NEW FLIP-FLOP JET NOZZLE WITHOUT CONTROL PORT AND FEEDBACK LOOP

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ABSTRACT

This paper reports experimental results of the mixing characteristics of a low-frequency flapping, slightly heated, jet from a self-exciting fluidic nozzle. The fluidic device used for the investigation contains no external feedback loop and no external trigger (Figure 1). Temperature measurements were carried out in both the flapping jet and a non-flapping free jet using a cold-wire probe. It is shown that the flapping jet from the nozzle mixes the ambient fluid at a higher rate than does the non-flapping free jet. The present study also suggests that the Strouhal number of the flapping have a significant impact on the jet mixing. A better performance in mixing is found at high Strouhal numbers.

INTRODUCTION

Turbulent jets are used extensively in practical applications including combustors and ejectors. The ability to control the mixing characteristics of a jet is an essential part of optimising the performance of a nozzle for any given application. In combustion-based industries, for example, the legal emission levels of pollutants, such as oxides of nitrogen (NO_x) and carbon monoxide (CO), are being progressively lowered, while economic constraints demand that the process efficiency and product quality be improved or, at least, maintained. The mixing characteristics of industrial diffusion flames influence both the heat-flux characteristics and the pollutant emissions (Manias and Nathan, 1993, 1994; Nathan and Manias, 1995). Many devices seeking to control the turbulent mixing characteristics of jets have been investigated, usually with a view to promote increased mixing rates. Notable excitation techniques assessed in laboratory studies include acoustic (e.g., Crow and Champagne, 1971) and mechanical techniques (e.g., Davis, 1982; Favre-Marinet et. al., 1981). These active excitation techniques can be effective as a means of increasing spreading rates and have advanced our understanding of the fundamental mechanisms involved in the mixing process in jets. However, they have not proved to be equally effective for practical applications due to their weight, power and maintenance requirements, particularly in the harsh industrial environments found in furnaces and boilers. For widespread practical applications, a mixing control device should be simple, effective and durable. With this view, several practical fluidic nozzles have been developed in the past decades. Typical examples are the flip-flop or flapping jet (FJ) nozzle (Viets, 1975), the precessing jet (PJ) nozzle (Luxton et al. 1990; Nathan 1988; Nathan et. al, 1998) and the recently developed oscillating jet devices (Mi et al., 1997). These fluidic devices excite a large-scale, low frequency oscillation of the entire jet without involving any moving parts. Such dynamic oscillations increase the initial jet spreading angle (Simmons et al., 1981) and appear, in general, to increase the entrainment rate of the jet (Nathan and Luxton, 1991; Plazer et al., 1978).

In the present study, a rectangular fluidic nozzle (Figure 1) was used to generate a self-excited, low-frequency flapping jet (Mi et al., 1997). Unlike the flip-flop nozzle of Viets (1975), this nozzle contains no external feedback loop and no control port. Also, no external trigger and no moving part are needed for the flapping motion to occur. We surmise that this self-excited oscillation originates from the feedback process triggered by natural instabilities under specific geometric conditions. Luxton et al. (1987) discovered a three-dimensional counterpart, i.e. the self-excited precession of a jet from an axisymmetric fluidic nozzle. The precessing jet (PJ) has found application in industrial burners. Full-scale installations of commercial gas-firing PJ burners in rotary kilns used in the process industries have consistently demonstrated a reduction of typically 50% in NO_x emissions and an input fuel saving of about 5% relative to the flames from the burners they replaced (Manias and Nathan, 1993, 1994). As such, the present new and simple flip-flop nozzle (Figure 1) should also find similar use in industry.

The first aim of this study is to investigate the effect of the operating parameters on the flapping

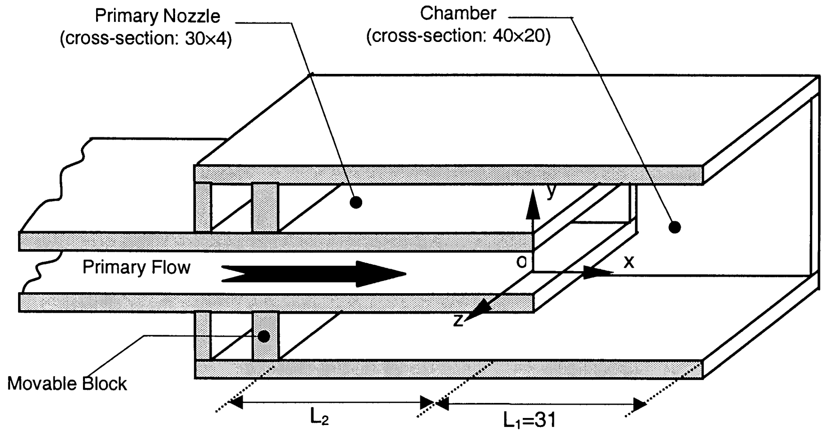

Figure 1: Schematic of the new flip-flop jet nozzle. The dimensions are in *mm*.

frequency (f_F) of a jet issuing from the fluidic nozzle detailed in Figure 1. The second aim is to make a comparison of the jet's mixing characteristics at different Strouhal numbers of the flapping defined by $St_F = f_F h/U_1$ (where h is the inlet pipe height and U_1 is the mean velocity at the inlet exit) and also that between the flapping jet and a non-flapping free jet from the same inlet nozzle with no chamber attached. For the second aim, we use temperature measurements made in a slightly heated flapping jet at St_F = 1.56x10^{-3} and 3.6x10^{-3} and also a slightly heated rectangular free jet.

EXPERIMENTAL DETAILS

The experimental facility includes a plenum chamber to which various nozzles can be attached. The plenum is supplied with filtered compressed air at pressures of up to 500 kPa at room temperature. The jet exit velocity can be varied by changing the plenum pressure. The FJ flow investigated herein is generated by a novel and simple "flip-flop" jet nozzle recently developed by Mi *et al.* (1997), which is a planar analogue of the axisymmetric PJ nozzle (Luxton et al., 1987).

The nozzle consists of a rectangular cross-section chamber with internal dimensions 40mmx20mm, into which a rectangular pipe protrudes by a distance of L_2 (Figure 1). The flow enters the chamber through the pipe. The cross-sectional dimensions of the pipe are 30mmx4mm. After entering the chamber, the jet expands through entrainment of the surrounding fluid. This generates a feedback process within the chamber, because the pipe is not as wide as the chamber, causing the jet to "flap" from side to side in a quasi-planar fashion. The circulation/ recirculation zone between the protruding pipe and the chamber walls maintains the feedback process so that the jet can flap continuously. This flapping "primary" jet discharges into a large quiescent room and mixes with the ambient fluid.

The origin of the (x,y,z) coordinate system is chosen to locate at the pipe inlet centre for both the flapping and the non-flapping jets (Figure 1). The use of the same inlet means that both jets have the identical initial boundary conditions. Based on the exit conditions, the Reynolds number is $Re_h \approx 15500$.

We examined the effects of the distance between the primary nozzle inlet lip and the chamber outlet lip (L_1), the protruding length (L_2) and jet inlet bulk velocity (U_1) on the jet flapping frequency (f_F). The frequency f_F of the air jet was measured using a 5 μm tungsten wire positioned just downstream from the chamber outlet. The hot wire was operated by in-house constant temperature circuit with an overheat ratio of 1.5. To investigate mixing characteristics, present temperature measurements were made along the centreline of a slightly heated jet for St_F = 0 (non-flapping), 1.56x10^{-3} and 3.6x10^{-3}, using a cold-wire probe. The probe consists of a short length of Wollaston wire (Pt-10%Ph) of 1.27 μm in diameter, operated with an in-house constant current (0.1 mA) circuit. The temperature signal from the circuit was offset, amplified and then digitized using a 16 channel, 12-bit A/D converter on a personal computer.

RESULTS

To enable a variation of the flapping Strouhal number St_F, we sought different ways to change the flapping frequency f_F. Previous experiments indicate that increasing the inlet velocity U_1 can increase the magnitude of f_F. However, f_F is found to vary linearly with U_1 (not shown), resulting in nearly no variation of St_F with U_1. We also tested the effect of the distance between the pipe exit (jet inlet) and the chamber outlet (L_1). It is found that the jet can flap continuously only over the range of L_1 between 26mm and 36mm and also that the corresponding frequency f_F changes very little.

Importantly, however, for the present nozzle, we can obtain different values of St_F by changing the distance (L_2) at which the pipe protrudes in the chamber. This distance is an important parameter because it is equivalent to the length of the feedback tube of the flip-flop nozzles used by Viets (1975) and Raman et al. (1993, 1994). Figure 2 shows the

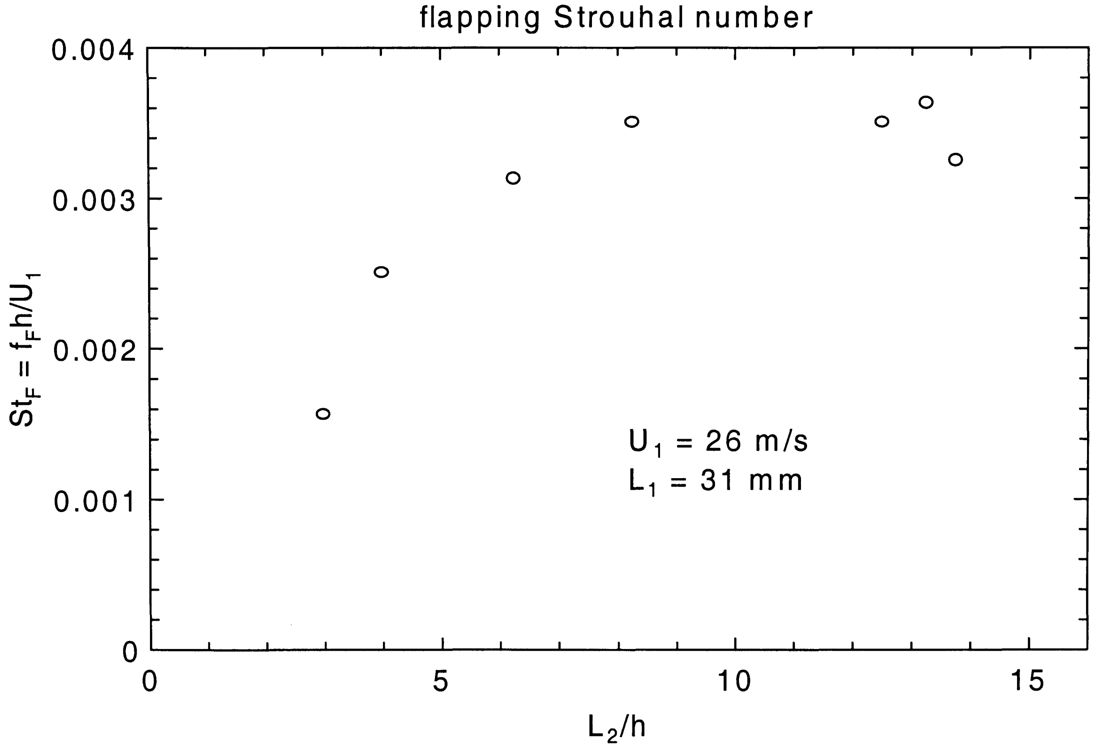

Figure 2: Variation of the Strouhal number of the flapping, St_F, with the protruding length L_2 for the case of $U_1 = 26$ m/s and $L_1 = 31$ mm.

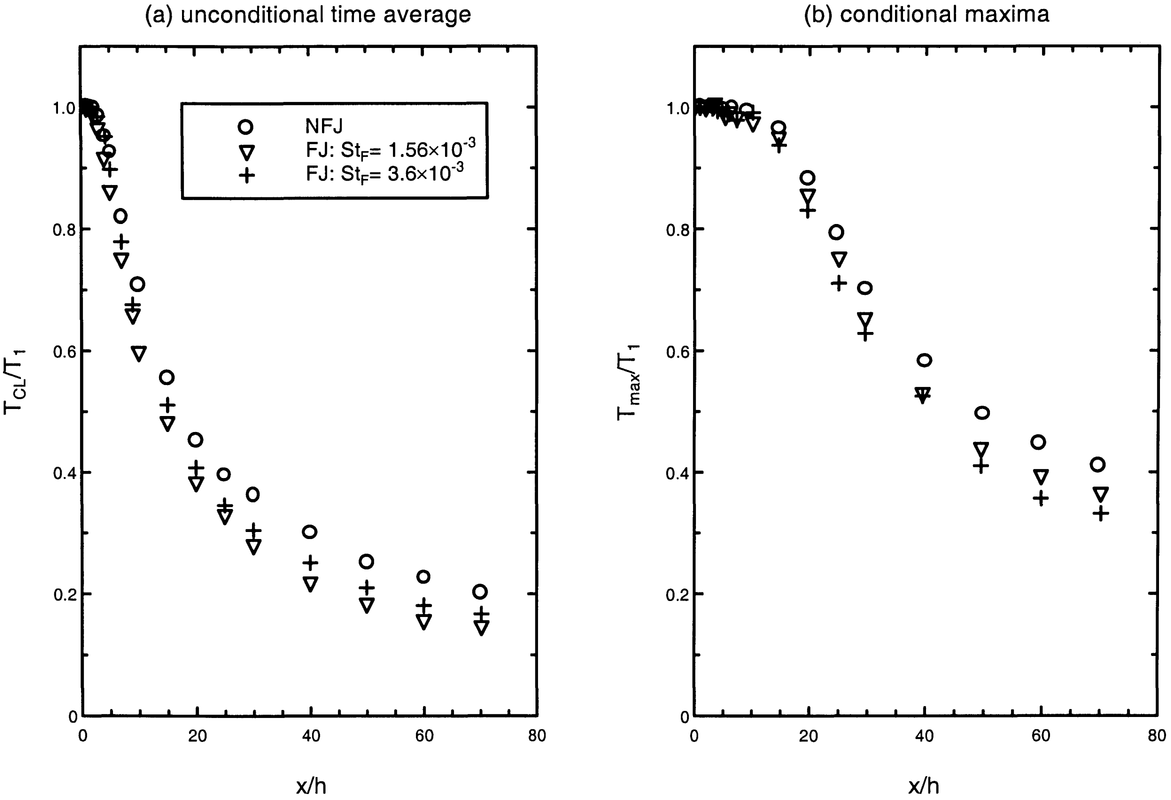

Figure 3: Centreline variations of (a) the mean temperature, T_{cl}/T_1, and (b) the conditional average of local instantaneous temperature maxima, T_{max}/T_1.

variation of St_F against L_2/h for the case of $U_1 = 26$ m/s and $L_1 = 31$ mm. It is seen in the figure that, as L_2 increases, St_F increases rapidly for $L_2/h < 7$ and changes little for $L_2/h \geq 7$. It is important to note that no change of the jet inlet conditions (i.e. h and U_1) occurs when varying L_2.

For present temperature measurements, we used the distance L_2 = 12mm (3*h*) and 53mm (13.25*h*) at which the Strouhal numbers is $St_F = 1.56\times10^{-3}$ and 3.6×10^{-3}, respectively. To make a non-flapping jet or $St_F = 0$, the chamber was removed from the nozzle, causing the distance $L_1 = 0$. Figure 3a shows the centreline mean temperature decay, T_{cl}/T_1, for St_F = 0, 1.56×10^{-3} and 3.6×10^{-3}.

Two observations can be made immediately from Figure 3a. Firstly, the mean temperature decays at a higher rate in the flapping jet than in the non-flapping jet. Secondly, the magnitude of the Strouhal number St_F has significant influence on the decay rate; the higher the value of St_F, the lower the decay rate of the mean temperature.

A likely explanation for the first observation is that the flapping motion enhances turbulent mixing between the primary warm jet fluid and the secondary cold ambient fluid so that the mean temperature decreases more quickly in the flapping jet flow. Another possible reason is that the decay rate of the mean temperature depends largely on the extent of the displacement of the entire jet between its two extremes. While the flapping jet occurs over a larger space (Mi et al., 2001), it is possible that the higher decay rate of the mean temperature results from a wider spread of the jet. Raman et al. (1993) conclude that the higher decay rate of the mean velocity is due only to the spreading, not to the enhancement of jet entrainment and mixing. Nevertheless, we believe that both the spreading increase and the mixing enhancement play a significant role in accelerating the temperature decay in the flapping jet. While the mean temperature decay rate cannot point unambiguously to the jet mixing rate, the conditional average of local instantaneous temperature maxima should serve as a better indicator because the decay of the temperature maxima is caused mainly, if not solely, by mixing (and thus heat transfer) between the warm and cold fluids. Figure 3b shows that the conditionally-averaging maxima, T_{max}/T_1 along the jet centreline. The result obviously supports our belief that the flapping jet can mix at a higher rate with ambient fluid.

The understanding of the above second requires the supplement of Figure 3b. As the Strouhal number St_F increases, the decay of the unconditional mean temperature becomes slower (Figure 3a) and, by comparison, that of the conditional maximum becomes faster (Figure 3b). This suggests that the flapping jet with the higher value of St_F is more efficient in mixing but that its mean temperature decreases less rapidly due to a narrower displacement of the entire jet. The narrower displacement results from the significantly higher frequency of flapping,, which can be deduced from the work of Mi et al (1998) for a mechanically precessing jet at different precessing frequencies.

Figure 4 shows the relative fluctuation intensity of the temperature along the jet centreline, $(\theta'/T)_{CL}$. The intensity is significantly higher in the flapping jet than in the non-flapping jet. This is expected because the large-scale, low-frequency flapping

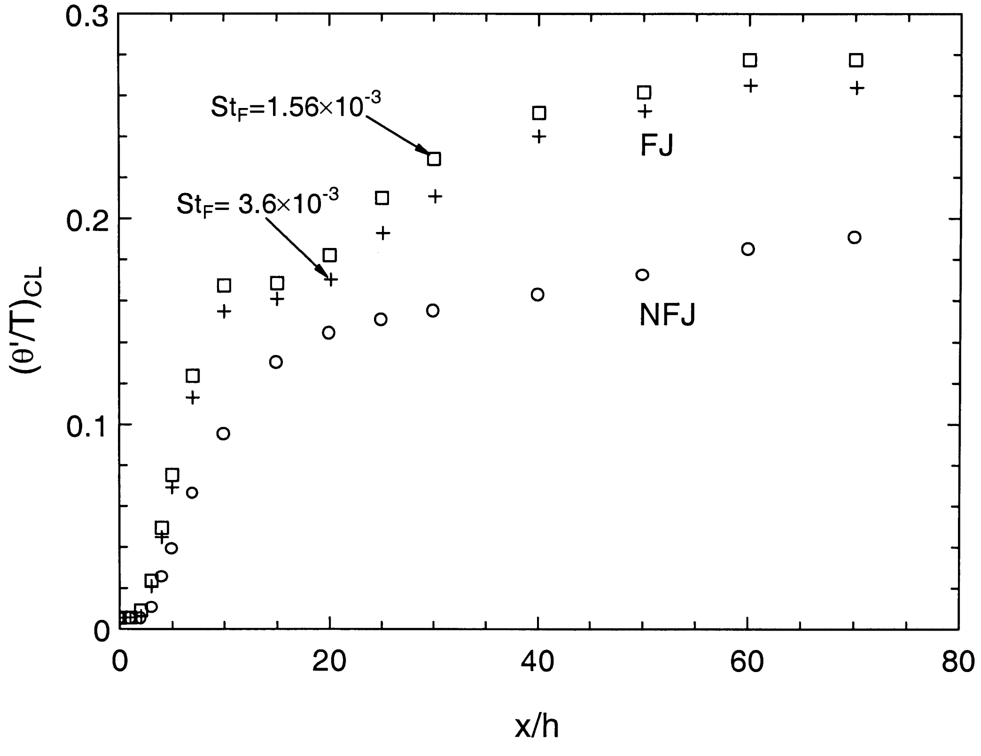

Figure 4: Relative fluctuation intensity of the temperature on the jet centreline.

motion induces some unmixed or partially-mixed (cooler) ambient air to cross the centreline. Furthermore, it appears from Figure 4 that the relative intensity decreases with increasing St_F due to the increasing displacement.

CONCLUSIONS

In conclusion, one of the fluidic nozzles developed by Mi et al. (1997) can well generate a self-excited flip-flop jet with practical significance. The flapping jet from this nozzle entrains, and then mixes, the ambient fluid at a higher rate than does the non-flapping free jet. More importantly, this study suggests that the Strouhal number of the flapping, St_F, has a significant impact on the jet mixing. The jet appears to provide a better performance in the mixing rate at high St_F.

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