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Effects of Flow Pulsing on Passive Scalar Mixing in a Turbulent Round Jet

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Abstract: This work presents a study on the effect of pulsing on a jet flow. Pulsing is used to modify jet inlet conditions with the objective of improving mixing. In this experimental work, a jet was slightly heated so that temperature could be considered as a passive scalar. The spectral behaviour of velocity and the passive scalar temperature was analyzed along the jet axis with and without pulsing. Low frequency pulsing ($f/f_S < 0.05$ f_S the Strouhal frequency) modifies the spectral composition of the velocity at the jet exit, but it does not affect the asymptotic profile reached in the fully developed region of the jet at approximately x/d = 30. The lower frequency pulsations travel far downstream and stay visible in the fully developed region on both the velocity and temperature spectra. This pulsing affects slightly the scalar spectral composition at the jet exit for only the highest frequency used (f/f_S = 0.04 (40 Hz) to 0.05 (80 Hz)). This indicates that mixing is improved since the change reflects mixing the main flow with the surrounding airflow. Also, the presence of low pulsing frequencies far downstream indicates the effect produced at the jet exit lasts into the far field.

Keywords: Turbulence, jet flow, passive scalar, mixing, pulsing

Nomenclature

b_{ru}	Velocity radial spreading rate coefficient
$b_{r\theta}$	Temperature radial spreading rate coefficient
b_u	Velocity decay rate coefficient on the jet axis
b_θ	Temperature decay rate coefficient on the jet axis
d	Jet pipe diameter
D	Enclosure diameter
f_s	Strouhal frequency
F	Frequency

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G_{uu}	Power spectrum of velocity fluctuations
$G_{\theta\theta}$	Power spectrum of temperature fluctuations
L	Pipe length
Re	Reynolds number
r_0	Pipe radius
$(r_{1/2})_u$	Half width of the velocity radial profiles
$(r_{1/2})_T$	Half width of the temperature radial profiles
T_a	Ambient temperature
T_j	Inlet jet temperature
u'	Velocity fluctuations
U_c	Jet central axial velocity
U_j	Jet inlet velocity
θ'	Temperature fluctuations

1 Introduction

The near field flow behaviour of jets determines their evolution in the far field. In this region, axisymmetric and helical shape structures form and as they continue to develop downstream of the flow, their motion and shape influence the evolution and spreading of the jets and their mixing process.

Different instability mechanisms were revealed and studied to understand the formation and development of large-scale coherent structures in the initial region of the jet. Many attempts were carried out to act on these mechanisms with active methods (Wiltse, J.M and Glezer A. (1998)) and passive methods (Rarker, R., Rajagopalan, S. and Antonia R.A. (2003)), the goal being to control the jet flows. Conclusions from Mi, J., Nobes, D.S. and Nathan, G.J. (2001) and Xu, G. and Antonia, R. A (2002) show that when the boundary layer at the jet exit is thicker and turbulent, instabilities are suppressed and no regular coherent structures are observed. Injection of small scalar structures at the jet exit using grids have been also studied (Buratini, P.R., Antonia, A., Rajogopalan, S., Stephens, M. (2004) and Buratini and Djenidi (2004), Benaissa, A., Lemay, J., Yimer, I., Djenidi, L. (2008)). The authors concluded that increasing turbulent intensity at the jet exit using grids weakens or inhibits the formation of large coherent structures and as a consequence, radial and axial spreading of velocity and scalar are reduced.

Pulsing was also used to modify jet exit conditions as a means of controlling the formation of coherent vortices or amplifying their impact on mixing, for instance Blacker, R., Cowling, K. Parker, V. Palero, J. Soria, A. (2006). Previous works focused on the dominant structures to set the pulsing frequencies (Crow S. and Champagne, F.H. (1971)). In fact, oscillations introduced by pulsing increased the entrainment (Bremhorst, K and Hollis, P.G (1990)) and consequently improved mixing. Many industrial applications use such processes to improve mixing.

In previous studies, pulsing was used to produce large velocity variations with amplitudes reaching 25% of the mean jet exit velocity (Blacker, R., Cowling, K. Parker, V. Palero, J. Soria, A. (2006)). In this study, pulsing at low amplitude (<6%) was used to introduce small perturbations at the jet exit without modifying the mean velocity profiles. The aim of this work was to study passive scalar mixing in a pulsed turbulent air jet. The pulsing frequencies were chosen below the Strouhal frequency. Pulsing was used to slightly change the jet inlet conditions similarly as obtained with a grid (Benaissa, A., Lemay, J., Yimer, I., Djenidi, L. (2008)). Results of velocity and temperature measurements are presented from a free round jet with and without pulsing. A comparison between velocity and temperature spectra is presented along the axis. Conclusions are drawn on the effect of jet pulsing on the jet flow spectral structures evolution.

2 Experimental Arrangement

In the present experiment, a jet flow was produced by a long pipe (L/d=180). The jet exited in a closed area with a diameter ratio of 50 (d/D) as shown in Figure 1. Air was supplied by compressed air passed through an electric heater that raised its temperature to 25°C above the ambient temperature. In these conditions, temperature acted as a passive scalar. The experimental setup consisted of a well-controlled and slightly heated jet. The jet exit velocity was set to 25 m/s which corresponded to a Reynolds number of Re = 7800.

The pulsing was produced by a piston related to a shaker as shown in Figure 1. The piston is operated in such a way that the volumetric flow rate introduced during the half cycle (∼2% of the main flow) stays constant when the frequency of the pulsing is increased. Because the net flow rate introduced by the pulsing was null, the mean inlet velocity and temperature profiles were unchanged with the pulsing; they are presented in Figure 2. The natural frequency of the jet was 1500 Hz which corresponded to a St of 0.28 close to the 0.3 reported in the literature (Crow, S. and Champagne, F.H. (1971)) (St = fd/U_j). Different flow rates and frequency ranges were tested to select the conditions where mean properties stay the same with and without pulsing. The pulsing did, however, produce an axial oscillating component of velocity that added to the mean flow to change the exit velocity spectral composition and maybe affect the entrainment. Velocity and temperature measurements were carried out with a DANTEC Streamline CTA. Velocity and temperature signals were acquired simultaneously and conditioned using an 8 channel dynamic signal conditioning module (WBK18) and were digitized with a 16 bit AD Wavebook from IOTEC. An automated traversing system allowed moving the two probes

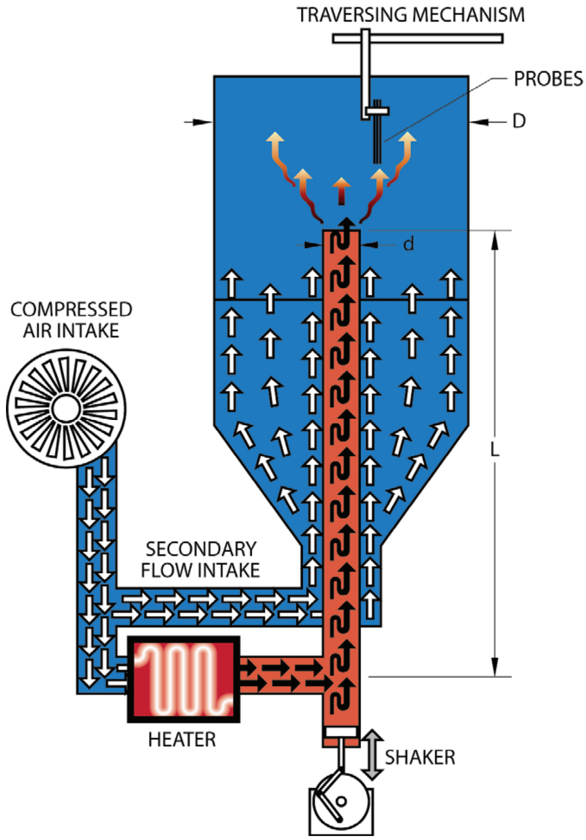

Figure 1: Experimental setup.

in three directions with a precision of 0.2 mm. Temperature and velocity were measured simultaneously at different positions in the jet flow. The signals were sampled at 5 kHz for a duration of 1 minute and 40 seconds which corresponds to 1000 to 8000 pulsing cycles and guarantees correct statistics.

Temperatures were measured with 1.27 μm Wollaston platinum wires and velocities were measured with 5.0 μm diameter tungsten wires. The wires were positioned at 0.9 mm from each other and in such a way to avoid contamination of the cold wire from the hot wire wake. The probes were located on different positions from x/d = 0 to 37 from the jet exit (d=4.7mm). The measurements were carried out without pulsing and with pulsing at frequencies from 10 to 80 Hz (corresponding to f/f_S between 0.006 and 0.05, f_S being the Strouhal frequency).

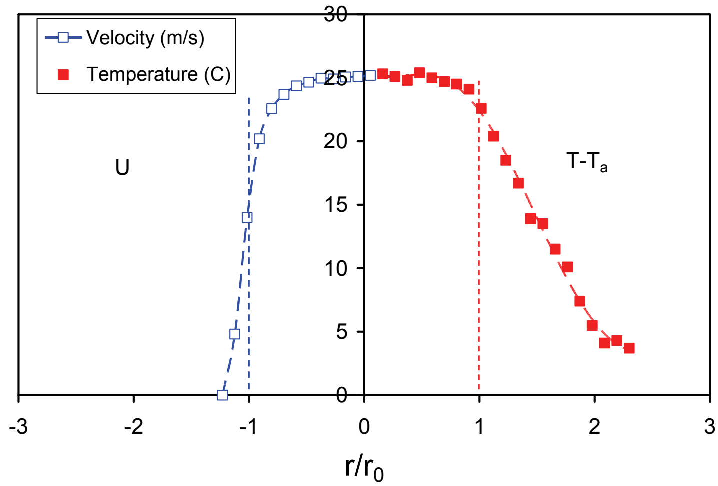

Figure 2: Velocity and temperature at the jet exit.

3 Results and Discussion

3.1 Mean velocity and temperature evolutions

The jet inlet profiles were measured and are presented in Figure 2 where half of each temperature and velocity profile is presented (r_0 being the radius of the pipe). The velocity profile shows a well developed pipe flow whereas the mean temperature shows a well mixed flow inside the tube with a well developed thermal boundary layer on the external wall of the tube. The experiments were carried out at the same exit velocity and at different pulsing frequencies. For all pulsing frequencies used, the centerline mean velocity and temperature on the jet axis are similar. As shown in Figures 3 and 4, no significant impact of the pulsing can be seen on the mean velocity and temperature evolutions along the jet axis. The velocity profile shows a region of constant velocity extending from 0 to about 5 diameters downstream. For temperature, the region of constant temperature is nearly visible over 1d distance from the jet exit. This can be explained by a more important radial spreading of temperature in the first region compared to velocity.

To analyse the radial spreading, the radial profiles of velocity and temperature at different stations downstream were measured and are presented in Figures 5 and 6. To summarize, the axial and radial evolutions of the jet, the main parameters are given in Table 1 and are compared to those reported in the literature. The axial decay for velocity is higher compared to the free jet shown in (Benaissa A. *et al* (2008); Lemay, J and Benaissa. A (2001); Capp S and Hussein J (1994)). In

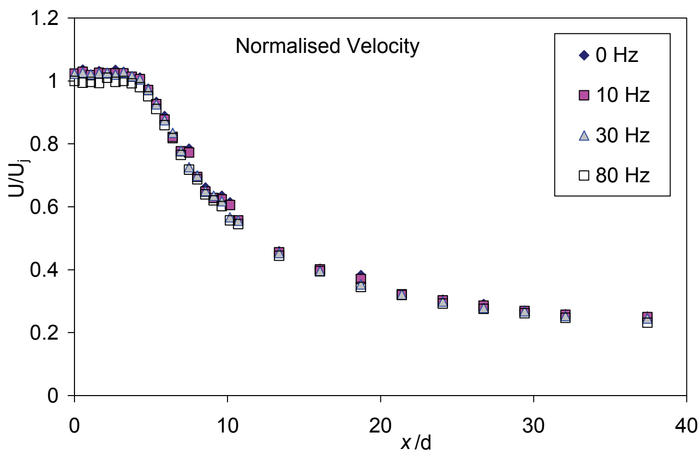

Figure 3: Mean axial velocity along the jet axis.

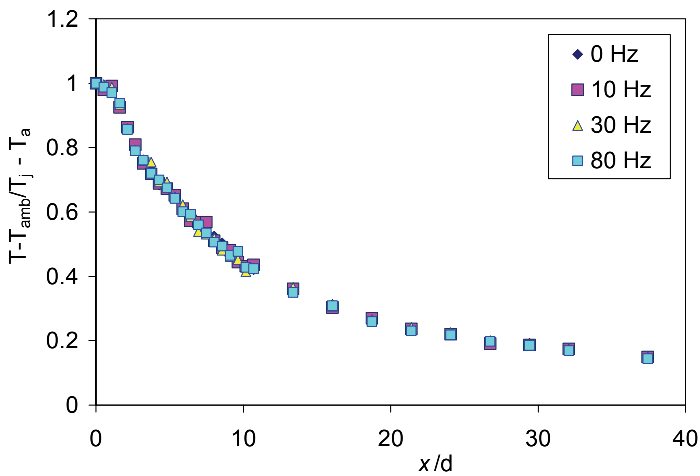

Figure 4: Mean temperature evolution along the jet axis.

contrast, the temperature axial decay is less than for a free jet. The half widths of velocity and temperature are comparable to those of a free jet. This implies that the radial spreading is similar to a free jet. The relationship used to define the axial decay rate and the radial spreading are given below:

$$\frac{U_j}{U_C} = \frac{1}{b_u}\left(\frac{x}{D} - \frac{x_0}{D}\right) \tag{1}$$

$$\frac{T-T_a}{T_j-T_a} = \frac{1}{b_a}\left(\frac{x}{D}-\frac{x_0}{D}\right) \tag{2}$$

$$\frac{2(r_{1/2})_u}{D} = 2b_{ru}\left(\frac{x}{D}-\frac{x_0}{D}\right) \tag{3}$$

$$\frac{2(r_{1/2})_T}{D} = 2b_{ra}\left(\frac{x}{D}-\frac{x_0}{D}\right) \tag{4}$$

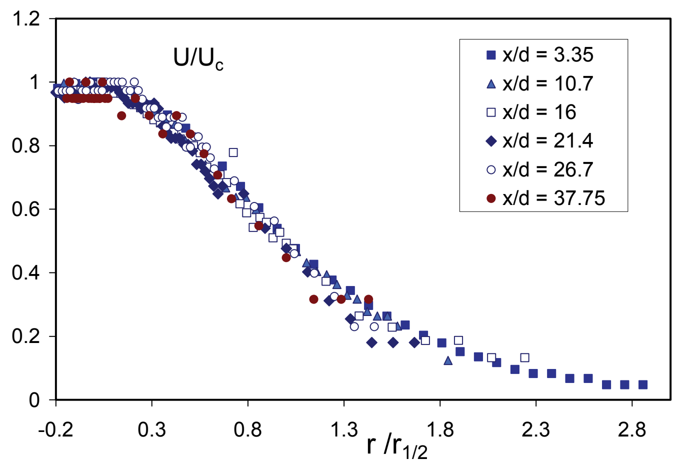

Figure 5: Radial velocity profiles along the jet axis.

Table 1: Mean velocity and temperature parameters

	Re	b_u	b_θ	b_{ru}	$b_{r\theta}$
Present Jet	7800	5.37	5.30	0.11	0.13
Benaissa *et al.* (2008)$\Delta T_j = 20^o$C	1.02E+05	5.9	3.42	0.10	0.11
J. Lemay and A. Benaissa (2001)	1.65E+04	6.0	-	0.09	0.10
S. Capp and J. Hussein (1994)	9.40E+04	5.9	-	-	-

3.2 Velocity and temperature fluctuation evolutions

Pulsing was used to create a change in the initial conditions of the jet without modifying its average dynamics. In fact, the pulsing affected the velocity fluctuation at the jet exit. Figure 7 presents the evolution of velocity fluctuation without pulsing

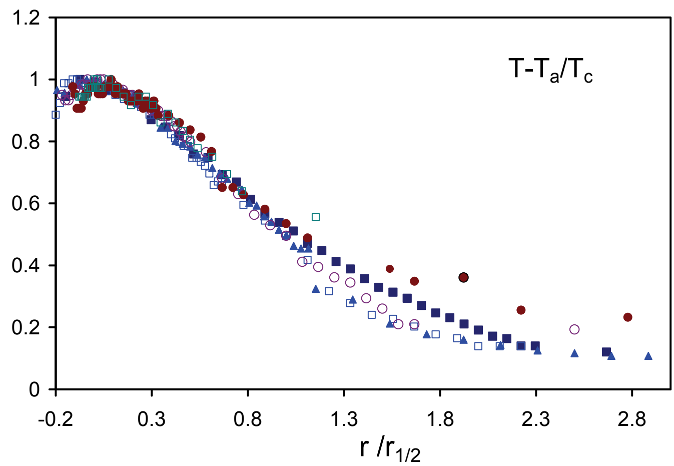

Figure 6: Radial temperature profiles along the jet axis (same legend as Figure 5).

and with pulsing at different frequencies. At the jet inlet with a frequency of 70 Hz (f/f_S =0.003), the velocity fluctuation was increased five times and went from 1 to 5% of the inlet velocity. At the maximum of the velocity fluctuation profile (x/d = 6), the fluctuation reached 10% of the exit velocity at a pulsing frequency of 50 Hz compared to 8% obtained without pulsing. It is interesting to note from Figure 8 that the pulsing did not seem to affect temperature fluctuation in a significant manner on the jet axis. The maximum difference of 2% in the case of no pulsing was obtained for a pulsing frequency of 70 Hz at x/d = 15. This finding will be investigated further using the spectra to understand where on the jet the pulsing affects the temperature fluctuations more.

3.3 Effect of pulsing on velocity spectra

Temperature was used as a passive scalar to mark jet turbulent structures. Velocity and temperature fluctuations were measured simultaneously at different axial and radial positions. Spectra were then calculated for different pulsing conditions and compared to the case with no pulsing. Velocity spectra are presented in Figures 9(a to h). Spectra were calculated for the case without pulsing and for six pulsing conditions. The spectra are normalized by the variances so that the integral under them is unity. At the jet exit, because the only velocity fluctuations are the ones produce by pulsing the normalised spectra do not collapse. The oscillations produced by the pulsing created a number of harmonics at higher frequencies. These harmonics tended to get mixed with the structures that the flow produced in its development

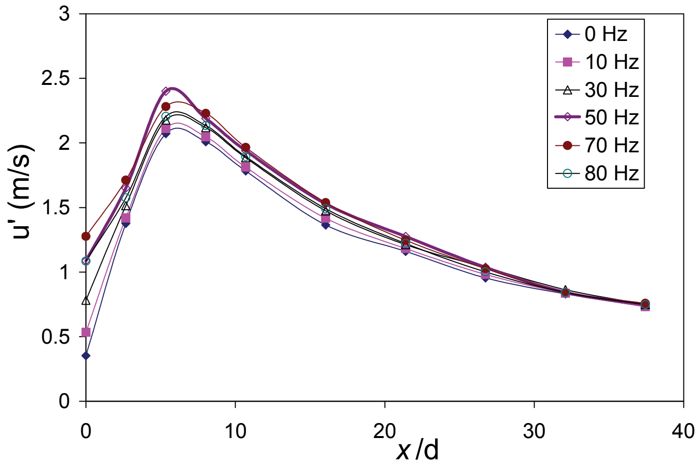

Figure 7: Axial velocity fluctuations along the jet axis.

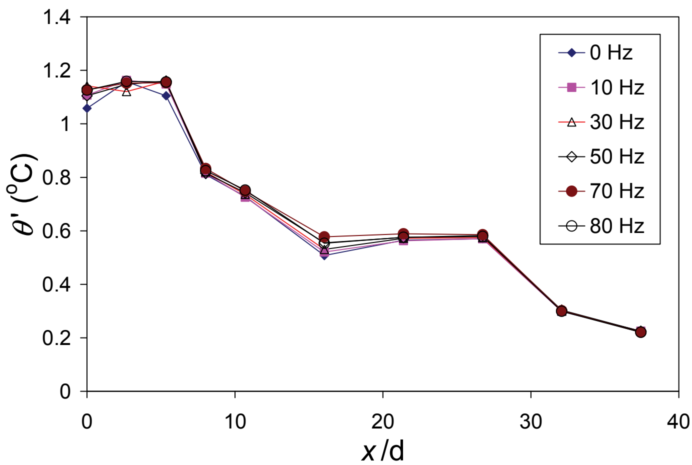

Figure 8: Temperature fluctuations along the jet axis.

downstream from the jet. With the exception of the lower pulsing frequency of 10 Hz, the general shape of the spectra did not change. The peculiarity of this low frequency was that it excited the jet on the increasing side of the spectrum. The excitations were amplified in the region right after the constant velocity zone (seen in Figure 4 for the velocity fluctuations). They then tended to diminish quickly. The asymptotic shape attained in the fully developed region of the jet, at around

30 d seemed to not be affected by the pulsing. However, low frequency pulsing at the maximum spectrum region maintained its signature far downstream of the flow as seen at 37d in Figure 9(h).

Temperature spectra are presented in Figures 10(a to h) for different pulsing frequencies. At the jet exit (Figure 10(a)), only frequencies above 50 Hz have their signature on the spectra. This suggests that the region of 'constant' velocity on average is modified to allow incursions of the surrounding low temperature fluid to a degree that does not affect the velocity distribution but exhibits little oscillations on the temperature signals. The oscillations were more visible at positions downstream; for example at x/d=10 (Figure 10(b)), frequencies that were not visible on the spectra at x/d=0 were apparent. For example, 30 Hz has its clear signature on the temperature spectrum. It was the lowest pulsing frequency clearly visible on the temperature spectrum. As we moved downstream, lower frequencies started to appear on the spectra. At the furthest position studied here (x/d=37) (Figure 10(h)), the lowest frequency appearing on the spectra was 20 Hz. All the spectra tended to the same asymptotic shape at x/d=37 with no effect of the pulsing frequency. The only difference with the velocity was that the low frequencies were more visible at this furthest position. For the velocity spectra, only three frequencies were apparent (20, 30 and 50 Hz). For the temperature spectra, the pulsing frequencies were more dominant compared to the velocity spectra. More frequencies were visible from 20 to 70 Hz.

One can follow the downstream evolution of the peak fundamentals for each pulsing frequency as shown in Figure 11(a) for velocity and Figure 11(b) for temperature. Theses fluctuations are normalized by the variance of the spectra. They represent the value of these normalized fluctuations relative to the non-pulsed case. As seen in Figure 11(a), velocity fluctuations at the jet exit are increased with the pulsing and with the increasing pulsing frequency. Moving downstream, the fluctuations tended to diminish. For pulsing frequencies above 30 Hz, the fluctuations were reenergized in the region between 10d and 25d. This region seems to be a zone of activity that may promote mixing when high pulsing frequencies are used. In fact, in this zone the scalar fluctuations (Figure 11(b)) were very high and reached a maximum for 70 Hz. This activity was concentrated on the jet axis. Similar analysis was used at x/d=5.35 but followed the fluctuation profiles along the radial direction. Figure 12 indicates that the presence of pulsing affects the radial profile of velocity fluctuations but the change in pulsing frequency has a minimal effect outside the jet centerline.

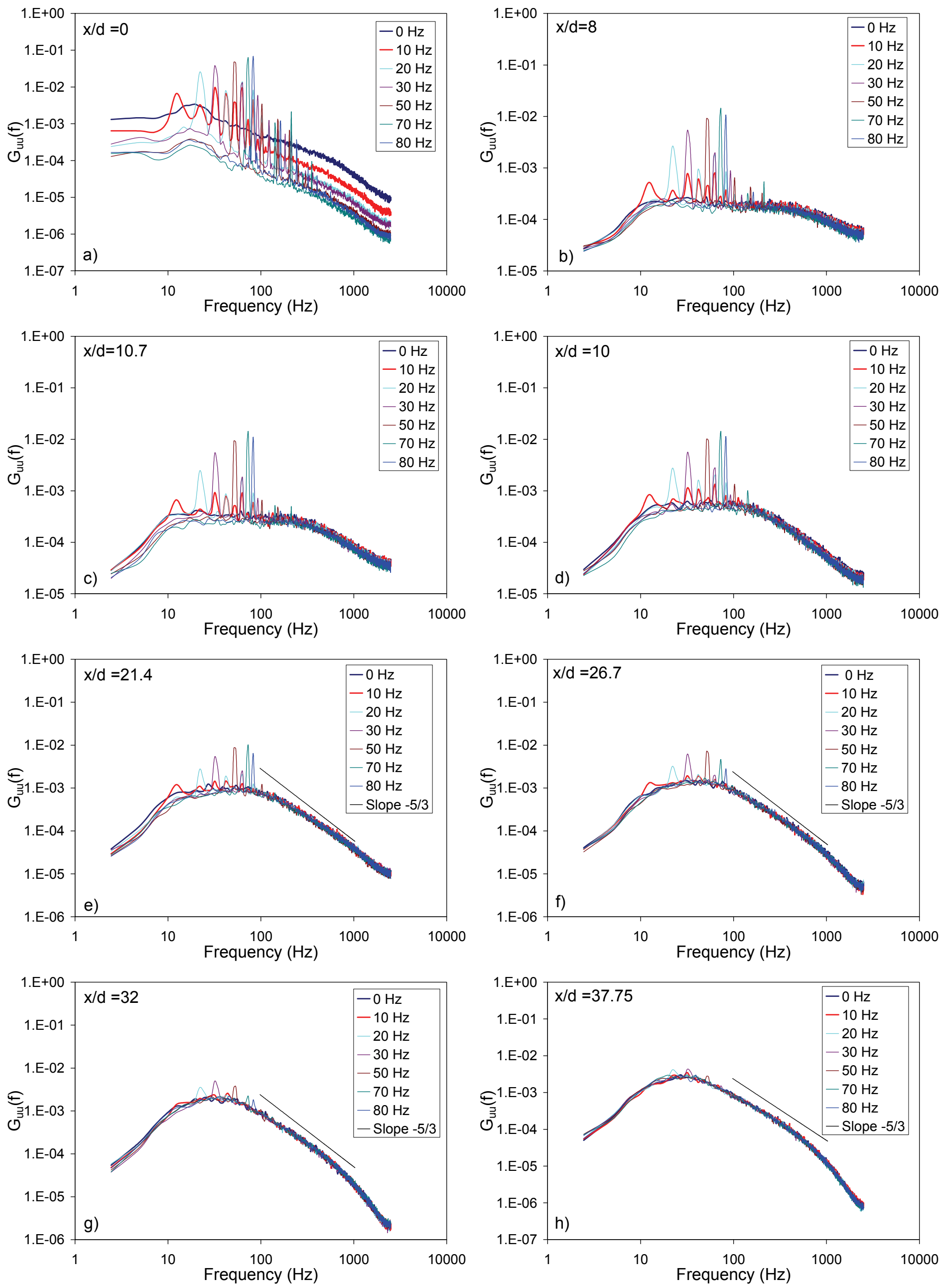

Figure 9: Velocity spectra evolution with and without pulsing on the jet axis.

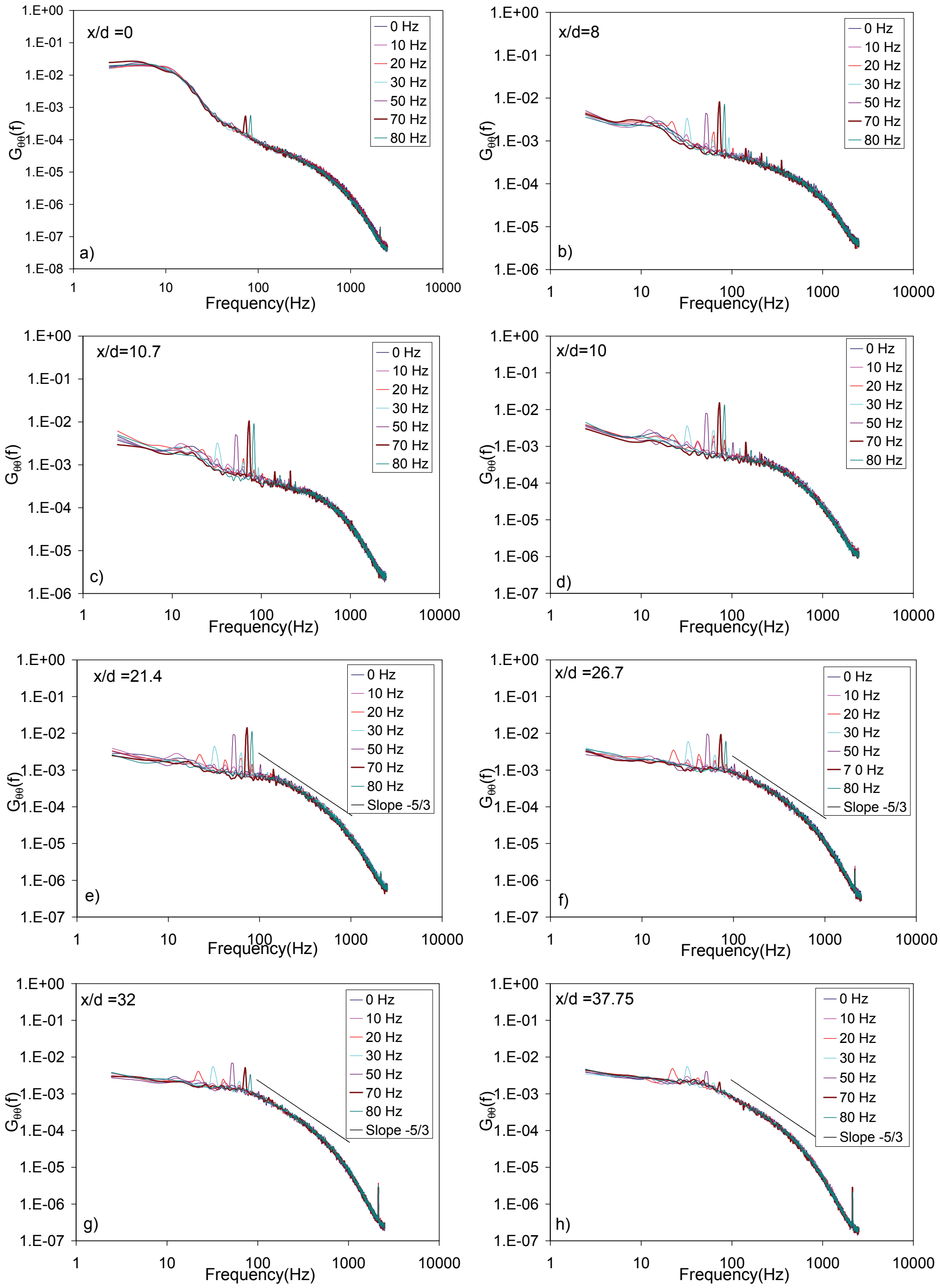

Figure 10: Temperature spectra evolution with and without pulsing on the jet axis.

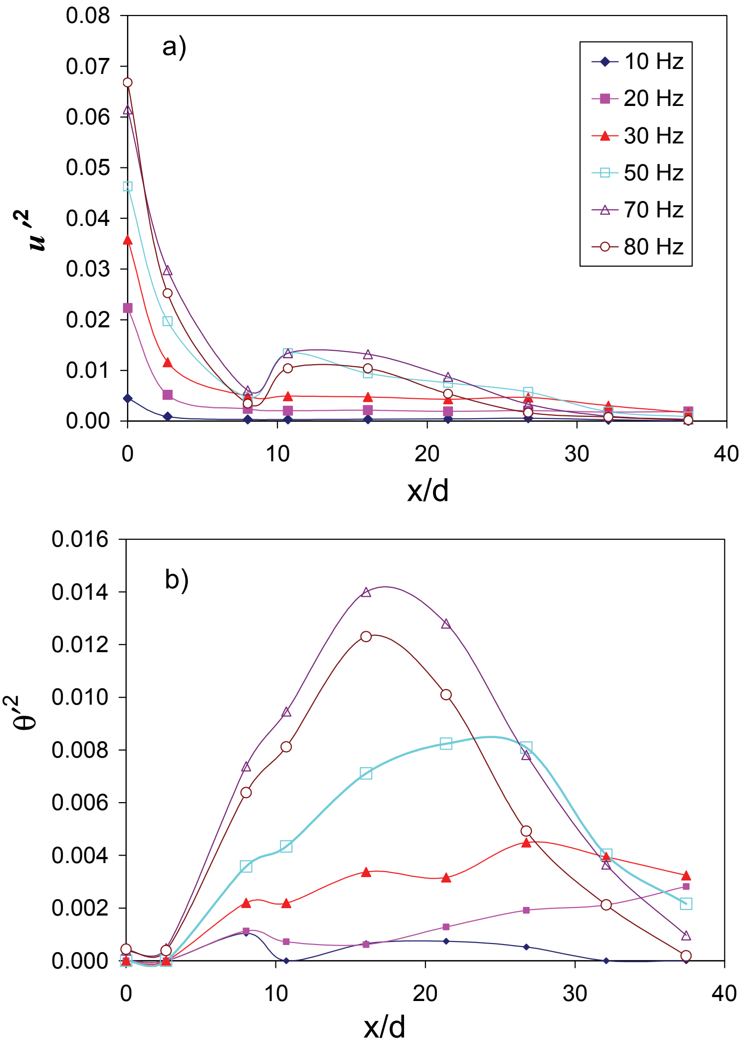

Figure 11: Evolutions of the energy in the fundamental peaks obtained from the spectra of velocity (a) and temperature (b) along the jet axis for different pulsing frequencies.

4 Conclusions

This work reports on the spectral behaviour of a passive scalar in a pulsed jet. Even though pulsing at low frequencies ($f/f_S < 0.06$) modifies the spectral composition of the velocity at the jet exit, it did not affect the asymptotic profile reached in the

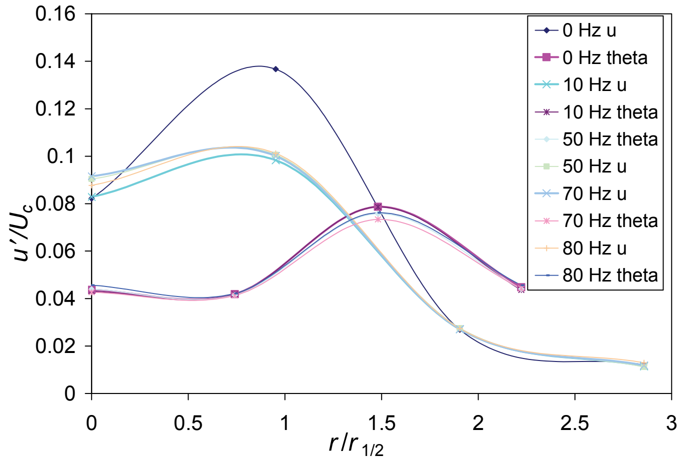

Figure 12: Evolutions of the energy in the fundamental peaks obtained from velocity and temperature spectra along the radial direction at x/d = 5.4 for different pulsing frequencies.

fully developed region of the jet at around x/ =30. Low frequency pulsations travel far downstream and stay visible in the fully developed region on both velocity and temperature spectra. The pulsing slightly affected the scalar spectral composition at the jet exit only for the highest frequency used (50Hz to 80Hz). This indicates that mixing was improved since the change reflected mixing the main flow with the surrounding air flow. The presence of low pulsing frequencies far downstream indicated that mixing was improved in the far field. To quantify mixing improvement, radial measurements were also carried out and they showed little effect of the pulsing along this direction.

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