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Visualization of Jet Mixing in a Fluidic Oscillator

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Abstract : The fluidic oscillator is a device that generates an oscillating jet when supplied with fluid at pressure. The oscillator has no moving parts – the creation of the unsteady jet is based solely on fluid-dynamic interactions. Fluidic oscillators can operate at frequencies ranging up to 20 kHz, and are useful for flow control applications. The fluidic oscillator evaluated in the current study is comprised of two fluid jets that interact in an internal mixing chamber, producing the oscillating jet at the exit. Both porous pressure-sensitive paint (PSP) and dye-colored water flow are used to visualize the internal and external fluid dynamics of the oscillator. Porous PSP formulations have been shown to have frequency responses on the order of 100 kHz, which is more than adequate for visualizing the fluidic oscillations. In order to provide high-contrast PSP data in these tests, one of the internal jets of the fluidic oscillator is supplied with oxygen, and the other with nitrogen. Results indicate that two counter-rotating vortices within the mixing chamber drive the oscillations. It is also shown that the fluidic oscillator possesses excellent mixing characteristics.

Keywords : Fluidic oscillator, Pressure-sensitive paint, Fluid mixing, Flow control.

1. Introduction

1.1 Fluidic Oscillator

The fluidic oscillator is a fascinating device that has many potential applications in fluid dynamics. An oscillating jet of fluid issues from the device when it is supplied with a pressurized gas or liquid. The oscillations are typically on the order of several kilohertz, and can range up to over 20 kHz for small devices. The internal geometry of the device may be tailored to produce specific jet wave patterns, such as sinusoidal, sawtooth, or even square waveforms (Raghu and Raman, 1999). Fluidic oscillators were originally developed in the 1960's, evolving out of research in fluid amplifiers (Raber and Shinn, 1964; Spyropoulos, 1964). Perhaps the single-largest application of fluidic oscillator technology is for windshield washer devices (Stouffer, 1985), with over 45 million produced annually (Bowles Fluidics Corporation, 2003). Since the operating frequency of the oscillator is directly related to the flow rate, fluidic oscillators have also been used extensively as flow-rate metering devices (Beale and Lawler, 1974; Beale, 1969; Wang et al., 1997). In recent years, the fluidic oscillator has been applied to a host of aerodynamic flow control applications, such as cavity resonance tone suppression (Raghu and Raman, 1999; Raman et al., 1999), jet thrust vectoring (Raman et al., 2001), and enhancement of jet mixing (Raman, 1997; Raman and Cornelius, 1995).

Fluidic oscillators may be classified into two different groups – wall attachment devices and jet interaction devices. The oscillators in the wall-attachment class are based on the attachment of a fluid jet to an adjacent wall, a phenomenon known as the Coanda effect (Coanda, 1936; Metral, 1939). The second class of oscillators is fairly new, and based on the interaction of two fluid jets inside a specially-designed chamber. This oscillator has been described as a 'feedback-free' type, details of which are described in Raghu's patent (2001).

The external flowfield of the feedback-free oscillator has been characterized in prior work. This type of oscillator was used by Sakaue et al. (2002) to demonstrate the fast response characteristics of pressure-sensitive paint. Gregory et al. (2001; 2002) characterized the flowfield using both pressure-sensitive paint and schlieren imaging. Typical schlieren results from this prior work are shown in Fig. 1 (Gregory, 2002). Past work with this type of oscillator has focused on the external flowfield. Thus, there is only limited information about the internal fluid dynamics of the device. The goal of the current work is to characterize the internal jet mixing characteristics through flow visualization techniques.

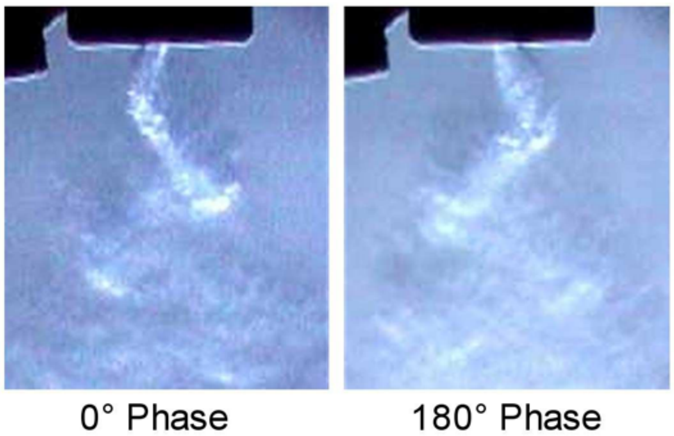


Fig. 1. Typical fluidic oscillator flowfield, visualized with schlieren imaging (Gregory, 2002).

1.2 Pressure-Sensitive Paint

Pressure-sensitive paint (PSP) is a relatively new optical measurement technique that enables full-field pressure measurements without the need for pressure taps. PSP measures surface pressure distributions through the processes of luminescence and oxygen quenching. Typically, PSP is illuminated with light of short wavelength, which excites luminescent molecules in the paint to a higher energy level. These molecules, referred to as the luminophore, convert this energy to light, which is emitted at a longer wavelength. In the presence of oxygen in a test gas, the luminescent intensity of the luminophore is reduced by oxygen molecules from the gas. This process is known as oxygen quenching. Therefore, the intensity of light emitted from the paint is inversely proportional to the oxygen concentration. Since the amount of oxygen in air is proportional to pressure, one can obtain static pressure levels from the change in the luminescent intensity of PSP. Further details of the PSP technique may be found in comprehensive reviews by Bell et al. (2001) and Liu et al. (1997). Recent developments in porous PSP have allowed measurements in unsteady flowfields. Essentially, the porous paints have an open structure for the paint binder, which allows for free interaction of the test gas with the luminophore. Sakaue et al. (2002) have shown that typical porous PSP formulations have a step response on the order of 100 μs. Gregory et al. (2002) have further developed the polymer/ceramic formulation to have a flat frequency response of over 15 kHz when compared with a Kulite pressure transducer. Since the oscillations in the current tests are on the order of 5 kHz, the frequency response of porous paints is more than adequate to visualize the flow without frequency roll-off concerns.

2. Experimental Setup

A schematic of the instrumentation setup used for the PSP experiments is shown in Fig. 2. A rough outline of the geometry of the patented oscillator (Raghu, 2001) is shown in the figure. The paint was applied to the inside back wall of the fluidic oscillator, and a clear acrylic cover was mounted on the other side for optical access. The particular PSP formulation used in these experiments was polymer/ceramic PSP (PC-PSP). The polymer/ceramic paint is a hybrid development – it is highly porous because of the ceramic particles, with only a small amount of polymer used to bind the paint together. Details of the polymer/ceramic paint development are available from Scroggin, et al. (1999) and Gregory (2002).

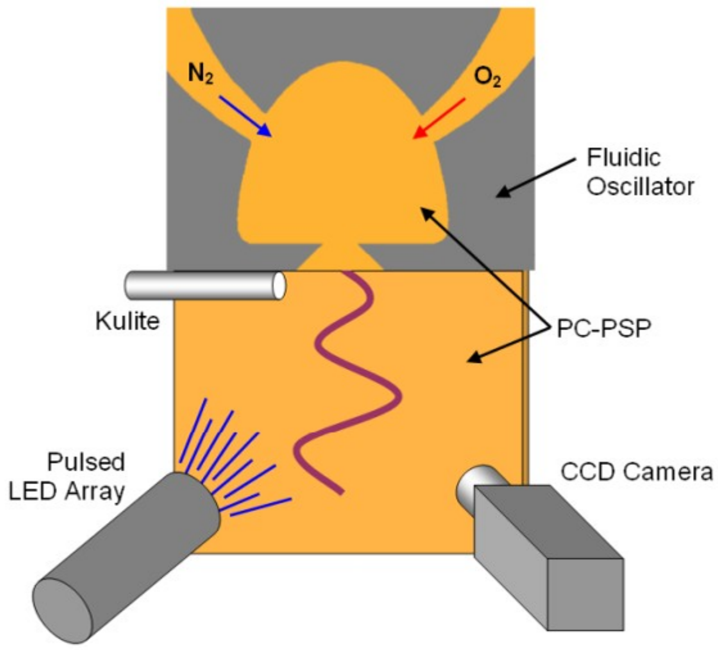


Fig. 2. Experimental setup for the pressure-sensitive paint measurements (not to scale).

Nitrogen gas was supplied to the left input, and oxygen gas to the right. The flow rates of each gas were measured with FT-133 calibrated flow rate tubes from Dwyer Instruments, and the pressures were measured with a Heise DXD pressure transducer. A Kulite pressure transducer (XCQ-062-15D) was mounted near the nozzle exit of the fluidic oscillator to record the operating frequency. The frequency bandwidth of the Kulite transducer and its signal conditioner is well over 100 kHz. The Kulite signal was passed through analog high-pass and low-pass filters before being measured on a Tektronix 466 analog oscilloscope and an Ono-Sokki CF-4220 personal FFT analyzer. PSP measurements were made with a Photometrics 14-bit CCD camera and an ISSI LM2 pulsed LED array for illumination. A camera shutter speed of 0.7 s (typical) was required to fill the pixel wells to near-capacity for best results. Since the flowfield is unsteady, phase-locking techniques were required to record time-resolved PSP data. The pulsing of the LED array was synchronized with the oscillations measured by the Kulite pressure transducer through the gating function on a triggered oscilloscope. A variable delay was added to the oscilloscope's TTL pulse with a Berkeley Nucleonics BNC-555 pulse/delay generator. Phase-locked time histories were recorded by varying the delay throughout the oscillation cycle. Thus, this system makes phase-averaged measurements of the unsteady flowfield. The excitation pulse width was typically 2.5% of the oscillation period, and each delay step was 5% of the period.

Once raw intensity images of the painted oscillator were acquired with the CCD camera, the data was reduced to provide gas concentration results. An intensity ratio was calculated by dividing the wind on image by a reference image, and then smoothed with a 3-pixel-square spatial filter. The intensity ratio was then converted to oxygen concentration through a Stern-Volmer calibration. The calibration for these tests was performed from pure oxygen at 1 atm, down to vacuum (simulating pure nitrogen at 1 atm). Once the oxygen concentration was obtained, the data was normalized between 0 (pure nitrogen) and 1 (pure oxygen). The data presented in this paper represents gas concentration only, since current PSP technology is unable to simultaneously measure pressure and gas concentration. Any effects of pressure are neglected, since the supply pressures are small and typically equal on both inlets.

3. Pressure-Sensitive Paint Visualization

3.1 Equal Supply Pressures

PSP visualization data in Fig. 3 shows the internal fluid dynamics of the oscillator at moderate flow rates and an oscillation frequency of 2.5 kHz. Each image represents a successive phase delay of 90° within the oscillation cycle of 400 μs. Nitrogen is the gas on the left, and oxygen is the gas on the right, with equal supply pressures (0.34 psig). The color scale for the flowfield data outside the oscillator (the lower half of each image) has been adjusted to enhance contrast. The contrast-adjusted color scale ranges from 0.2 to 0.5.

Notice that the jets collide near the center of the mixing chamber, but the interface between the two jets is not stationary. The shear layer between the two jets oscillates at the same frequency

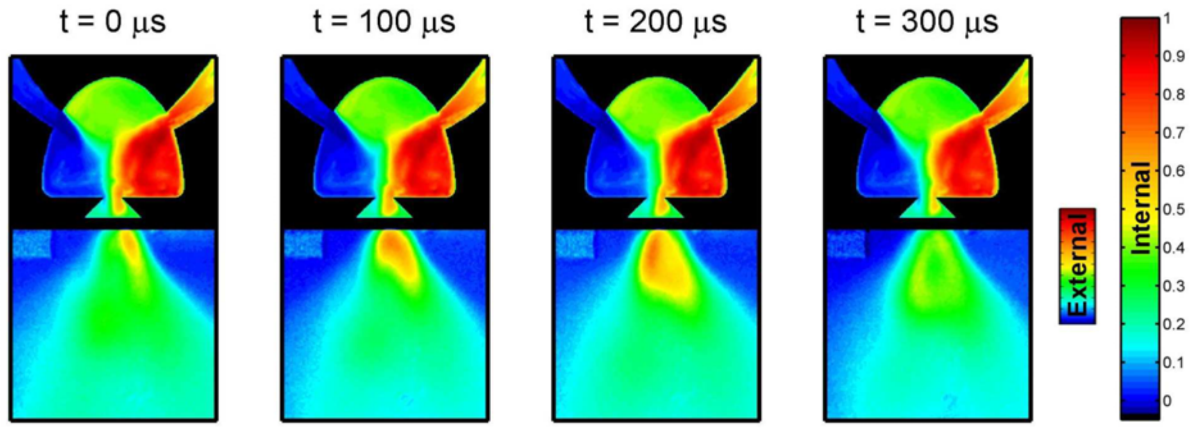
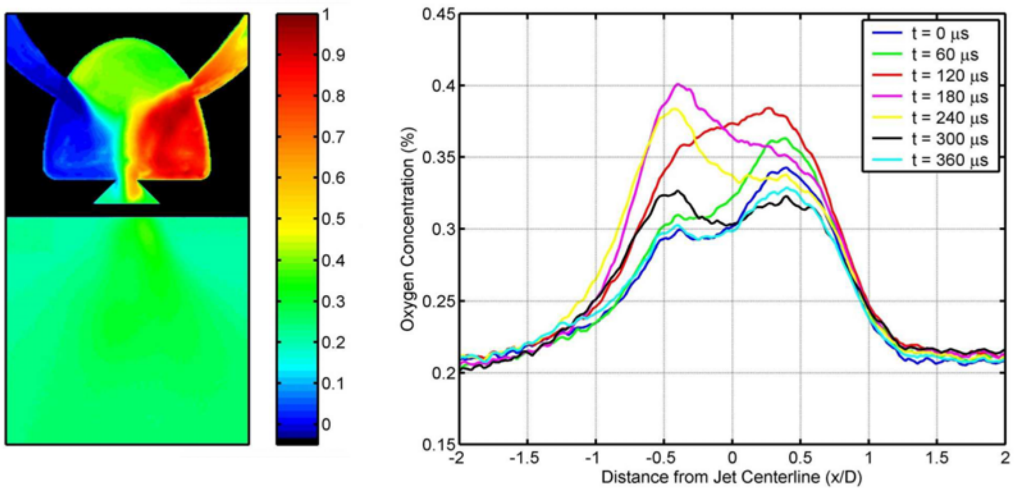


Fig. 3. Visualization of jet mixing at several time steps within the oscillation period of 400 μs. The color scale represents oxygen concentration: pure oxygen is 1, pure nitrogen is 0, and 0.21 is atmosphere. The flowfield data outside the oscillator (in the lower portion of each image), has been adjusted to enhance color contrast, as shown by the color bar marked external (a range from 0.2 to 0.5).

as the external jet produced by the device. In general, the amplitude of this interface motion is larger for higher supply pressures. The shape of the shear layer also changes as the jets oscillate. When the shear layer moves towards the left it exhibits rightward-facing concave curvature. When the shear layer moves to the right, the curvature is concave left. The shape of the internal mixing chamber controls the formation and oscillatory growth of counter-rotating vortex pairs, which drive the shear-layer oscillations.

The jet issuing from the nozzle is fairly well mixed, because the jet interface is directly in line with the exit. This characteristic highlights the utility of the fluidic oscillator for fluid mixing applications. The mixing characteristics are clearly seen in Fig. 4. The lower portion of Fig. 4(a) shows the same external flowfield as Fig. 3, but not adjusted for contrast. In a short distance downstream of the nozzle exit, the jet is very well mixed. The curves shown in Fig. 4(b) are cross-sections taken one jet diameter downstream of the nozzle exit. Each curve represents a different time step, as shown in the legend. The movement of the peak correlates with the external jet oscillations shown in Fig. 3. The evolution of the jet magnitude in time is not yet symmetric because the output contains disproportionate levels of oxygen and nitrogen at various points in the cycle. The excellent mixing characteristics of the oscillator are evidenced by the 10% variation in oxygen concentration. Thus, the original nitrogen and oxygen jets have achieved 90% mixing at a distance of one jet diameter downstream of the nozzle. Note that the values at the edge of the jet cross-section in Fig. 4(a) are 0.21, corresponding to atmospheric conditions.



(a) (b)

Fig. 4. (a) Visualization of jet mixing with equal supply pressures. The color scale represents oxygen concentration, with 1 being pure oxygen, 0 being pure nitrogen, and 0.21 being atmospheric conditions. (b) Cross-sections of the data along a line one jet-diameter downstream of the exit.

3.2 Asymmetric Supply Pressures

Data from a test with asymmetric flow rates is shown in Fig. 5, with oscillations at 5.25 kHz. In this case, the supply pressure for the oxygen (right side, 3.8 psig) was slightly higher than the nitrogen supply pressure (left side, 3.6 psig). The asymmetry in the flowfield is clearly evident. The oxygen jet is dominant throughout the oscillation cycle, both inside and outside the mixing chamber, yet it is remarkable that the device is still oscillating. The shear layer created by the confluence of the two jets is slanted towards the incident angle of the oxygen jet. With the higher supply pressures, there is a corresponding larger range of motion of the jets and shear layer within the mixing chamber. There is also a wider oscillation spread of the external flowfield.

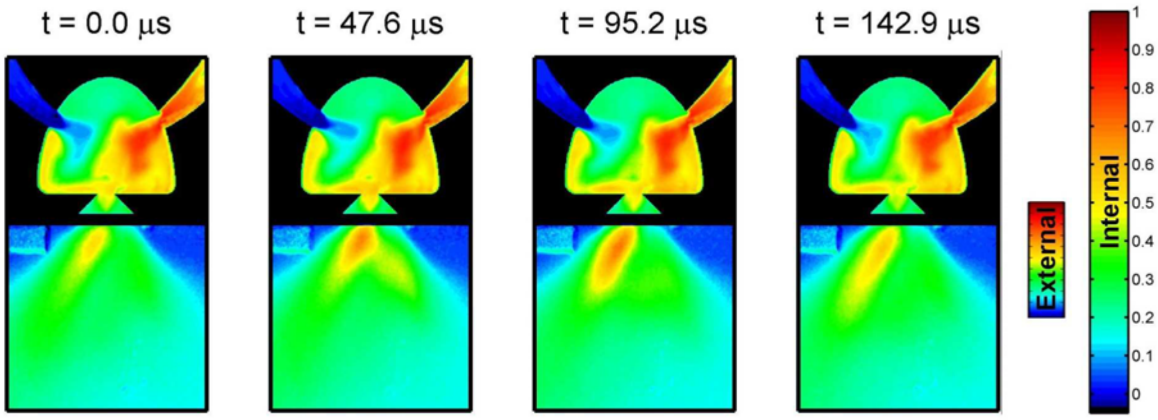
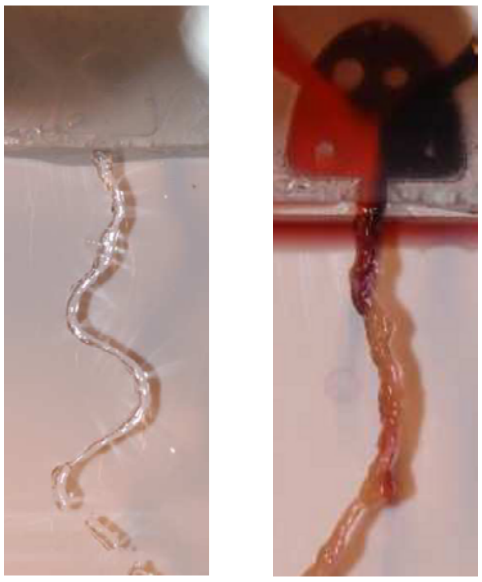


Fig. 5. Visualization of jet mixing at several time steps for asymmetric flow inputs. The left inlet is nitrogen at 3.61 psig, and the right inlet is oxygen at 3.81 psig, resulting in 5.25-kHz oscillations. The flowfield data outside the oscillator has been adjusted in a manner similar to Fig. 3.

4. Water Visualization

The fluidic oscillator was also operated with water as the supply fluid for simple flow visualization studies, and to validate the PSP measurements. Both clear water and dyed water were used in these tests. Since the density of water is much higher than either nitrogen or oxygen, the oscillation frequency is much lower for a given supply pressure. Thus, it is possible to capture one instant in the oscillations with flash photography or with a fast shutter speed on an SLR camera. Typical results with clear water (a) and colored water (b) are shown in Fig. 6. Both images clearly show the sinusoidal waveform that is generated by the fluidic oscillator at a water supply pressure of 1.8 psig. The colored water was supplied with pure red dye on the left input and pure blue dye on the right input. Bubbles are visible in each of the lower corners of the oscillator mixing chamber. These bubbles were observed to rotate in circles, coincident with the expected vortical motion. Notice that the color of the fluid exiting from the oscillator just a few jet diameters downstream from the nozzle is very homogeneous. This indicates that the red and blue jets are mixed together thoroughly by the oscillator.



(a) (b)

Fig. 6. Water visualization of the fluidic oscillator at a supply pressure of 1.8 psi.

5. Conclusion

Both pressure-sensitive paint and dyed water have been used for flow visualization studies with the fluidic oscillator. These techniques have been used to visualize the internal fluid dynamics, as well as the external flow field of the oscillator. This patented feedback-free device oscillates via the interaction of confluent jets in a mixing chamber. Pairs of counter-rotating vortices within the mixing chamber drive the oscillation of the shear layer, resulting in an external oscillatory flowfield. The fluidic oscillator also exhibits excellent mixing characteristics. PSP data shows that the jets are 90% mixed at a distance only one jet-diameter downstream of the oscillator exit.

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