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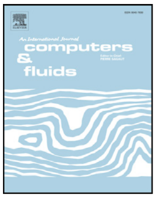

Numerical study of amplitude and frequency effects upon a pulsating jet

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ABSTRACT

Sinusoidal pulsation effects on a turbulent plane jet are investigated numerically. In the nozzle exit, the flow is characterized by a uniform temperature, and submitted to a longitudinal and periodic velocity disturbance: $\bar{u}(x, y, t) = \bar{u}_0 + a \sin(\omega t)$. Upon mixing the spreading and heat exchange with the surrounding medium, properties are influenced obviously by pulsation in the potential core region but they are similar to the steady jet after the end of the potential core.

1. Introduction

The majority of the jet flows are of a turbulent origin, which justified many studies and results concerning the production of an abundant bibliography on the turbulent jet. Among these researches, some investigated the influence of an initial perturbation on the jet structure, which has a considerable practical interest in widespread industrial applications such as the mixing process conditions, the propulsion force of the aircraft engines, the efficiency of combustion in the mixing chambers, the pollutants dispersion in industrial sites and finally, in the habitable spaces, the amount of the air diffused and therefore the thermal comfort of the users [1].

In the literature, we note that the majority of works which were interested in this problem are experimental. Some of them studied the influence of a periodic acoustic excitation on the structures of a turbulent plane jet (for example: Becker and Massaro [2], Farrington and Claunch [3], Goldschmidt and Kaiser [4], Hsiao and Huang [5], Hussain and Rayclark [6], Hussain and Thompson [7], Hussain and Zaman [8], Kelmanson [9], Thomas and Goldschmidt [10], Thompson [11], Sato [12], Vulis et al. [13], Zaman and Hussain [14]).

At the numerical level, and in our research team, the solutions were obtained concerning the plane or circular jet submitted to a sinusoidal excitation in a laminar mode after studies carried out by Marzouk et al. [15,16]. The results showed that the development of the pulsed jet depends, at the same time, on the pulsation amplitude and the Strouhal number. Also, the pulsation does not modify the flow parameters in the plume region (very far from the nozzle). On the other hand, it accelerates the initial development of the jet and improves the diffusion and the entrainment of the ambient air in the first diameters.

At the experimental level, a turbulent plane air jet subjected to a transversal acoustic excitation was studied by Goldschmidt and Kaiser [4] and Thomas and Goldschmidt [10]. They found that the jet spreading and disintegration rates are sensitive to the excitation frequency, although the resemblance between the field of the pulsed and non-pulsed flow is maintained. Thomas and Goldschmidt [10] showed that the two-dimensional jet can be much more sensitive to the external disturbances than the three-dimensional jet dealt with by Thompson [11] and Hussain and Rayclark [6]. The large increases in the spreading rate are noted at Strouhal numbers St of 0.29, 0.34, 0.42 and 0.48.

This increase can go up to 45% compared to the steady jet in the similarity area (for $x/w > 20$) and for great pulsation amplitudes. These results are in good agreement with the increase in the jet spread observed by Goldschmidt and Kaiser [4] for a two-dimensional jet with a Strouhal number of 0.42 and by Chambers and Goldschmidt [17] at 0.38. However, the latter does not mention the value of the amplitude. At Strouhal numbers higher than 1, Thomas and Goldschmidt [10] found a little variation of the spreading rate. Moreover, they note that the increases in the spreading rate are

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Nomenclature

a	pulsation amplitude (m/s)
A	dimensionless pulsation amplitude
E	dimensionless turbulent kinetic energy dissipation
f	pulsation frequency (s^{-1})
Fr	Froude number $\frac{u_0^2}{g\beta(T_0-T_\infty)w}$
g	gravity constant (m s−2)
Gr	Grashof number based on the width of the nozzle $\frac{g\beta(T_0-T_\infty)w^3}{\nu^2}$
k	turbulent kinetic energy (m^2 s−2)
p	pressure (Nm^{-2})
Pr	Prandtl number, $\mathrm{Pr} = \nu/\alpha$
St	Strouhal number, $St = f\ w/u_0$
T	temperature (K)
t	time (s)
w	width of the nozzle (m)
u,	v : longitudinal and transversal velocity components ($m\ s^{-1}$)
x,	y : dimensional longitudinal and transversal coordinates (m)
Greek symbols	
α	thermal diffusivity of the fluid ($m^2\ s^{-1}$)
β	thermal expansion coefficient (K^{-1})
θ	dimensionless temperature, $\theta = \frac{T-T_\infty}{T_0-T_\infty}$
λ	thermal conductivity of fluid ($W\ m^{-1}\ K^{-1}$)
ν	kinematic viscosity of the fluid ($m^2\ s^{-1}$)
ρ	density of the fluid ($kg\ m^{-3}$)
ε	turbulent kinetic energy dissipation (m^2 s−3).
υ	kinematic viscosity of the fluid ($m^2\ s^{-1}$).
υ_t	turbulent viscosity ($m^2\ s^{-1}$).
σ_t	turbulent Prandtl number
τ	dimensionless time
ω	angular velocity, $\omega = 2\pi f$ (rd s−1)
Subscripts	
c	jet axis
0	nozzle exit
∞	ambient environment
Superscripts	
–	time average
′	fluctuation components

accompanied by increases in the turbulent intensities which significantly occur at Strouhal numbers St of 0.34 and 0.44. In addition, the measurements in the initial region (for $x/w < 20$) show that the acoustic excitation affects the flow structure.

In the case of the excited turbulent plane jet, Hussain and Rayclark [6], Kelmanson [9] and Vulis et al. [13] found larger increase in the entrainment rate closer to the nozzle. In another publication, Hussain and Thompson [7] studied experimentally the response of a plane free air jet submitted to a controlled sinusoidal disturbance. The excitation was introduced with a loudspeaker placed into a plenum chamber upstream the jet. The excitation amplitude is fixed at 1.4% of the ejection velocity, the Strouhal number ranges from 0.15 to 0.6 whereas the Reynolds number ranges from 8000 to 31,000. They observed that the excitation influence on the mean velocities and fluctuating fields was much lower than in the circular jet studied by Zaman and Hussain [14] and Hussain and Zaman [8].

They also found that the growth rate was much higher on the jet axis and the wavelength was much smaller in the shear layer. The fundamental wave attains its maximum amplitude at St = 0.18 on the jet axis and at St = 0.45 in the shear layer. In addition, Hussain and Thompson [7] show that the growth rate and the disturbance wavenumbers increase with the Strouhal number both in the shear layer and on the jet axis, but tend to approach constant values at higher Strouhal numbers. Thereafter, they conclude that at a low Strouhal number, the perturbed plane jet acts as a non-dispersive waveguide.

Hsiao and Huang [5] studied the dynamic coherent structure in the development region of the plane jet under an acoustic excitation experimentally by hot-wire and with a smoke-wire visualization. The results showed that flow property behavior is related to vortex formation and the merging processes which are the dominant mechanisms controlling the flow behavior in the development region of a plane jet.

The vertical evolutions and spreading characteristics of a low-speed plane jet under anti-symmetric long-wave excitations are studied experimentally by Yung-Lan et al. [18]. The excitation is introduced with two oscillating strips located at the nozzle exit. The results showed that the mixing and spreading properties are influenced obviously by the long-wave perturbation after the end of the potential core, say after $X = 9$ or 10 (where $X = x/w$ is the dimensionless longitudinal coordinate).

Smoke-wire visualizations are carried out by Farrington and Claunch [3]. They proved that the periodic, large-amplitude, low-frequency perturbations on a planar jet can increase the spreading and mixing of a jet with the surrounding fluid. Indeed, the mixing that occurred at Strouhal number of 0.168 was about 32% greater at seven nozzle widths than that of the natural jet.

As an indication, a detailed bibliography study concerning a pulsed jet was carried out by Marzouk [19]. This work made it possible to determine two types of motivation. At the practical plan, the pulsation accelerates considerably the initial development of the jet and clearly improves diffusion and entrainment in the nozzle vicinity. Indeed; the entrainment rate occurred when the pulsed jet at 2% was about 20% greater than that of steady jet dealt with by Crow and Champagne [20]. At the fundamental level, the superposition of a periodic disturbance to the steady jet constituted a very fruitful method of investigation to understand the transition to turbulence.

The effects of pulsation on the jet behavior, at fixed moments, were discussed in the previous study (Marzouk et al. [21]). In this work, temporal evolutions of turbulent plane jet subjected to a sinusoidal disturbance of the ejection velocity were investigated numerically. Dynamics, thermal and turbulent behaviors of the pulsed jet are examined while varying Strouhal number, pulsation amplitude and Froude number.

2. Assumptions

We consider a vertical flow ejected from a plane nozzle emerging into an atmosphere. The equations governing the problem are written in a Cartesian coordinates system whose axes origin is located in the middle of the nozzle (Fig 1). We consider also the following assumptions:

❶ The jet and the ambient environment consist of the same fluid (air).
❷ The nozzle width is supposed larger than its thickness w in order to neglect the edges effects and to have a two-dimensional flow, the second component of the transversal velocity always supposed null.
❸ The fluid density varies linearly with the temperature in the buoyancy force term and it is considered constant elsewhere, according to the Boussinesq approximations.
❹ The jet is submitted to a longitudinal and periodic disturbance of the ejection velocity $u(t) = u_0(1 + A\sin(\omega t))$.
❺ The flow is supposed in a turbulent, non-stationary, fully developed mode at a high Reynolds number.