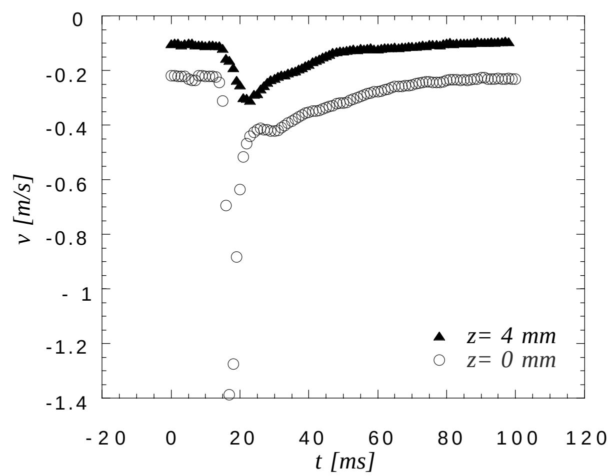

Fig. 2: Phase-averaged gas velocity as a function of ti
at two axial locations

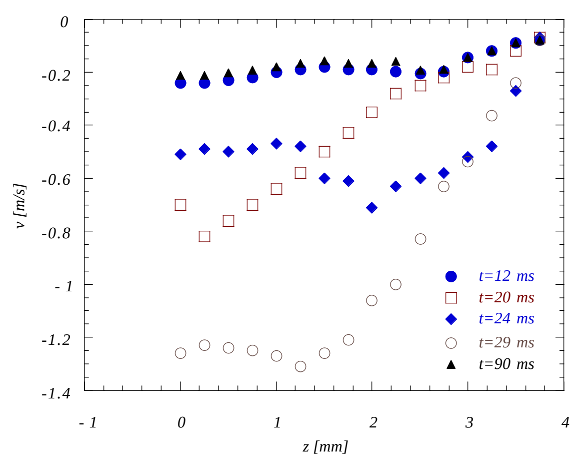

Fig. 3: Velocity plotted as a function of the axial
coordinate at selected times

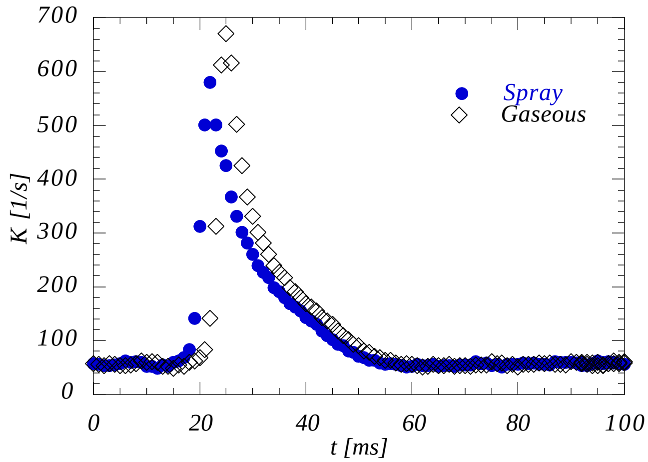

Fig. 4: Strain rate evolution at the flame for both gaseous and spray flames

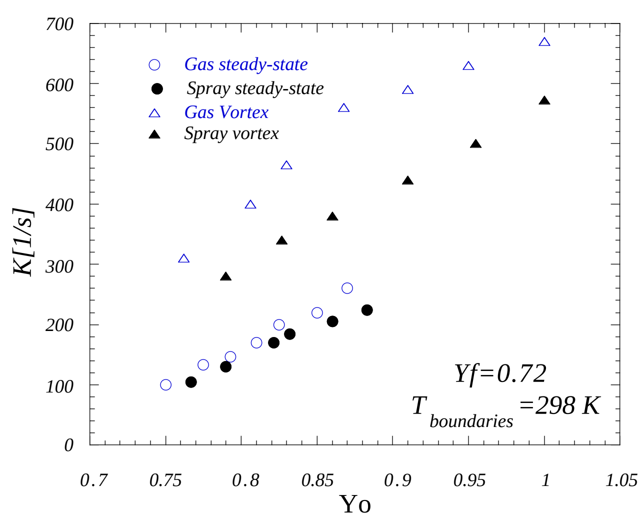

Fig. 5: Extinction strain rates under steady state and vortex-induced conditions for both gaseous and spray flames