Vortex Injection of Noble Gases in an Opposed-Jet Burner

G. J. Fiechtner,[1,2] J. R. Gord,[1] C.D. Carter,[1,2] K. D. Grinstead, Jr.,[1,2] V. R. Katta,[1,2] P.-H. Renard,[3] and J. C. Rolon[3]

[1]Air Force Research Laboratory, Propulsion Directorate,
Wright-Patterson Air Force Base, OH 45433-7103, USA.
[2]Present Address: Innovative Scientific Solutions, Inc., 2766 Indian Ripple Road, Dayton, OH 45440-3638, USA. G.J.F. Contact E-Mail: gjfiech@ward.appl.wpafb.af.mil, Tel: (937) 255-8373.
[2]Laboratoire d'Énergétique Moléculaire et Macroscopique, Combustion, École Centrale Paris and CNRS, Grande Voie des Vignes, 92295 Châtenay-Malabry Cedex, France.

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1. Introduction

Numerical modeling and experimental measurements of reacting flows have led to important advances in the understanding of combustion. Numerous investigations, including those on the interaction of a laminar flame and a vortex, have contributed to these advances. The resulting data are useful in a variety of applications such as the identification of fundamental regimes of vortex-flame interactions.[1] Vortical structures are an important feature in unsteady and turbulent combustion, and experimental data can be used to develop models for use in practical combustion areas such as experimental gas turbine combustors. Using a burner developed at École Centrale Paris and CNRS, we recently performed a series of studies in which numerical predictions[2] were later validated using measurements of flame extinction in a nonpremixed hydrogen/air flame by an air-filled vortex.[3] The recent ban on the manufacture of halon has led to the need for alternative fire suppressants. In this study, we explore the possibility of extending vortex-flame extinction studies to basic research in fire-suppression dynamics. A valve-switching mechanism is demonstrated for filling a vortex with a fluid. Synchronization of the filled-vortex injector with laser diagnostics is then demonstrated. In the preliminary results presented here, local flame extinction is promoted with a helium-filled vortex. We propose that carefully-controlled vortex-flame experiments and modelling can be a useful tool in the search for Halon replacements.

2. Background

The search for replacements for bromine-containing fluorocarbons has resulted in intense research. These studies[4] have addressed the effect of halon replacements on global parameters such as burning velocity, HF and CF_2O production, extinction strain rate, flame temperature, and species concentration profiles (see, for example, Reference 4 and the references therein). During past development of combustion codes for gas turbine combustor modelling, experimental studies of vortex-flame interactions have been of great benefit.[5] Similar benefit may result from vortex-flame studies when applied to the problem of fire suppression. Numerous experimental studies of the interaction dynamics of vortices and flames have been conducted. For premixed flame fronts, most measurements have been made using two types of flames. Hertzberg et al.[6] and Escudie[7] conducted an experiment in which a Karman vortex street was produced using a cylindrical rod in a cross flow of premixed gases. A V-flame was supported behind a wire positioned downstream of the rod that produced the vortex street. Planar tomographic imaging was used to study the interaction of the vortex street and the flame. A similar interaction of a Karman vortex street and a flame was investigated by Lee et al.[8] using PLIF imaging of OH and by Nye et al.[9] using both OH PLIF and PIV. A disadvantage of using the vortex street is the difficulty in isolating a single vortex. Samaniego[10,11] developed a means of injecting an isolated line vortex through a horizontal slot in the wall of a vertical wind tunnel and presented results on the interaction of a line vortex and a V-flame. Schlieren images of the time-dependent vortex-flame interaction along with CH emission data from the entire flame were presented. Paul and coworkers[12-14] studied vortex-flame interactions using the Samaniego burner; PLIF measurements of OH and CH radicals were reported initially, and quantities such as heat release were presented during later studies.

In a second type of study involving premixed combustion, Jarosinski et al.[15] studied a flame that was ignited at one end of a tube of premixed gases. A vortex was injected at the other end of the tube. The interaction dynamics were then photographed using a mercury-xenon arc lamp and a rotating-drum streak camera with a rotating-disc shutter. Recently, Driscoll and co-workers produced an impressive series of papers concerning a similar vortex-flame facility in which PIV, OH PLIF, or a combination of these imaging techniques was applied (see Driscoll et al.,[16] Mueller et al.,[17] Sinibaldi et al.,[18] and the references therein).

Nonpremixed flames have also been the subject of experimental study. Rolon and co-workers (see Renard et al.,[19] Thevenin et al.,[20] and the references therein) recently developed an apparatus in which a vortex was injected into a flame supported between the nozzles of an opposed-jet burner. Takagi and coworkers[21,22] performed planar Rayleigh-scattering measurements of temperature on a similar type of opposed-jet burner in which a small jet of fuel or air was injected using a micro-nozzle with an inner diameter of only 0.25 mm. Either a jet of air was injected from the air side of the diffusion flame or a jet of fuel was injected from the fuel side. Chen and Dahm[23] developed a facility for generating a nonpremixed burning layer that wraps into a vortex ring. The facility permits experiments to be performed under conditions of both normal gravity and microgravity, allowing the study of the influence of buoyancy.

3. Apparatus and Procedure

The opposed-jet burner used in these experiments has been described elsewhere.[3] The flame is supported between upper and lower nozzles that are separated by 40 mm, each with an exit diameter of 25 mm. The fuel consists of hydrogen diluted with nitrogen and flows from the upper nozzle. Air flows from the lower nozzle. Unique to this type of apparatus is a tube with ~2-mm inner diameter that is installed concentrically within the lower nozzle. This tube is attached to a cylinder that contains a piston which, in turn, is attached to an actuator. Feeding an appropriate current to the actuator causes a solenoid to force the piston upward abruptly, resulting in the emergence of a vortex from the tube. The vortex travels upward within the surrounding oxidizer flow. As configured during past experiments, a flow of air is supplied to the vortex tube such that, in the absence of a vortex, the exit velocity matches the velocity of the air from the surrounding nozzle. The air supply has been modified for the present experiments by inserting two three-way valves—one connected to the air supply and the other connected to the helium supply. For filling a vortex with helium, the vortex piston is moved to its farthest position from the flame, at which time the currents supplied to the two three-way valves are reversed. The air valve switches to vent air to the fume hood, and the helium valve switches to provide a flow of helium to the vortex nozzle. When the desired amount of helium has been delivered, the solenoid currents are again reversed such that the air valve admits air to the vortex nozzle and helium is vented to the fume hood. At this instant, upward motion of the vortex piston is initiated, forcing a vortex into the opposed-jet burner. To minimize the impact of room-air disturbances, upper and lower guard flows of nitrogen are supported through outer nozzles, which are concentric with the respective upper and lower inner nozzles that support the flame.

PLIF measurements are accomplished by exciting hydroxyl radicals at 281.3414 nm via the $R_1(8)$ transition of the (1,0) band in the A-X system. Fluorescence from the A-X (1,1) and (0,0) bands is detected at right angles using WG-295 and UG-11 colored-glass filters, a 105-mm-focal-length f/4.5 UV lens, an image intensifier, and CCD pixels that are binned in 2x2 groups, resulting in an imaged area of 25.6 x 38.4 mm^2. The bottom of the image is 0.25-mm above the surface of the lower nozzle. A color table is used, with a maximum value set to 120% of the maximum signal for the flame condition in which a vortex is not injected. The low-signal color is assigned by calculating the background noise and selecting a minimum value that is two standard deviations above this level. Therefore, in cases where "extinction" of the OH layer is observed, "extinction" refers to signal levels that fall below this minimum value and are, therefore, assigned the last color in the table. All images represent the signal collected during a single laser shot, and no smoothing of the resulting images is attempted.

4. Results and Discussion

The PLIF images of OH shown in Figure 1 correspond to an air-filled vortex that interacts with the hydrogen-air flame. An effective temporal delay of 1 ms is used between images. "Extinction" of the OH layer is absent. Initially, the vortex creates a small dent in the flame, and this dent begins to grow. In the later interaction stages, the OH PLIF signal level is observed to increase by more than a factor of five over the levels observed without a vortex.

The images of Figure 2 are taken under experimental conditions identical to those for the images of Figure 1, except that the vortex is filled with helium. Local extinction of the OH layer takes place at a point on the top surface of the vortex. After extinction, the vortex travels upward toward the other nozzle through the hole created in the flame. The flame then burns back behind the vortex and closes the hole.

While acquiring the data in Figures 1 and 2, simultaneous images were captured using Rayleigh scattering. Rayleigh scattering can be used to compute the temperature in the vicinity of the flame; this temperature is needed to place OH images on a quantitative basis.[3] In addition, the helium vortex entrains surrounding air before

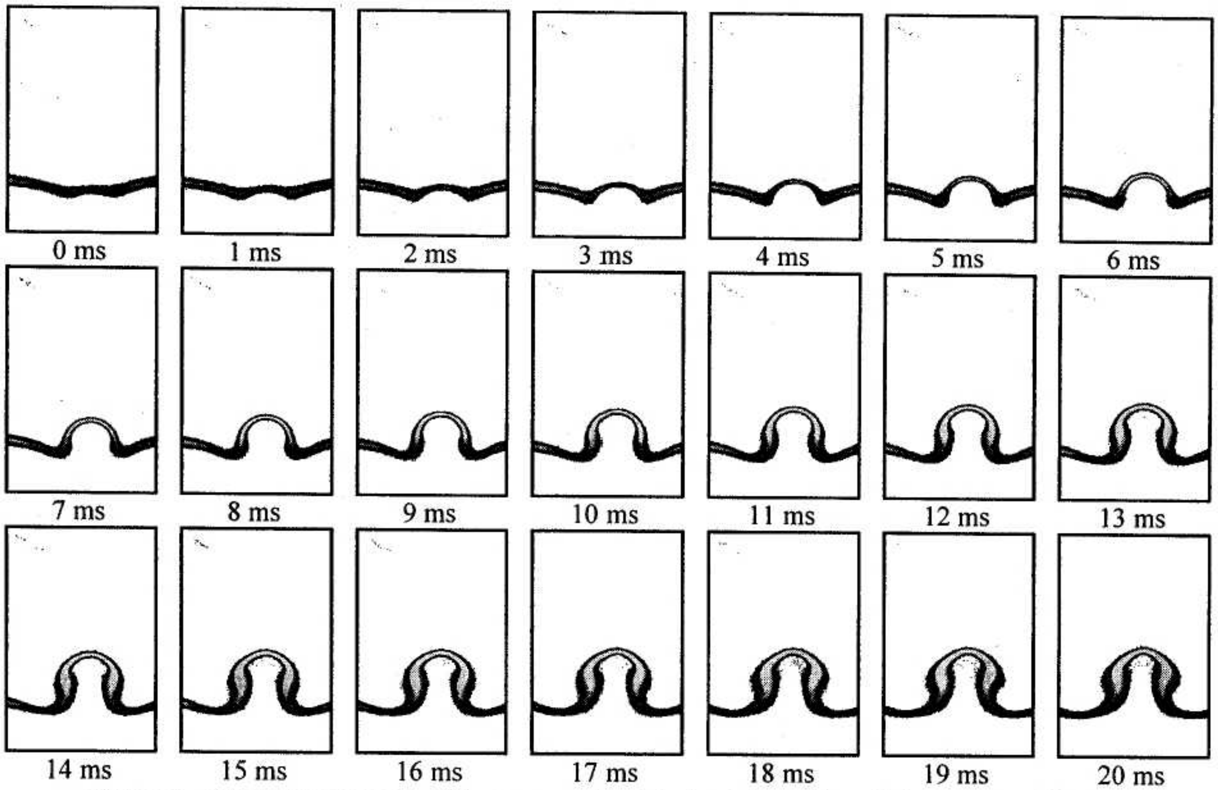

Figure 1. Temporal sequence of images acquired during interaction of air vortex and flame.

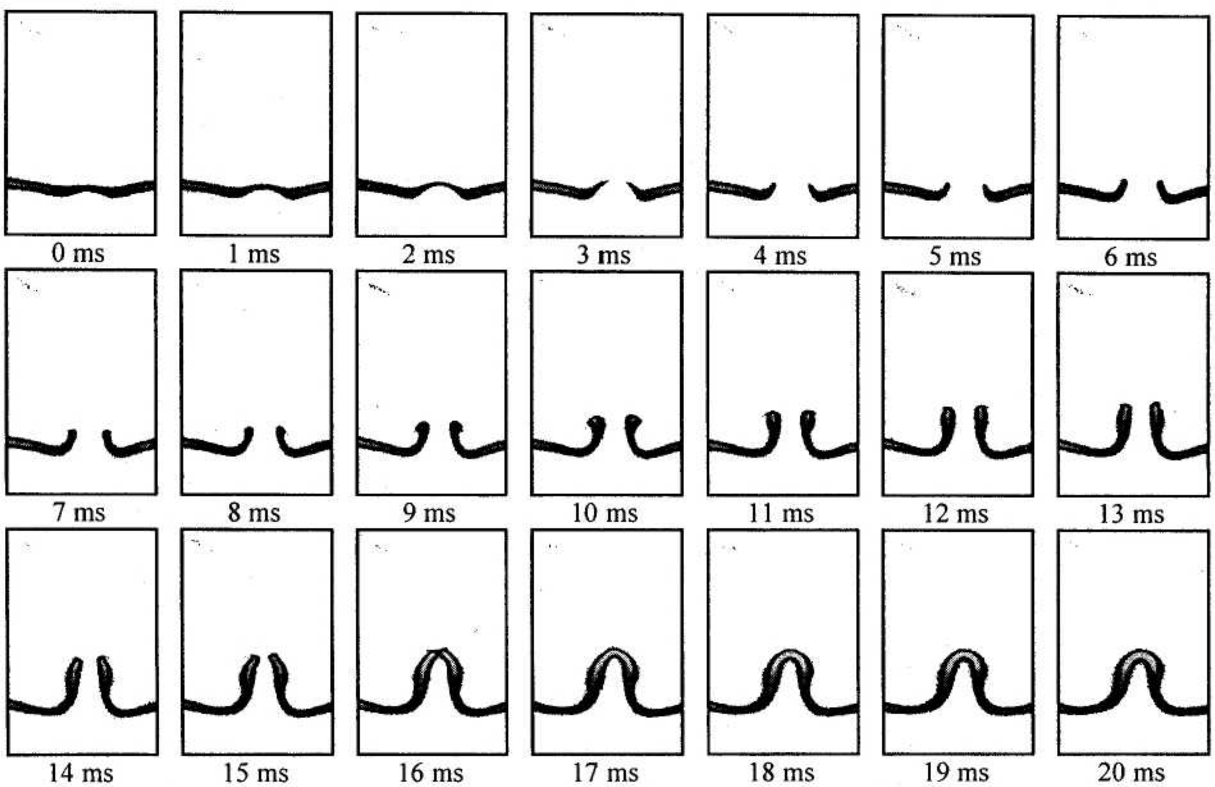

Figure 2. Temporal sequence of images acquired during interaction of helium-air vortex and flame.

reaching the flame, and Rayleigh scattering can be used to estimate the concentration of helium in the vortex. Future studies will utilize hydrocarbon fuels, and more realistic suppressants will be used to fill vortices.

5. Conclusions

The apparatus of Rolon and co-workers[1,20] has been used to study the interaction of a vortex and a flame using PLIF measurements of OH. The process of filling the vortex has been demonstrated to be highly repeatable. A preliminary experiment has been completed in which a helium-air vortex extinguished a hydrogen-air flame locally at a point. An analogous vortex filled exclusively with air does not extinguish of the flame.

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