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Brief communication

The influence of inlet flow condition on the frequency of self-excited jet precession

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Abstract

A precessing jet flow can be generated naturally by a fluidic nozzle comprising a cylindrical nozzle-chamber with a large sudden expansion at its inlet and a small lip at its outlet. Such a precessing jet flow is offset with respect to the chamber axis, about which it rotates. The aim of the present study is to investigate the influence of the chamber-inlet configuration on the frequency of such precession. Three different inlet configurations, classified as long pipe, smooth contraction, and sharp-edged orifice plate, are tested. It is found that the frequency of precession from the orifice is highest, whereas that of the pipe jet is lowest. These differences appear to result partly from the distinct differences in their respective initial boundary layers.

1. Introduction

A continuous precession of an initially axisymmetric jet has been observed within a short cylindrical chamber following a large sudden expansion (Hallett and Gunther, 1984; Dellenback et al., 1988; Nathan et al., 1998). Distinct from a swirling motion, the precession of a jet refers to a "gyroscopic-like" motion of the entire jet about an axis in space other than its own centerline. The patented, wholly axisymmetric nozzle to generate such a precessing jet (PJ) flow, see Fig. 1, is characterized by a small inlet (diameter = d), a large chamber (diameter = D; length = L) and an outlet lip (Luxton and Nathan, 1988; Nathan et al., 1998). The configuration of the device must be within specific geometric ratios, namely $D/d \geqslant 4$ and $L/D = 2$–3.5 to enable the jet precession. The flow within the chamber is nevertheless bistable, so that an axisymmetric flow mode can also be generated, and the probability, or prevalence, of the precessing mode depends upon these ratios (Nathan et al., 1998). However, when an axisymmetric center-body (C-B) is mounted upstream of the outlet lip (Wong et al., 2003), the probability of precession is effectively unity, provided that the Reynolds number $\mathrm{Re} \equiv U_b d/v$ (where U_b is the bulk mean velocity of the jet at the inlet exit) is sufficiently high.

The PJ flow within the nozzle chamber is complex. Any alteration to the chamber configuration is expected to cause a significant change to the flow behavior such as the precession frequency (f_p). Mi et al. (1999) and Mi and Nathan (2000) have investigated the effect of various geometric parameters on f_p. They observed that f_p increases significantly with

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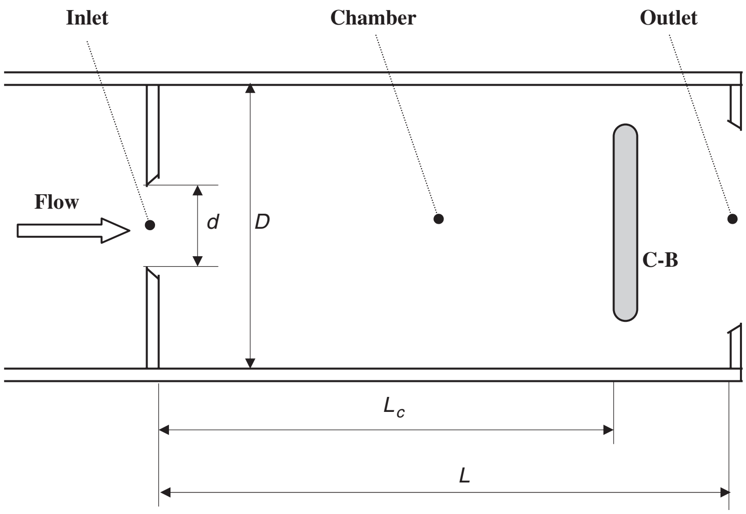

Fig. 1. Sketch of a precessing jet (PJ) nozzle with relevant notation.

increasing L (or L_c). It was also revealed that the precession frequency is even more sensitive to the distance between the C-B and the outlet exit. By comparison, the outlet diameter has little influence on f_p.

Wong et al. (2004) have demonstrated that the characteristics of the inlet flow to the chamber influences the probability of precession. Specifically the probability of precession depends on the type of inlet, and is greater with a sharp-edged orifice plate than with a long pipe, and least with a smooth contraction inlet. This indicates the importance of the inflow condition for the occurrence of jet precession. However, the effect of the inlet flow on the precession frequency f_p has yet to be investigated, prompting the present study.

In this Brief communication, the effect of different inlet configurations on the precession frequency and Strouhal number is examined. We use three different types of inlet: i.e., smooth contraction, which generates a 'top-hat' velocity profile, sharp-edged orifice, which leads to a near-field vena contracta, and a long straight pipe, through which fully developed turbulent pipe flow emerges. Previous investigations of an axisymmetric free jet [e.g., Mi et al. (2001a, b)] have shown significant differences between the near-field structures from similar configured nozzles. For instance, there are well-defined large-scale coherent structures in the near field from a smooth contraction, while such structures are considerably smaller and less coherent in the pipe jet. Likewise, the coherent structures in the orifice jet are formed at a considerably higher rate than in the contraction jet. Similar trends are anticipated to occur with such jets confined in a circular chamber. If this is true, the frequency of jet precession could be expected to be different for the three cases. Present measurements of f_p will check this speculation.

2. Experimental details

The geometric ratios of the nozzle have been selected to provide a high probability of precession (Wong et al., 2002). The nozzle system is supplied with filtered and compressed air at pressures of up to 500 kPa at room temperature of approximately 20 °C. The jet exit velocity can be varied by changing the supply pressure. The present study uses two geometrically similar, but different-sized, PJ nozzles, with $D = 26$ mm and 80 mm, respectively. These nozzles all have a C-B with $L_c/D = 2.2$ and identical expansion ratio of $D/d \approx 5$. However, they have different upstream incoming flow conditions, as specified below.

The large nozzle. Three inlet sections are separately connected to the chamber of $D = 80$ mm and their inlet exit diameters are all nominally $d = 16$ mm.The pipe inlet, with an upstream development length of about 63 inner diameters, is found to generate approximately a one-seventh power-law profile of the mean velocity, typical of a fully developed turbulent pipe flow. This pipe section was mounted concentric with, and normal to, a flat plate, to which the chamber is attached. The smooth contraction and the orifice plate are mounted to an upstream flow conditioner which provides swirl-free and unbiased flow. The smooth contraction inlet generates a 'top-hat' mean-velocity profile via a 5th polynomial contraction with a contraction area ratio of about 10 and a length to diameter ratio of about 1.5. The orifice plate is 5 mm thick and has a 45-degree chamfer facing downstream (Fig. 1).

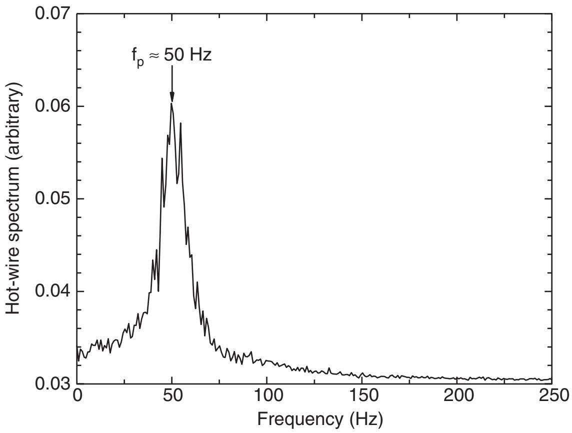

Fig. 2. Hot-wire spectrum obtained at Re $\approx$ 49000 for the PJ from the 26 mm nozzle.

The small nozzle. This system consists of a $D = 26$ mm cylindrical chamber, with an outlet diameter of 22 mm. The inlet diameter, d, was 5.2 mm for each of the three inlets. The upstream (air) supply tube used for the orifice plate and smooth contraction nozzles is of 25.4 mm inner diameter and 1 m long, with no screens or honeycombs installed to condition the incoming flow. This can be attached either a 5th polynomial smooth contraction section or a sharp-edged orifice plate.

The precession frequency f_p was measured using a hot-wire probe positioned downstream from and near to the chamber outlet exit. The exact probe location was optimized to obtain the signal whose power spectrum exhibits a distinct peak at the particular frequency of the precession. The hot wire was made from tungsten wire of 5 μm diameter and 1 mm length. The wire was operated with an in-house constant temperature circuit of overheat ratio 1.5. The signal from the circuit was offset, amplified and analyzed by a spectrum analyzer (HP3582A) for about a minute to obtain power spectra. A peak frequency of the jet precession for each nozzle configuration at a particular value of U_b was estimated from the corresponding spectrum. For some cases, the hot-wire signals were also digitized using a 12-bit A/D converter (PC30) on a personal computer. Fig. 2 shows a typical hot-wire spectrum, whose broad peak occurs around f_p for the PJ produced by the 26 mm nozzle at Re $\approx$ 49 000.

3. Results and discussion

Fig. 3 shows the jet precession frequency f_p against the Reynolds number $\mathrm{Re} \equiv U_b d/v$, instead of U_b, to provide information about Re although only U_b has been varied. All three inlet configurations have been tested for the large nozzle ($D = 80$ mm), while only the smooth contraction and orifice inlets have been used for the small nozzle ($D = 26$ mm). Several observations can be made immediately. First, the precession frequency f_p scales approximately linearly with U_b over the measured range of Re, regardless of the nozzle size and inlet configuration[1]. This is consistent with our previous measurements (Mi and Nathan, 2000, 2004). Secondly, there is a strong dependence of f_p on the chamber diameter D. As the diameter is increased from $D = 26$ mm to $D = 80$ mm, the precession frequency decreases dramatically from $f_p = (30-80)$ Hz to $f_p = (2.5-10)$ Hz. This is expected because, for a given nozzle configuration, the precession should occur approximately at a constant Strouhal number (Nathan et al., 1998) defined, e.g., by $\mathrm{St}_p \equiv f_p d/U_b$. Since the inlet diameter ratio of the two nozzles is $(d)_{\mathrm{large}}/(d)_{\mathrm{small}} = 16/5.2 \approx 3$, the velocity ratio must take $(U_b)_{\mathrm{large}}/(U_b)_{\mathrm{small}} = (d)_{\mathrm{small}}/(d)_{\mathrm{large}} \approx \frac{1}{3}$ to achieve the same Re, thus resulting in f_p being about $[(d)_{\mathrm{large}}/(d)_{\mathrm{small}}]^2 \approx 9$ times higher for the small than the large nozzle, broadly consistent with Fig. 3.

The third, and the most important, observation which can be made from Fig. 3 is that f_p depends strongly on the inlet geometric profile. As clearly demonstrated by the result for the large nozzle, f_p is greatest for the orifice and smallest for the pipe. The measurements for the small nozzle show a similar trend, despite there being no data for the pipe case. This trend signifies that, given the same initial diameter and velocity, a jet expanding into a large chamber from an orifice generally precesses much faster than does that from either a pipe or a smooth contraction. In other words, the

[1]Note that f_p only scales linearly with Re when U_b is varied independently. The frequency would scale inversely with Re if D were to be varied at constant U_b.

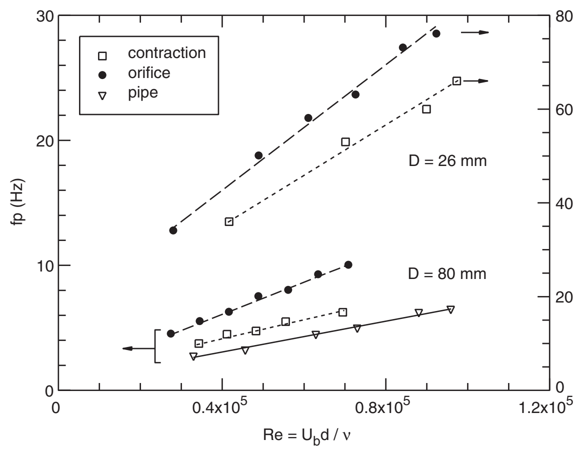

Fig. 3. Dependence of the precession frequency f_p on the Reynolds number Re.

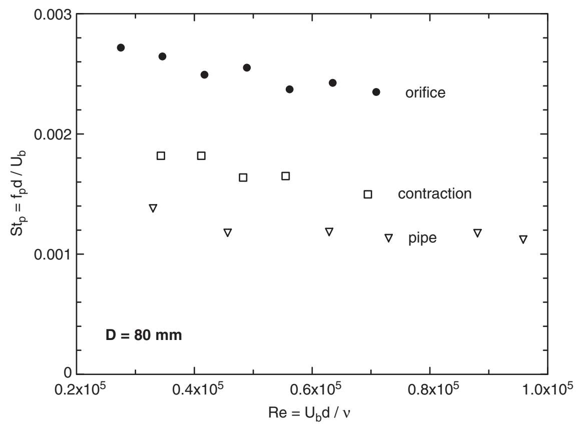

Fig. 4. Dependence of St_p on Re, measured for the 80 mm nozzle.

precession Strouhal number $St_p \equiv f_p d/U_b$ should be highest with the orifice inlet. This is indeed the case, as demonstrated in Fig. 4 that shows the result of St_p versus Re for $D = 80$ mm. The Strouhal number for the orifice jet, $St_p = (2.3-2.75) \times 10^{-3}$, is approximately double that of the pipe jet, $St_p = (1.1-1.4) \times 10^{-3}$, and 60% higher than the contraction jet, where $St_p = (1.5-1.8) \times 10^{-3}$.

This trend in St_p due to the different inlet configurations coincides with that of the Strouhal number (St_n) at which the natural instability occurs in circular free jets issuing from the similar nozzle configurations. Mi et al. (2001b) demonstrate that the Strouhal number of the primary ring-like vortices is higher from the sharp-edged orifice ($St_n \approx 0.7$) than from the smooth contraction ($St_n \approx 0.4$) and also that these large-scale coherent structures are rarely seen in the near field of a pipe jet. Presumably, the trends in St_n and St_p are both related to differences in the initial shear-layer of the jet, often characterized by the boundary-layer displacement thickness δ_d (or momentum thickness δ_m). The magnitude of δ_d (or δ_m) is very different for the three cases. The thickness is expected to be nearly zero for the sharp-edged orifice, and the measurements of Mi et al. (2001a) show that $\delta_d \approx 0.004d$ for the smooth contraction and $\delta_d \approx 0.063d$ for the pipe. These values can be used to estimate those for the present confined cases, since it is reasonable to expect that δ_d will not be influenced significantly by the addition of the nozzle chamber. Russ and Strykowski (1993) show that the wavelength of the initial instability in the shear layer of a jet increases proportionally with the boundary-layer thickness. It follows that the wavelength must be smallest from the orifice and greatest from the pipe, inherently differing their f_n and f_p (and thus St_n and St_p).

However, it is important to note that f_p is related (if at all) to the initial shear-layer of the jet in a much more complex fashion than f_n for a free jet. The latter is likely determined only by the characteristics of the shear layer, while the precession frequency of a confined jet is also influenced strongly by the chamber configuration, as demonstrated in Mi et al. (1999). Hence, more work in future is required to provide a detailed explanation of the relationship between f_p and f_n, with $f_n/f_p = \mathrm{St}_n/\mathrm{St}_p \approx 100-300$ for the present case.

We also note from Fig. 4 that St_p decreases slightly with an increase in Re for all three nozzles. However, this dependence seems to be weakest for the pipe jet, for which St_p is nearly independent of Re for Re > 40000.

4. Concluding remarks

We have investigated the dependence of a self-excited jet precession within an axisymmetric chamber on the inflow condition from three nozzles of the same diameter but different profiles. It is found that the precession Strouhal number St_p depends on the geometric profile of the inlet nozzle. Specifically for the present cases, St_p with a sharp-edged orifice is approximately double that from a long pipe, and 60% higher than that from a smooth contraction.

Using a mechanically precessing jet (MPJ) nozzle, Mi and Nathan (2005) and Schneider (1996) demonstrate that St_p is the primary parameter controlling the downstream development and mixing characteristics of the non-reacting MPJ flow. In comparison, the influence of Re is negligible. Similarly, Nathan et al. (1996) find that St_p has a dominant influence on the characteristics of a MPJ flame. These observations for the MPJ are also valid for the self-excited PJ cases (Mi and Nathan, 2004). On this basis it is reasonable to expect that the choice of inlet geometry of the PJ flow will influence the downstream flow and flame. Of course, other considerations, such as noise, also need to be considered.

Acknowledgements

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