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Injection of Single and Multiple Vortices in an Opposed-Jet Burner

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Abstract**:** A thorough understanding of turbulent reacting flows is essential to the continued development of practical combustion systems. Combustor codes can be validated using data such as those generated in this study of a vortex interacting with a nonpremixed, opposed-jet hydrogen-air flame. When experimental results are compared with model predictions, the underlying flowfield must be matched carefully. Since the vortex-injection process used in the present experiments can result in many types of vortices, including multiple vortices, restrictions on the experimental operation of the burner are required as well as careful vortex characterization. Vortex-characterization data are acquired using digital, two-color particle-image velocimetry (PIV), and the hydroxyl (OH) layer produced by the flame is imaged using planar laser-induced fluorescence (PLIF). The PIV and OH PLIF measurements are performed simultaneously. Good agreement with previous numerical-modeling predictions is obtained when experiments and computations are performed using similar vortex conditions.

Keywords**:** visualization, turbulence, vortex, flamelet, PLIF, PIV.

1. Introduction

Recent predictions from numerical modeling combined with results of experimental measurements have led to important advances in the understanding of combustion. Numerous investigations have contributed to these advances, including a particular type of study in which the interaction of a laminar nonpremixed flame and a vortex is examined. The resulting data can be used for a variety of purposes such as identifying fundamental regimes of vortex-flame interactions (Renard et al., 1999). Vortical structures play an important role in unsteady and turbulent combustion (Takahashi et al., 1996; Roquemore and Katta, 1998; Roquemore and Katta, 1999), and experimental data from studies of these structures can be used to develop models for application to practical combustion devices such as experimental gas-turbine combustors (Roquemore et al., 1991; Durbin et al., 1996; Katta and Roquemore, 1997; Katta and Roquemore, 1998; Hsu et al., 1999).

In recent numerical calculations, Katta predicted that during the interaction of a nonpremixed hydrogen-air flame and an isolated vortex, the extinction of the OH layer would occur in an annular pattern (Katta et al., 1998a). Later experimental results confirmed this computational prediction (Katta et al., 1998a; Fiechtner et al., 1998; Fiechtner et al., 1999). Agreement of experimental and computational results relies on careful matching of the underlying flowfields of the techniques. Because the vortex-injection process used in the present study can result in many types of vortices, including multiple vortices, careful vortex characterization is necessary. This is accomplished by seeding particles into the flowfield and detecting the scattered light during digital, two-color particle-image velocimetry (PIV) measurements. Digital PIV measurements are made simultaneously with planar laser-induced fluorescence (PLIF) measurements of the hydroxyl radical (OH), which is formed during combustion in a nonpremixed, hydrogen-air opposed-jet burner. Good agreement with previous computational-modeling predictions is obtained when vortex conditions are matched.

2. Background

The experiments described in this paper concern vortex-flame interactions, and the importance of the vortex-injection process is emphasized; therefore, a review of vortex-flame studies is presented, followed by a review of vortex-formation measurements.

2.1 Vortex-flame Experiments

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 experimental configurations: V-flames can be supported behind a wire, or flames can be propagated inside a cylinder. A variety of vortex-injection methods can be applied. In one case, a Karman vortex street was produced using a cylindrical rod in a cross flow of premixed gases (Hertzberg et al., 1984; Escudie, 1988), and the resulting vortices interacted with a V-flame. 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 using PLIF imaging of OH (Lee et al., 1993) and using both OH PLIF and PIV (Nye et al., 1996). A disadvantage of using the vortex street is the difficulty in isolating a single vortex. To replace the vortex street in experiments with V-flames, a means of injecting an isolated line vortex through a horizontal slot in the wall of a vertical wind tunnel was developed (Samaniego, 1992a). A year later, schlieren images of the time-dependent vortex-flame interaction along with CH emission data from the entire V-flame were presented (Samaniego, 1992b). Paul and co-workers also studied vortex-flame interactions using the Samaniego burner, initially reporting results of PLIF measurements of OH and CH radicals (Nguyen and Paul, 1996), with more recent results including images of quantities such as heat release (Najm et al., 1998; Paul and Najm, 1998).

In a second configuration involving premixed combustion, a flame was ignited at one end of a tube of premixed gases, and a vortex was injected at the other end of the tube (Jarosinski et al., 1988). The vortex-flame interaction was 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 (Roberts and Driscoll, 1991; Roberts et al., 1992; Roberts et al., 1993; Driscoll et al., 1994; Mueller et al., 1995; Mueller et al., 1996; Mueller et al., 1998; Sinibaldi et al., 1998a; Sinibaldi et al., 1998b).

Nonpremixed flames have also been the subject of experimental study. Rolon and co-workers (Rolon et al., 1995; Thevenin et al., 1996; Renard et al., 1998; Thevenin et al., 1998; Renard et al., 1999) developed an apparatus in which a vortex is injected into a flame supported between the nozzles of an opposed-jet burner. This geometry has numerous advantages. First, a stationary nonpremixed flame can be produced and isolated easily, which is not possible with the above geometries. Second, the flame thickness can be varied by changing either the nozzle velocities or the spacing between the upper- and lower-burner nozzles. The device has also been extended to the study of vortices that interact with premixed opposed-jet flames (Renard et al., 1998). Takagi and co-workers (Takagi et al., 1996; Yoshida and Takagi, 1998) performed planar Rayleigh-scattering measurements of temperature in 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. Santoro and co-workers modified a vortex counterflow burner to permit the study of spray flames (Santoro et al., 1999).

In a different class of measurements, Hsu and co-workers modulated the axial velocity of a laminar jet diffusion flame using a loud speaker to produce vortex-flame interactions (Hsu et al., 1993; Katta et al., 1998b). Additional studies were performed with this apparatus using a number of techniques including reactive Mie scattering, PLIF, and digital PIV (Hancock et al., 1996). In a similar type of study, OH PLIF measurements were performed in a Wolfhard-Parker slot burner that was forced acoustically by loud speakers on the side walls of the upstream fuel duct (Mueller and Schefer, 1998). PLIF imaging of acetone was used as a marker for the fuel.

A facility was developed recently for generating a nonpremixed burning layer that wraps into a vortex ring (Chen and Dahm, 1998). The facility has been operated under conditions of both normal gravity and microgravity, allowing the study of the influence of buoyancy. In contrast, a facility has been developed in which the vortex is ignited just as the fluid begins to exit a tube (You et al., 1998). The experiments described in the present paper are based on the counterflow geometry of Rolon and co-workers (Rolon et al., 1995; Thevenin et al., 1996; Renard et al., 1998; Thevenin et al., 1998; Renard et al., 1999).

2.2 Vortex-production Process

Vortex formation has been the subject of intense study for many years (Magarvey and MacLatchy, 1964; Widnall, 1975; Maxworthy, 1977; Pullin, 1979; Didden, 1979; Glezer, 1988; Glezer and Coles, 1990; Southerland et al., 1991; Saffman, 1992; Shariff and Leonard, 1992; Nitsche and Krasny, 1994; Nitsche, 1996; Weigand and Gharib, 1997; Fabris and Leipmann, 1997; Heeg and Riley, 1997); thus, a large amount of information is available for analyzing the results of the present experiments. The mechanism used to create vortices during the present experiments relies on a piston/cylinder with stroke length L attached to a nozzle with diameter D. The maximum circulation which a vortex ring can attain is reached for a formation number, L/D, of ~ 4; additional trailing vortex rings form for larger ratios (Gharib et al., 1998). Use of larger formation numbers results in the formation of a starting jet (Garside et al., 1943; Rizk, 1958; Abramovich and Solan, 1973; Yaros, 1977; List, 1982; Witze, 1983; Kuo et al., 1986; Cattolica and Vosen, 1987; Brombacher, 1997; Johari et al., 1997; Hill and Ouellette, 1999). The vortex-formation process is illustrated in Fig. 1. In Frame 1 a slug of fluid begins to exit the tube, while in Frame 2 the vortex begins to form. After Frame 2 one of two paths is followed, depending on the motion of the piston. If the piston is stopped after a comparatively small value of the formation number (Path A), the vortex pinches off as it travels upward, as illustrated in Frames 3A and 4A of Fig. 1. This case has been reported numerous times in the literature (Magarvey and MacLatchy, 1964; Widnall, 1975; Maxworthy, 1977; Pullin, 1979; Didden, 1979; Glezer, 1988; Glezer and Coles, 1990; Southerland et al., 1991; Saffman, 1992; Shariff and Leonard, 1992; Nitsche and Krasny, 1994; Nitsche, 1996; Weigand and Gharib, 1997; Fabris and Leipmann, 1997; Heeg and Riley, 1997). The trailing fluid is entrained into the vortex during the pinch-off process (Gharib et al., 1998), resulting in a "bubble" defined by leading and trailing stagnation points (James and Mandia, 1996). The pinch-off process can require up to two formation numbers for completion (Gharib et al., 1998).

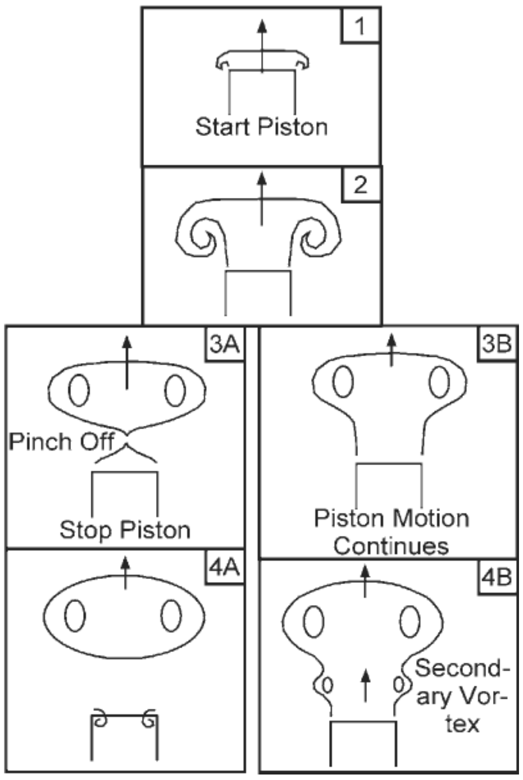

Fig. 1. Schematic diagram of vortex-formation processes.

If the piston motion is allowed to continue (Path B), the developing vortex travels initially above a column of fluid, as shown in Frame 3B. If the piston motion continues, multiple vortices can be produced from the tube, as illustrated in Frame 4B of Fig. 1 (Auerbach, 1991; Gharib et al., 1998). The trailing vortex may eventually overtake the leading vortex, resulting in the interaction of two coaxial vortices. Additional vortices can also interact with the leading vortex. Interactions of multiple coaxial vortices have received considerable attention in the literature (Oshima et al., 1975; Yamada and Matsui, 1978; Maxworthy, 1979; Yamada and Matsui, 1979a; Yamada and Matsui, 1979b; Oshima et al., 1986; Shariff and Leonard, 1992; Riley, 1993; Weidman and Riley, 1993; Leung et al., 1996; Konstantinov, 1997; Lim, 1997; Leung et al., 1997).

3. Apparatus and Procedure

3.1 Burner Facility

A photograph of the opposed-jet burner can be found in the literature (Gord et al., 1998; Renard et al., 1999; Fiechtner et al., 1999). The flame is supported between upper and lower nozzles 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 5-mm inner diameter that is installed concentrically within the lower nozzle. This tube is attached to a cylinder containing a piston that, in turn, is attached to an actuator. When an appropriate current is delivered to the actuator, a solenoid forces the piston upward abruptly, resulting in the emergence of a vortex from the tube. In the present study, vortices are generated using a 10-ms piston risetime.

Studies comparing vortex production via nozzles and orifices have revealed subtle differences in parameters such as vortex size (James and Mandia, 1996); this must be considered when comparing the results of the present study with those obtained during experiments in which vortices are generated using orifices (Roberts and Driscoll, 1991; Roberts et al., 1992; Roberts et al., 1993). When vortices are characterized fully, such concerns are minimized. The volume that a vortex can contain based on the diameter of our nozzle is ~ 0.4 cm^3 (Gharib et al., 1998). Our vortex generator can sweep a maximum volume of ~ 3 cm^3, for a maximum attainable formation number of ~ 30. The condition illustrated in Frame 3B of Fig. 1 was chosen in our experiments to match the vortices used in the computations of Katta (Roquemore and Katta, 1998; Roquemore and Katta, 1999; Katta and Roquemore, 1999). An example of such a vortex is shown in Fig. 2, where the numerically computed vortex is observed to travel above a column of fluid. Numerical routines that rely on an artificially created vortex pair by specifying the vortex field (Poinsot et al., 1987; Rutland and Ferziger, 1991; Ashurst, 1993) may not model our experimental conditions properly. It is also possible for vortices that are initially laminar to become unsteady and turbulent (Widnall, 1975; Glezer and Coles, 1990; Shariff and Leonard, 1992; You et al., 1998) – conditions that are avoided in the present study. In addition, if the piston/cylinder is not aligned and lubricated properly, an undesired turbulent puff of fluid may exit the tube.

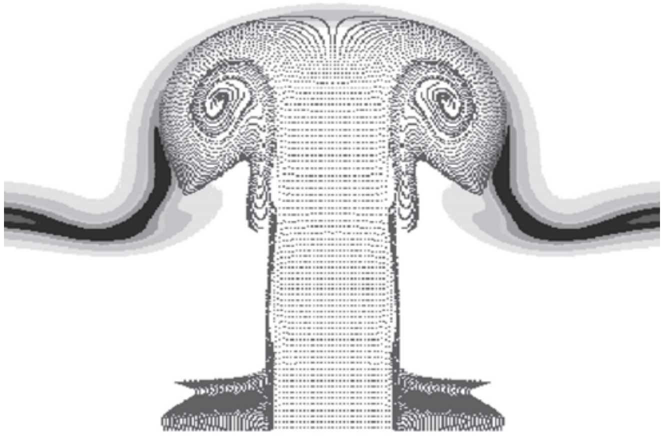

Fig. 2. Example of numerically computed vortex interacting with laminar flame.

The laminar vortices travel upward within the surrounding oxidizer flow. 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. To minimize the impact of room-air disturbances, upper and lower guard flows of nitrogen are supported through outer nozzles that are concentric with the respective upper and lower inner nozzles supporting the flame. The hydrogen, nitrogen-diluent, and oxidizer-air flows are furnished by mass-flow controllers with respective full-scale ranges of 20, 20, and 30 *l*/min. A continuous flow of air is provided to the vortex tube by a 5-*l*/min controller, while the guard flows for the upper and lower guard (outer) nozzles are furnished by two 50-*l*/min mass-flow controllers. The flow rates of the controllers are accurate to ±1% of the full-scale range.

Hollow ceramic seed particles with an approximate mean diameter of 2.4 μm are introduced into the burner flows when digital PIV measurements of the vortex velocity are performed. Three particle seeders are installed – one placed after the air mass-flow controller, another after the vortex-air mass flow controller, and a third after the junction where the hydrogen and nitrogen gases are mixed.

3.2 Laser Diagnostics

The PLIF system includes a frequency-doubled, Q-switched Nd:YAG laser that is used to pump a dye laser which, in turn, is frequency doubled. The UV radiation is directed through a telescope that is adjusted to produce a light sheet with a height that matches as nearly as possible the 40-mm burner separation. The resulting beam thickness is ~ 300 μm, which corresponds to the full width (defined as the distance between the locations of the 25% peak-intensity points).

Hydroxyl radicals absorb the laser radiation 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 through WG-295 and UG-11 colored-glass filters using a 105-mm-focal-length f/4.5 UV lens. The resulting light is recorded on an intensified CCD camera with an intensifier gate width of 100 ns. CCD pixels are binned in 2×2 groups, resulting in an effective array size of 288×192 pixels with an imaged area of 25.6×38.4 mm^2. The bottom of the image rests immediately above the surface of the lower nozzle. A color table is used with a maximum value set to 95% of the maximum signal for all images taken at a given flame condition. The low-signal color is assigned by calculating the background noise and selecting a minimum value that is two standard deviations above this level.

Measurements of the velocity field are carried out using digital, two-color PIV (Gogineni et al., 1998a; Gogineni et al., 1998b). Here, a color digital CCD with an array of 3060×2036 pixels is used. A magnification of 78,368 pixels/m is employed, resulting in an imaged area of 26.0×39.0 mm^2. The color CCD camera and the intensified CCD array are aligned using a transparent mask printed with a graduated scale. Two lasers are used; one PIV light sheet is produced by doubling the output of a Q-switched Nd:YAG laser (30 mJ/pulse at the test section). The remainder of this beam is used to pump the dye laser that is frequency doubled to excite OH fluorescence. The second PIV light sheet is produced by pumping a dye laser (employing DCM laser dye) with a second frequency-doubled, Q-switched Nd:YAG laser, resulting in laser radiation at 640 nm (40 mJ/pulse at the test section). The thickness of both the red and green light sheets is set to ~ 700 μm at the probe region. A digital delay generator is used to drive the timing of the two lasers such that the red pulses are delayed precisely with respect to the green ones. Velocity vectors are calculated using correlation software (Gogineni et al., 1998a). A correlation area of 128×128 pixels is used in the calculation, corresponding to a correlation area of 0.269 cm^2 and a spatial resolution of 1.6 mm. Digital PIV measurements are applied to obtain the propagation velocity of the primary vortex, and this correlation area is acceptable for such purposes.

3.3 Synchronization and Timing

For the present experiments, precise synchronization of several experimental events is required, including vortex generation and propagation, production of laser pulses, and activation of the camera shutter or intensifier. As described in previous papers (Fiechtner et al., 1998; Gord et al., 1998; Fiechtner et al., 1999), lasers, cameras, and the vortex injector are synchronized electronically with an effective temporal jitter of ~10 ns. This electronic jitter is much smaller than the fastest event probed to date, which occurs on an ~ 10-μs time scale. Temporally resolved data are acquired utilizing the following phase-locked timing sequence: 1) an image is recorded, 2) the delay between vortex production and laser/camera events is adjusted, and 3) another vortex is initiated and a second image recorded.

This process is repeated to acquire numerous images at increasing delays, and an animation is created by assembling the individual images in temporal order. The burner facility results in highly reproducible events, even at delays as short as 10 µs.

4. Results and Discussion

Simultaneous and superimposed images of the OH PLIF signal and the PIV velocity field are shown in Fig. 3. The annular break of the OH layer corresponds closely to that predicted during previous numerical computations (Katta et al., 1998a).

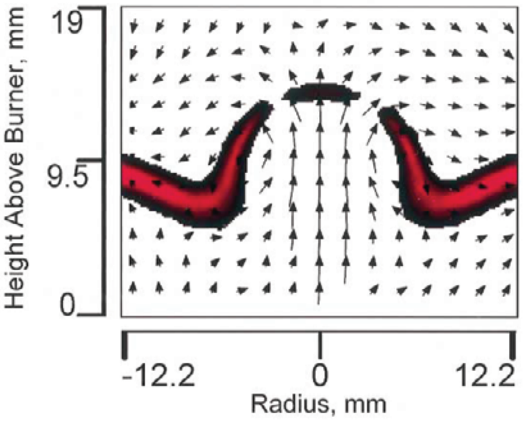

Fig. 3. OH PLIF image and superimposed velocity field demonstrating annular extinction of OH layer. OH PLIF image and digital PIV data are acquired simultaneously. Vortex propagates upward at velocity of 4.2 m/s.

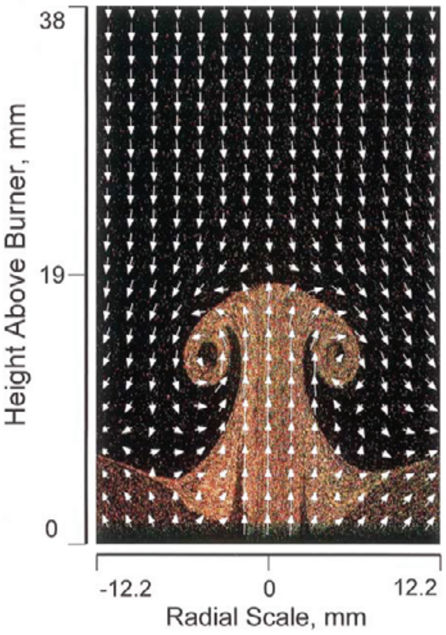

Fig. 4. Vortex injected into cold flow. Vortex propagates upward at velocity of 1.5 m/s.

The scattering image of Fig. 4 was obtained when the vortex-tube flow was seeded with a slightly higher particle density than that produced by the upper and lower burners. As shown, the "mushroom" vortex advances ahead of a column of fluid because the piston continues to push fluid from the vortex nozzle. The scattering image of Fig. 4 was acquired in a cold flow. If the flame is ignited, a vortex such as that depicted in the scattering image of Fig. 5 is obtained. Here, the flame causes the vortex to take on a shape much like that observed in the numerical simulation of Fig. 2, which also corresponds to a reacting flow. However, the vortex images of Figs. 4 and 5 have additional wing-like structure about their stems. This structure results from the pattern formed by the seed particles that exit the vortex tube prior to injection of a vortex, as demonstrated in the scattering image in the upper half of Fig. 6. The velocity vectors superimposed on the OH PLIF image in the lower half of Fig. 6 demonstrate that in

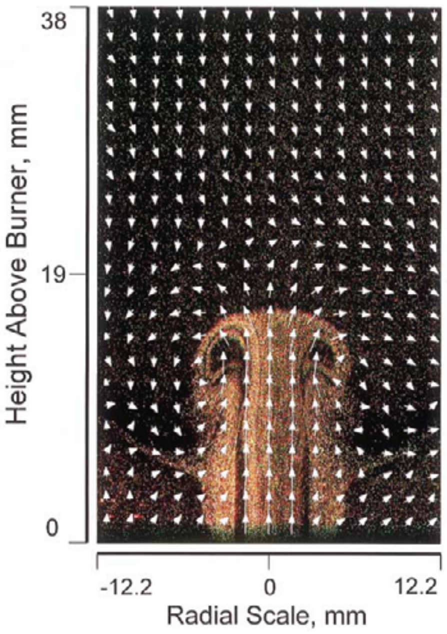

Fig. 5. Vortex injected into opposed-jet flame. Vortex propagates upward at velocity of 8.3 m/s.

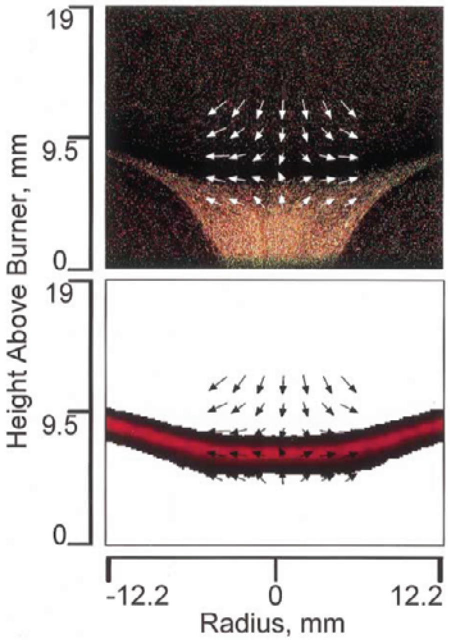

Fig. 6. Simultaneous scattering (upper) and OH PLIF (lower) images. Superimposed vectors demonstrate that stagnation point is located slightly above location of peak OH signal.

the absence of a vortex, the stagnation plane is located slightly above the position of the peak OH signal.

The sequence of four scattering images in Fig. 7 demonstrates the temporal development of an overfilled leading vortex (Gharib et al., 1998; Chen and Dahm, 1998), in which a second and a third vortex are observed. In addition, the high temperatures caused by combustion produce a low-density region that is identified by a smaller scattering signal around the vortices and the stem. This rich structure is repeatable and, therefore, may provide precisely controlled regions of flame curvature and additional regions in which multiple flame layers can interact (Petrov and Ghoniem, 1998). The rainbow appearance of the images results from variations in the irradiance of the red and green lasers across the respective light sheets; these variations were less pronounced when the images of Figs. 4-6 were recorded. Variations in image brightness are caused by different particle seed levels (for each of the three seeders) from image to image.

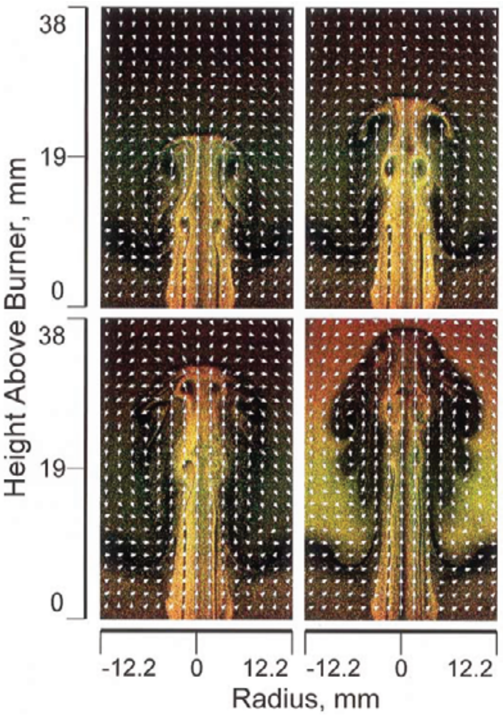

Fig. 7. Multiple-vortex injection observed using temporal sequence of scattering images, with time increasing from left to right, top to bottom: Relative to the first image, subsequent images are delayed by 1, 2.5, and 3.5 ms. Primary vortex in the first image propagates upward at velocity of 9.1 m/s.

5. Conclusions and Future Research

The apparatus of Rolon and co-workers (Rolon et al., 1995; Thevenin et al., 1996; Renard et al., 1998; Thevenin et al., 1998; Renard et al., 1999) has been implemented to study the interaction of a vortex and a flame. Digital, two-color PIV has been applied to characterize the vortices injected into the opposed-jet flow. PLIF images of OH have been used to observe the dynamics of the interaction of the vortex and the flame. An annular break in the OH layer has been observed experimentally, in excellent agreement with prior predictions from numerical computations (Katta et al., 1998a). This agreement results from careful experimental characterization of the vortical flowfield, with the chosen conditions matching those of the corresponding vortex-injection process in the numerical computations.

The present discussion of multiple-vortex formation is limited to a preliminary example. Indeed, most of our previous studies have been limited to the interaction of an isolated vortex and a flame (Fiechtner et al., 1998; Gord et al., 1998; Katta et al., 1998a; Fiechtner et al., 1999). Further investigations of multiple-vortex formation dynamics are being performed to address a wider range of formation numbers. Vortex-vortex interactions are being studied in greater detail, and regions suitable for studying flame-flame interactions are being probed. These studies are being accomplished simultaneously with numerical modeling.

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References

Abramovich, S. and Solan, A., The Initial Development of a Submerged Laminar Round Jet, Journal of Fluid Mechanics, 59 (1973), 791-801.

Ashurst, W. T., Flame Propagation Through Swirling Eddies, A Recursive Pattern, Combustion Science and Technology, 92 (1993), 87.

Auerbach, D., Stirring Properties of Vortex Rings, Physics of Fluids A, 3 (1991), 1351-1355.

Brombacher, E. J., Flow Visualisation of Natural Gas Fuel Injection, M.S. Thesis, University of Toronto (1997).

Cattolica, R. and Vosen, S., Combustion-Torch Ignition: Fluorescence Imaging of OH Concentration, Combustion and Flame, 68 (1987), 267-281.

Chen, S.-J. and Dahm, W. J. A., Diffusion Flame Structure of a Laminar Vortex Ring Under Microgravity Conditions, Twenty-Seventh Symposium (International) on Combustion, (1998), 2579-2586, The Combustion Institute, Pittsburgh, PA.

Didden, N., On the Formation of Vortex Rings Rolling-Up and Production of Circulation, Zeitschrift für Angewandte Math. physik, 30 (1979), 101-116.

Driscoll, J. F., Sutkus, D. J., Roberts, W. L., Post, M. E. and Goss, L. P., The Strain Exerted by a Vortex on a Flame – Determined from Velocity Field Images, Combustion Science and Technology, 96 (1994), 213-229.

Durbin, M. D., Vangsness, M. D., Ballal, D. R. and Katta, V. R., Study of Flame Stability in a Step Swirl Combustor, Transactions of the ASME, 118 (1996), 308-315.

Escudie, D., Stability of a Premixed Laminar V-Shaped Flame, Progress in Astronautics and Aeronautics, 113 (1988), 215-239.

Fabris, D. and Leipmann, D., Vortex Ring Structure at Late Stages of Formation, Physics of Fluids, 9 (1997), 2801-2803.

Fiechtner, G. J., Carter, C. D., Grinstead, K. D., Gord, J. R., Roquemore, W. M. and Rolon, J. C., Flame-Vortex Interactions in a Non-Premixed H_2/N_2/Air Counterflow Burner, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (Cleveland, OH), (1998), AIAA 98-3770.

Fiechtner, G. J., Carter, C. D., Katta, V. R., Gord, J. R., Donbar, J. M. and Rolon, J. C., Regimes of Interaction Between a Nonpremixed Hydrogen-Air Flame and an Isolated Vortex, 37th AIAA Aerospace Sciences Meeting and Exhibit (Reno, NV), (1999), AIAA 99-0320.

Garside, J. E., Hall, A. R. and Towsend, D. T. A., Flow States in Emergent Gas Streams, Nature, 152 (1943), 748.

Gharib, M., Rambod, E. and Shariff, K., A Universal Time Scale for Vortex Ring Formation, Journal of Fluid Mechanics, 360 (1998), 121-140.

Glezer, A., The Formation of Vortex Rings, Physics of Fluids, 31 (1988), 3532-3542.

Glezer, A. and Coles, D., An Experimental Study of a Turbulent Vortex Ring, Journal of Fluid Mechanics, 221 (1990), 243-283.

Gogineni, S., Goss, L., Pestian, D. and Rivir, R., Two-Color Digital PIV Employing a Single CCD Camera, Experiments in Fluids, 25 (1998a), 320-328.

Gogineni, S., Goss, L. P. and Roquemore, W. M., Manipulation of a Jet in a Cross Flow, Experimental Thermal Fluid Science, 16 (1998b), 209-219.

Gord, J. R., Donbar, J. M., Fiechtner, G. J., Carter, C. D., Katta, V. R. and Rolon, J. C., Experimental and Computational Visualization of Vortex-Flame Interactions in an Opposed-Jet Burner, International Conference on Optical Technology and Image Processing in Fluid, Thermal, and Combustion Flow (Yokohama, Japan), (1998), Paper No. AB-082.

Hancock, R. D., Schauer, F. R., Lucht, R. P., Katta, V. R. and Hsu, K. Y., Thermal Diffusion Effects and Vortex-Flame Interactions in Hydrogen Jet Diffusion Flames, Twenty-Sixth Symposium (International) on Combustion, (1996), 1087-1093, The Combustion Institute, Pittsburgh, PA.

Heeg, R. S. and Riley, N., Simulations of the Formation of an Axisymmetric Vortex Ring, Journal of Fluid Mechanics, 339 (1997), 199-211.

Hertzberg, J. R., Namazian, M. and Talbot, L., Tomographic Study of a Laminar Flame in a Karman Vortex Street, Combustion Science and Technology, 38 (1984), 205-216.

Hill, P. G. and Ouellette, P., Transient Turbulent Gaseous Fuel Jets for Diesel Engines, Journal of Fluids Engineering, 121 (1999), 93-101.

Hsu, K. Y., Carter, C. D., Katta, V. R. and Roquemore, W. M., Characteristics of Combustion Instability Associated with Trapped-Vortex Burner, 37th AIAA Aerospace Sciences Meeting and Exhibit (Reno, NV), (1999), AIAA-99-0488.

Hsu, K. Y., Chen. L. D., Katta, V. R., Goss, L. P. and Roquemore, W. M., Experimental and Numerical Investigations of the Vortex-Flame Interactions in a Driven Jet Diffusion Flame, 31st AIAA Aerospace Sciences Meeting & Exhibit (Reno, NV), (1993), AIAA-93-0455.

James, S. and Mandia, C. K., Direct Numerical Simulation of a Laminar Vortex Ring, Physics of Fluids, 8 (1996), 2400-2414.

Jarosinski, J., Lee, J. H. S. and Knystautas, R., Interaction of a Vortex Ring and a Laminar Flame, Twenty-Second Symposium (International) on Combustion, (1988), 505-514, The Combustion Institute, Pittsburgh, PA.

Johari, H., Zhang, Q., Rose, M. J. and Bourque, S. M., Impulsively Started Turbulent Jets, AIAA Journal, 35 (1997), 657-662.

Katta, V. R., Carter, C. D., Fiechtner, G. J., Roquemore, W. M., Gord, J. R. and Rolon, J. C., Interaction of a Vortex With a Flat Flame Formed Between Opposing Jets of Hydrogen and Air, Twenty-Seventh Symposium (International) on Combustion, (1998a), 587-594, The Combustion Institute, Pittsburgh, PA.

Katta, V. R., Hsu, K. Y. and Roquemore, W. M., Local Extinction in an Unsteady Methane-Air Jet Diffusion Flame, Twenty-Seventh Symposium (International) on Combustion, (1998b), 1121-1129, The Combustion Institute, Pittsburgh, PA.

Katta, V. R. and Roquemore, W. M., Study on Trapped-Vortex Combustor – Effect of Injection on Dynamics of Non-Reacting and Reacting Flows in a Cavity, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (Seattle, WA), (1997), AIAA-97-3256.

Katta, V. R. and Roquemore, W. M., Numerical Studies on Trapped-Vortex Concepts for Stable Combustion, Transactions of the ASME, 120 (1998), 60-68.

Katta, V. R. and Roquemore, W. M., Studies on Unsteady Opposing-Jet Diffusion Flames, 37th AIAA Aerospace Sciences Meeting and Exhibit (Reno, NV), (1999), AIAA 99-0322.

Konstantinov, M., Numerical Investigation of the Interaction of Coaxial Vortex Rings, International Journal of Numerical Methods for Heat & Fluid Flow, 7 (1997), 120-140.

Kuo, T.-W., Syed, S. A. and Bracco, F. V., Scaling of Impulsively Started, Incompressible, Laminar Round Jets and Pipe Flows, AIAA Journal, 24 (1986), 424-428.

Lee, T.-W., Lee, J. G., Nye, D. A. and Santavicca, D. A., Local Response and Surface Properties of Premixed Flames During Interactions with Karman Vortex Streets, Combustion and Flame, 94 (1993), 146-160.

Leung, R. C. K., Chu, W. F., Tang, S. K. and Ko, N. W. M., Control of Vortex Pairing with Sound, AIAA Journal, 35 (1997), 802-809.

Leung, R. C. K., Tang, S. K., Ho, I. C. K. and Ko, N. W. M., Vortex Pairing as a Model for Jet Noise Control, AIAA Journal, 34 (1996), 669-677.

Lim, T. T., On the Role of Kelvin-Helmholtz-Like Instability in the Formation of Turbulent Vortex Rings, Fluid Dynamics Research, 21 (1997), 47-56.

List, E. J., Turbulent Jets and Plumes, Annual Reviews of Fluid Mechanics, 14 (1982), 189-212.

Magarvey, R. H. and MacLatchy, C. S., The Formation and Structure of Vortex Rings, Canadian Journal of Physics, 42 (1964), 678-683.

Maxworthy, T., Some Experimental Studies of Vortex Rings, Journal of Fluid Mechanics, 81 (1977), 465-495.

Maxworthy, T., Comments on 'Preliminary Study of Mutual Slip-Through of a Pair of Vortices,' Physics of Fluids, 22 (1979), 200.

Mueller, C. J., Driscoll, J. F., Reuss, D. L. and Drake, M. C., Vorticity Generation and Attenuation as Vortices Convect Through a Premixed Flame, Combustion and Flame, 112 (1998), 342-358.

Mueller, C. J., Driscoll, J. F., Ruess, D. L. and Drake, M. C., Effects of Unsteady Stretch on the Strength of a Freely-Propagating Flame Wrinkled by a Vortex, Twenty-Sixth Symposium (International) on Combustion, (1996), 347-355, The Combustion Institute, Pittsburgh, PA.

Mueller, C. J., Driscoll, J. F., Sutkus, D. J., Roberts, W. L., Drake, M. C. and Smooke, M. D., Effect of Unsteady Stretch Rate on OH Chemistry During a Vortex-Flame Interaction: To Assess Flamelet Models, Combustion and Flame, 100 (1995), 323-331.

Mueller, C. J. and Schefer, R. W., Coupling of a Diffusion Flame Structure to an Unsteady Vortical Flowfield, Twenty-Seventh Symposium (International) on Combustion, (1998), 1105-1112, The Combustion Institute, Pittsburgh, PA.

Najm, H. N., Paul, P. H., Mueller, C. J. and Wyckoff, P. S., On the Adequacy of Certain Experimental Observables as Measurements of Flame Burning Rate, Combustion and Flame, 113 (1998), 312-332.

Nguyen, Q.-V. and Paul, P. H., The Time Evolution of a Vortex-Flame Interaction Observed via Planar Imaging of CH and OH, Twenty-Sixth Symposium (International) on Combustion, (1996), 357-364, The Combustion Institute, Pittsburgh, PA.

Nitsche, M., Scaling Properties of Vortex Ring Formation at a Circular Tube Opening, Physics of Fluids, 8 (1996), 1848-1855.

Nitsche, M. and Krasny, R., A Numerical Study of Vortex Ring Formation at the Edge of a Circular Tube, Journal of Fluid Mechanics, 276 (1994), 139-161.

Nye, D. A., Lee, J. G., Lee, T.-W. and Santavicca, D. A., Flame Stretch Measurements During the Interaction of Premixed Flames and Karman Vortex Streets Using PIV, Combustion and Flame, 94 (1996), 167-176.

Oshima, Y., Kambe, T. and Saburo, A., Interaction of Two Vortex Rings Moving along a Common Axis of Symmetry, Journal of the Physical Society of Japan, 38 (1975), 1159-1166.

Oshima, Y., Noguchi, T. and Oshima, K., Numerical Study of Interaction of Two Vortex Rings, Fluid Dynamics Research, 1 (1986), 215-227.

Paul, P. H. and Najm, H. N., Planar Laser-Induced Fluorescence Imaging of Flame Heat Release Rate, Twenty-Seventh Symposium (International) on Combustion, (1998), 43-50, The Combustion Institute, Pittsburgh, PA.

Petrov, C. and Ghoniem, A. F., Dynamics and Structure of Interacting Nonpremixed Flames, Combustion and Flame, 115 (1998), 180-194.

Poinsot, T., Trouve, A., Veynante, D., Candel, S. and Esposito, E., Vortex Driven Acoustically Coupled Combustion Instabilities, Journal of Fluid Mechanics, 177 (1987), 265-292.

Pullin, D., Vortex Ring Formation at Tube and Orifice Openings, Physics of Fluids, 22 (1979), 401-403.

Renard, P.-H., Rolon, J. C., Thevenin, D. and Candel, S., Wrinkling, Pocket Formation and Double Premixed Flame Interaction Processes, Twenty-Seventh Symposium (International) on Combustion, (1998), 659-666, The Combustion Institute, Pittsburgh, PA.

Renard, P.-H., Rolon, J. C., Thevenin, D. and Candel, S., Investigations of Heat Release, Extinction, and Time Evolution of the Flame Surface for a Non-Premixed Flame Interacting with a Vortex, Combustion and Flame, 117 (1999), 189-205.

Riley, N., On the Behaviour of Pairs of Vortex Rings, Quorterly Journal of Mechauies and Applied Mathematics, 46 (1993), 521-539.

Rizk, W., Experimental Studies of the Mixing Processes and Flow Configurations in Two-Cycle Engine Scavenging, Proceedings of the Institution of Mechanical Engineers, Series E, 172 (1958), 417-424.

Roberts, W. L. and Driscoll, J. F., A Laminar Vortex Interacting with a Premixed Flame: Measured Formation of Pockets of Reactants, Combustion and Flame, 87 (1991), 245-256.

Roberts, W. L., Driscoll, J. F., Drake, M. C. and Goss, L. P., Images of the Quenching of a Flame by a Vortex – To Quantify Regimes of Turbulent Combustion, Combustion and Flame, 94 (1993), 58-69.

Roberts, W. L., Driscoll, J. F., Drake, M. C. and Ratcliffe, J. W., OH Fluorescence Images of the Quenching of a Premixed Flame During an Interaction with a Vortex, Twenty-Fourth Symposium (International) on Combustion, (1992), 169-176, The Combustion Institute, Pittsburgh, PA.

Rolon, J. C., Aguerre, F. and Candel, S., Experiments on the Interaction Between a Vortex and a Strained Diffusion Flame, Combustion and Flame, 100 (1995), 422-429.

Roquemore, W. M. and Katta, V. R., Role of Flow Visualization in the Development of UNICORN, International Conference on Optical Technology and Image Processing in Fluid, Thermal, and Combustion Flow (Yokohama, Japan), (1998), Paper No. KL-310.

Roquemore, W. M. and Katta, V. R., Role of Flow Visualization in the Development of UNICORN, to appear in Journal of Visualization, 2-314, 1999.

Roquemore, W. M., Reddy, V. K., Hedman, P. O., Post, M. E., Chen, T. H., Goss, L. P., Trump, D., Vilimpoc, V. and Sturgess, G. J., Experimental and Theoretical Studies in a Gas-Fueled Research Combustor, 29th AIAA Aerospace Sciences Meeting (Reno, NV), (1991), AIAA-91-0639.

Rutland, C. J. and Ferziger, J. H., Simulations of Flame-Vortex Interactions, Combustion and Flame, 84 (1991), 343-360.

Saffman, P. G., Vortex Dynamics, (1992), Cambridge University Press, New York.

Samaniego, J.-M., Generation of Two-Dimensional Vortices in a Cross Flow, Annual Research Briefs-1992, Center for Turbulence Research (NASA Ames Research Center/Stanford University), (1992a), 431-441.

Samaniego, J.-M., Stretch-Induced Quenching in Vortex-Flame Interactions, Annual Research Briefs-1993, Center for Turbulence Research (NASA Ames Research Center/Stanford University), (1992b), 205-218.

Santoro, V. S., Kyritsis, D. C. and Gomez, A., A Comparison of the Interaction of Laminar Vortices with Either Gaseous or Spray Counterflow Diffusion Flames, First Joint Meeting of the United States Sections of the Combustion Institute (Washington, DC), (1999), Paper No. 21.

Shariff, K. and Leonard, A., Vortex Rings, Annual Reviews of Fluid Mechanics, 24 (1992), 235-279.

Sinibaldi, J. O., Mueller, C. J. and Driscoll, J. F., Local Flame Propagation Speeds Along Wrinkled, Unsteady, Stretched Premixed Flames, Twenty-Seventh Symposium (International) on Combustion, (1998a), 827-832, The Combustion Institute, Pittsburgh, PA.

Sinibaldi, J. O., Mueller, C. J., Tulkki, A. E. and Driscoll, J. F., Suppression of Flame Wrinkling by Buoyancy: The Baroclinic Stabilization Mechanism, AIAA Journal, 36 (1998b), 1432-1438.

Southerland, K. B., Porter, J. R., Dahm, W. J. A. and Buch, K. A., An Experimental Study of the Molecular Mixing Process in an Axisymmetric Laminar Vortex Ring, Physics of Fluids A, 3 (1991), 1385-1392.

Takagi, T., Yoshikawa, Y., Yoshida, K., Komiyama, M. and Kinoshita, S., Studies on Strained Non-Premixed Flames Affected by Flame Curvature and Preferential Diffusion, Twenty-Sixth Symposium (International) on Combustion, (1996), 1103-1110, The Combustion Institute, Pittsburgh, PA.

Takahashi, F., Schmoll, W. J., Trump, D. D. and Goss, L. P., Vortex-Flame Interactions and Extinction in Turbulent Jet Diffusion Flames, Twenty-Sixth Symposium (International) on Combustion, (1996), 145-152, The Combustion Institute, Pittsburgh, PA.

Thevenin, D., Renard, P.-H., Rolon, J. C. and Candel, S., Structure of a Nonpremixed Flame Interacting with Counterrotating Vortices, Twenty-Sixth Symposium (International) on Combustion, (1996), 1079-1086, The Combustion Institute, Pittsburgh, PA.

Thevenin, D., Renard, P.-H., Rolon, J. C. and Candel, S., Exctinction Processes During a Non-Premixed Flame/Vortex Interaction, Twenty-Seventh Symposium (International) on Combustion, (1998), 719-726, The Combustion Institute, Pittsburgh, PA.

Weidman, P. D. and Riley, N., Vortex Ring Pairs: Numerical Simulation and Experiment, Journal of Fluid Mechanics, 257 (1993), 311-337.

Weigand, A. and Gharib, M., On the Evolution of Laminar Vortex Rings, Experiments in Fluids, 22 (1997), 447-457.

Widnall, S. E., The Structure and Dynamics of Vortex Filaments, Annual Review of Fluid Mechanics, 7 (1975), 141-165.

Witze, P. O., Hot-Film Anemometer Measurements in a Starting Turbulent Jet, AIAA Journal, 21 (1983), 308-309.

Yamada, H. and Matsui, T., Preliminary Study of Mutual Slip-Through of a Pair of Vortices, Physics of Fluids, 21 (1978), 292-294.

Yamada, H. and Matsui, T., Mutual Slip-Through of a Pair of Vortex Rings, Physics of Fluids, 22 (1979a), 1245-1249.

Yamada, H. and Matsui, T., Reply to Comments of T. Maxworthy, Physics of Fluids, 22 (1979b), 201.

Yaros, R., The Evolution of a Suddenly Initiated Semiconfined, Two-Dimensional, Turbulent Jet, Ph.D. Dissertation, Pennsylvania State University (1977).

Yoshida, K. and Takagi, T., Transient Local Extinction and Reignition Behavior of Diffusion Flames Affected by Flame Curvature and Preferential Diffusion, Twenty-Seventh Symposium (International) on Combustion, (1998), 685-692, The Combustion Institute, Pittsburgh, PA.

You, Y. H., Lee, D. K. and Shin, H. D., Visual Investigation of a Vortex Ring Interacting with a Nonpremixed Flame, Combustion Science and Technology, 139 (1998), 365-383.

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