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Scalar Mixing Characteristics of a Self-Excited Flip-Flop Jet Nozzle

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Abstract

This paper reports an experimental study that investigates a self-excited flapping jet nozzle which contains no external feedback loop and triggers. We first examine those factors that have significant influence on the Strouhal number, i.e., dimensionless frequency, of the flapping of an initially rectangular jet from the nozzle. Then we compare the scalar mixing characteristics of the flapping jet with those of a free (non-flapping) jet. Small temperature differential above ambient acts as a passive scalar marker and is measured with a fine (1.27 μm) cold-wire probe.

It is found that the mean scalar decays significantly faster in the flapping jet than in the non-flapping jet, indicating enhanced large-scale mixing and increased jet spreading due to the flapping motion. Concurrently, however, the flapping motion suppresses fine-scale scalar mixing. Moreover, the present study suggests that the flapping Strouhal number has a significant impact on the jet mixing. Higher mixing rates appear to occur at higher Strouhal numbers.

Introduction

Turbulent jets have been used widely in practical applications including combustors and ejectors. As a result, the understanding of mixing processes in jet flows has long been a central objective of fundamental research. In an effort to alter mixing characteristics, many practical systems have become far more complex and include such features as swirl, bluff-bodies and multiple jets. The ability to control the mixing characteristics of a jet can provide improvement in the performance of a nozzle for many applications. 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 can influence both the heat-flux characteristics and the pollutant emissions [5,6,15]. 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 [1] and mechanical techniques [2,3]. 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 nozzle [20], the precessing jet nozzle [4,13,14] and the more recently developed oscillating jet devices [8]. 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 and appear, in general, to increase the entrainment rate of the jet [15,16]. However, their measurements are almost exclusively of the velocity field, and very little scalar data exit.

In the present study, a rectangular fluidic nozzle (Figure 1) was used to generate a self-excited, low-frequency flapping jet [7,8]. Unlike the flip-flop nozzle of Viets [20], the present nozzle contains no external feedback loop and no control port. Also, no external trigger and no moving parts are needed for the flapping motion to occur. We surmise that this self-excited oscillation originates from an internal feedback process triggered by natural instabilities in specific geometric configurations. Luxton *et al.* [4] discovered a three-dimensional counterpart, i.e. the self-excited precession of a jet from an axisymmetric fluidic nozzle. The precessing jet has found application in industrial burners. Full-scale installations of commercial gas-firing precessing burners in high temperature 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 [5,6]. As such, the present new and simple flip-flop nozzle (Figure 1) also has potential benefits for industry.

In this study, we first look at the effect of the nozzle operating parameters on the dimensionless flapping frequency (or Strouhal

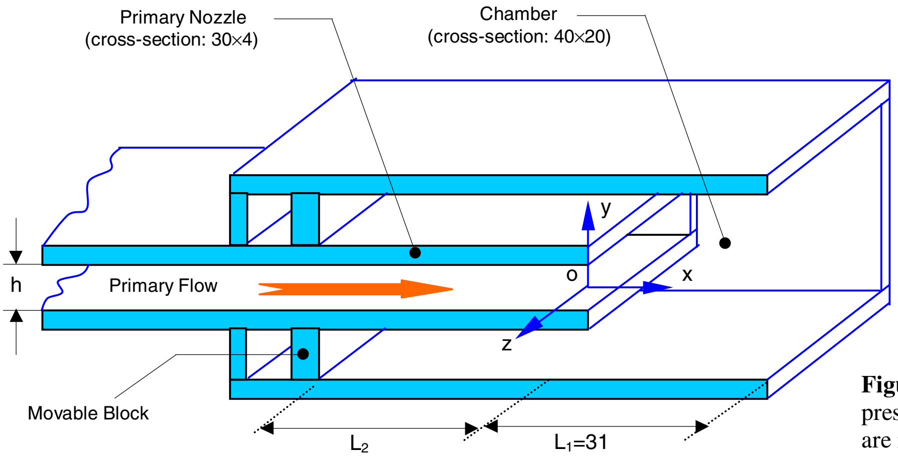

Figure 1. Schematic diagram of the present flip-flop jet nozzle. Dimensions are in *mm*.

numbers of the flapping) of a jet issuing from the fluidic nozzle detailed in Figure 1. Then we investigate the centreline variations of the passive scalar mean and turbulent fields of the flapping jet at different values of the flapping Strouhal number and a non-flapping free jet. Here the flapping Strouhal number is defined by $St_F \equiv f_F h/U_1$, where h is the inlet primary nozzle height and U_1 is the mean velocity at the inlet exit. We use small temperature differential above ambient to mark the passive scalar field whose measurements are realised by slightly heating the working fluid (air) before it enters the nozzle system.

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 flapping jet flow investigated here is generated by a novel and simple "flip-flop" jet nozzle recently developed by Mi *et al.* [8], which is a planar analogue of the axisymmetric precessing jet nozzle [4].

The nozzle consists of a rectangular cross-section chamber with internal dimensions 40 mm × 20 mm, 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 30 mm × 4 mm. The origin of the (x,y,z) coordinate system is chosen to be at the exit of the primary (inner) nozzle for both the flapping and the non-flapping jets (Figure 1). The choice of this coordinate system results in both the flapping and non-flapping jets having identical initial conditions.

We examined the effects of the distance between the primary nozzle exit and the chamber exit (L_1), the protruding length of the primary nozzle within the chamber (L_2) and the jet inlet bulk velocity (U_1) on the jet flapping frequency (f_F). The flapping 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 an in-house constant temperature circuit with an overheat ratio of 1.5. To investigate the mixing characteristics, present temperature measurements were made along the centreline of a slightly heated jet for $St_F = 0$ (non-flapping), 1.56×10^{-3} and 3.6×10^{-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 12-bit A/D converter on a personal computer. The square wave frequency responses of the hot and cold wires were tested and they were beyond 10 kHz and 2.5 kHz, respectively. These response frequencies are much higher than the frequency of jet flapping which is below 100 Hz for the present nozzle (see Figure 2). Based on the jet inlet parameters, the Reynolds number for the present temperature measurements is $Re_h \approx 15500$.

Results and Discussion

Figure 2 shows the effect of the jet inlet velocity U_1 on the jet flapping frequency f_F for the nozzle with $L_1 = 31$ mm and $L_2 = 48$ mm. As demonstrated, f_F depends strongly on, and increases linearly with, U_1. It is worth noting that similar results were observed for the precessing jet nozzle [9] where the precessing frequency replaces the present f_F. The approximately linear relationship between f_F and U_1 suggests a very weak dependence of the Strouhal number St_F ($\equiv f_F h/U_1$) on the jet inlet velocity U_1. As indicated on the plot, St_F exhibits almost no change as U_1 increases from 11 m/s to 86 m/s. It is hence concluded that the magnitude of St_F cannot be largely changed by varying U_1.

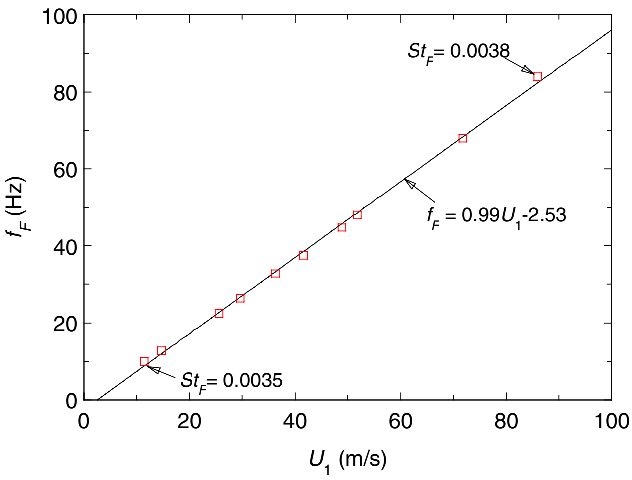

Figure 2. Effect of the jet inlet velocity U_1 on the jet flapping frequency f_F ($L_1 = 31$ mm and $L_2 = 48$ mm for the nozzle of investigation).

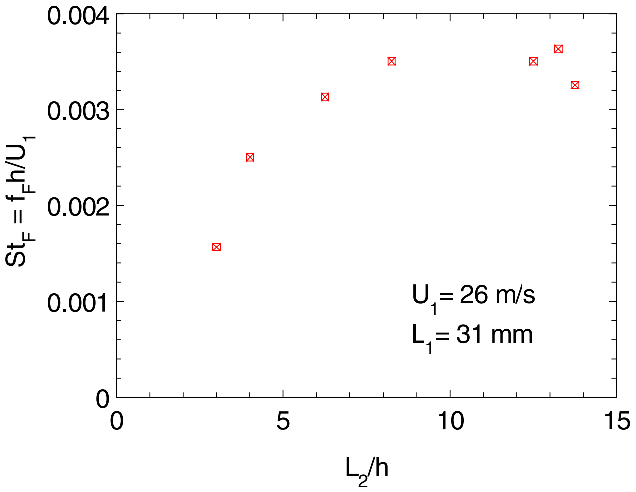

Figure 3. Variation of the Strouhal number of the flapping, St_F, with the protruding length L_2 for the case of $U_1 = 26$ m/s and $L_1 = 31$ mm.

In this context, to enable the control of St_F, various geometric changes of the nozzle have been explored. It was found that there is no significant effect of the distance between the primary nozzle (or jet inlet) exit and the chamber exit (L_1) on the flapping frequency. In fact, the flapping motion occurs continuously only over a narrow range of L_1 between 26 mm and 36 mm with the present nozzle configuration.

However, we have found that significant variation of St_F can be obtained by changing the distance (L_2) at which the primary nozzle protrudes in the chamber. Figure 3 shows the variation of St_F against L_2/h for the case of $U_1 = 26$ m/s and $L_1 = 31$ mm. As L_2 increases, St_F increases rapidly when $L_2/h < 7$ and changes little when $L_2/h \geq 7$. The jet ceases flapping at $L_2/h < 2$. Of importance, no change occurs to any inlet condition (i.e. h and U_1) when varying L_2. Clearly, the distance L_2 is a controlling parameter for the occurrence of the jet flapping. The reason is that the distance L_2 relates to a space over which a feedback path may be established to enable a communication between the upper and lower sides of the inlet rectangular jet (Figure 1). Such a feedback path, once established, acts like the external feedback loop tube of the flip-flop jet nozzles used by Viets [20] and Raman et al.

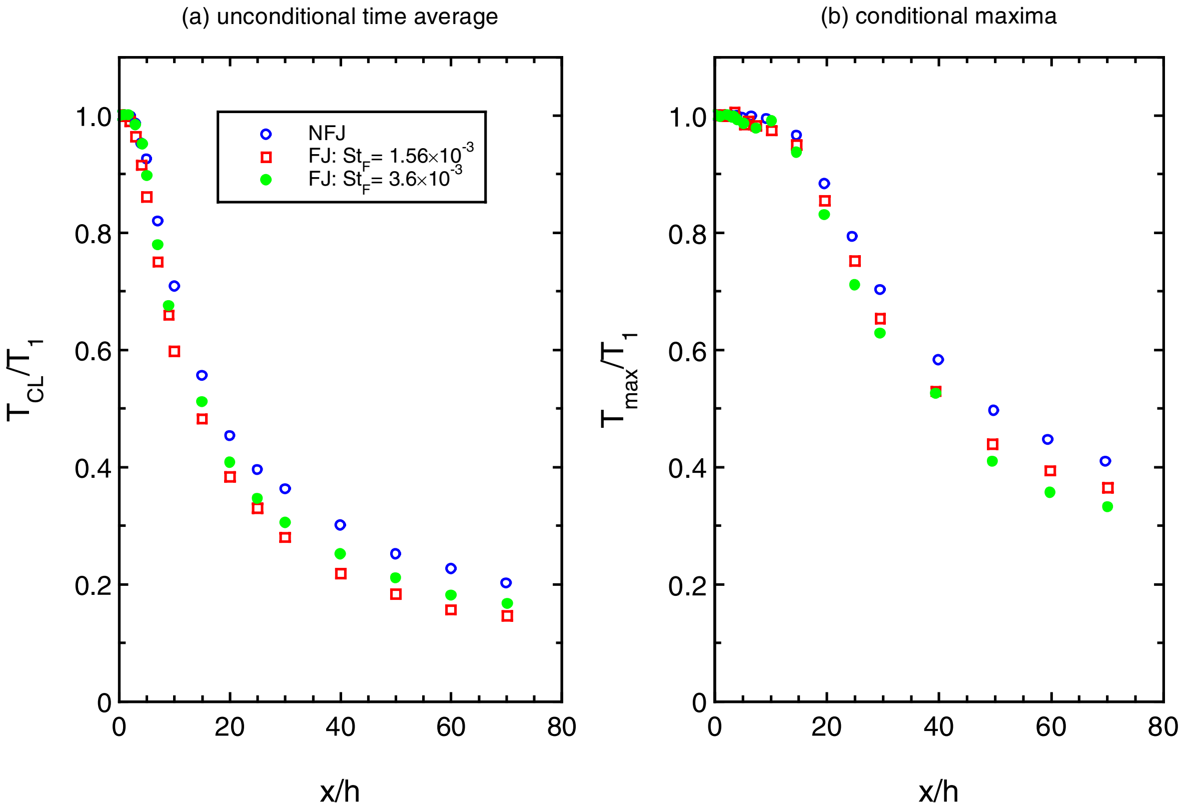

Figure 4. Centreline normalised profiles of (a) the mean temperature differential, T_{cl}/T_1, and (b) the conditional averaged temperature differential maxima, T_{max}/T_1. Here, T_1 is the mean temperature (≈ 50 °C) above ambient at the jet inlet exit. FJ and NFJ represent the flapping jet and non-flapping jet, respectively.

[17,18]. Once giving an enough distance of L_2, the pressure waves can travel around the jet from side to side so that the feedback process is formed within the chamber, causing the jet to oscillate in a planar fashion. The circulating "feedback" fluid between the protruding pipe and the chamber walls sets up the oscillation to occur continuously.

Present measurements of temperature differential above ambient ($Re_h \approx 15500$) were made for investigation of the scalar mixing. We chose L_2 = 12 mm (3*h*) and L_2 = 53 mm (13.25*h*) so that the corresponding Strouhal number is $St_F = 1.56\times10^{-3}$ and $St_F = 3.6\times10^{-3}$, respectively. The reference non-flapping jet, $St_F = 0$, was configured simply by removing the chamber. Figure 4a shows the centreline decay of the mean temperature differential, T_{cl}/T_1, for St_F = 0, 1.56×10^{-3} and 3.6×10^{-3}. Here, T_{cl} is the local mean temperature differential on the centreline and T_1 is the exit temperature above ambient.

It is immediately apparent from Figure 4a that the mean temperature decays more rapidly in the flapping jets than in the non-flapping jet. A likely reason for the differences observed is that the large-scale coherent (gross) flapping motion promotes turbulent large-scale mixing between the warm jet fluid and the cold ambient fluid so that the temperature decreases faster in the flapping jet flow. Another possible reason is that the decay rate of the mean temperature depends on the extent of the displacement of the entire jet between its two extremes. While the flapping jet occurs over a larger space [11], it is possible that the higher decay rate of the mean temperature differential results from a wider spread of the jet. Raman *et al.* [17] argue that the higher decay rate of the mean velocity of the flapping jet is due only to the jet spreading more widely. Nevertheless, we believe that both the wider spread and increased large-scale mixing lead to the mean temperature differential decaying more rapidly in the present flapping jets. While the mean temperature differential decay rate cannot be associated 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 4b shows that the conditionally-averaging maxima, T_{max}/T_1 along the jet centreline. Note that for the flapping jet T_{max} is the average of the maxima obtained over each flapping cycle while for the non-flapping jet T_{max} is the average of the maxima found over the time period of 0.018 seconds, corresponding to the average flapping period for the case of $St_F = 3.6\times10^{-3}$. Similar to the mean temperature case, T_{max}/T_1 also decays faster in the flapping jets. The result thus supports our belief that the large-scale mixing with ambient fluid occurs at a higher rate for the flapping jet than for the non-flapping jet.

However, an increased mean decay rate (conditional or unconditional) does not necessarily mean an increase in the uniformity of mixture composition. Figure 5 shows the relative fluctuation intensity of the temperature differential along the jet centreline, $(\theta'/T)_{CL}$, sometimes referred to as unmixedness. The intensity is significantly higher in the flapping jets than in the non-flapping jet. This implies that the centreline fluid is less well mixed at the molecular level in the flapping jets. It suggests that in the near field, at least, the large-scale flapping motion induces some unmixed or partially-mixed (cooler) ambient air toward the jet centreline.

It is also instructive to compare the two different Strouhal number jet flows. Figures 4a shows that the lower St_F jet has a higher centreline decay of the mean scalar, while Figure 4b shows that

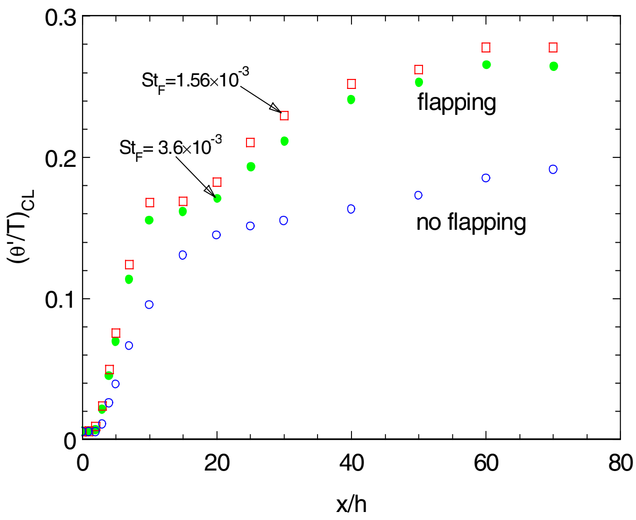

Figure 5. Relative temperature fluctuation intensity along the jet centreline.

the higher St_F jet has a higher rate of the conditional mean scalar. Moreover, the lower Strouhal number jet has the highest relative intensity of the scalar fluctuations (Figure 5). These observations suggest that the flapping jet with the higher St_F has higher mixing rates but lower decay rates of mean temperature due to narrowed displacement of the entire jet. The narrower displacement results from the significantly higher frequency of flapping. These observations are consistent with measurements of a mechanically precessing jet, which is an axisymmetric analogue of the flapping jet, at different precessing Strouhal numbers by Mi *et al.* [10]. They suggest that a higher frequency of large-scale oscillation results in better fine-scale mixing but poorer large-scale mixing.

Concluding Remarks

The present fluidic nozzle with no external feedback loop and trigger, developed by Mi *et al.* [8], generates a self-excited flip-flop jet with practical significance. Similar to the precessing frequency of an initially circular jet from the precessing nozzle [9], the flapping frequency of an initially rectangular jet from this nozzle increases linearly as the inlet velocity U_1 increases. This linear relationship results in the flapping Strouhal number being nearly independent of U_1. It has been found, however, that a significant variation of the Strouhal number can be made by changing the distance at which the primary inner nozzle protrudes in the chamber (Figure 1).

In this study, we have also investigated the centreline scalar mixing characteristics of the flapping jet and those of a non-flapping jet. Small temperature differential above ambient has been used as a passive scalar marker and measured with a cold-wire probe. It is found that the mean temperature decays faster in the flapping jet than in the non-flapping jet due to increased large-scale mixing and increased spreading of the jet. At the same time, the flapping motion results in poorer fine-scale mixing around the centreline. This study has also suggested that the flapping Strouhal number has a significant impact on the jet mixing. It appears that the jet mixing rates increase as the Strouhal number increases.

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