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Numerical study of free pulsed jet flow with variable density

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Abstract

In this work, we propose a numerical study of a free pulsed plane jet with variable density in unsteady and laminar modes. At the nozzle exit, the flow is characterized by a uniform temperature and submitted to a longitudinal and periodic velocity disturbance: $u = u_0(1 + A\sin(\omega t))$. A finite difference method is performed to solve the equations governing this flow type. The discussion relates to the effect of the most significant parameters, such as the pulsation frequency and amplitude, on the flow characteristic fields. The effects of Reynolds and Galileo numbers was also examined. The results show that the pulsation affects the flow in the vicinity of the nozzle, and further, the results of the unsteady mode join those of the steady non-pulsed jet. The results state also that the Strouhal number has no influence on the flow mixture degree, whereas the amplitude of pulsation affects, in a remarkable way, the mixture and, consequently, the concentration core length.

Keywords: Pulsed jet; Variable density; Unsteady and laminar modes

1. Introduction

Jet type flows where density varies strongly are met in various engineering applications related to energy and propulsion, such as cooling turbine blades of turbo shaft engines, welding in aerodynamic and hydrodynamic areas, fuel injection in burners, etc.

In practice, these flows are turbulent, and they have been studied in experiments to identify the jet regions and to determine the variation laws of the characteristic parameters of these flows [1–8]. The emission conditions adopted by these authors are the developed tube jet type.

In numerical studies, turbulent jets with variable density were analyzed by adopting first- and second-order turbulence models [9,10]. The differences between the results of the two models were analyzed by Sanders et al. [11], who showed that the second-order closure model describes the experimental results well. The emission profiles considered are the developed tube jet type.

The solutions suggested in laminar mode are obtained by numerical resolution of the equations governing this flow type [12]. The initial profiles considered are uniform or parabolic. However, it is known that the flow properties of a jet can be modified by the application of a periodic force, such as an acoustic excitation.

The majority of works performed on pulsed jets are experiments [13–20]. Chambers et al. [13,14] studied a turbulent plane jet subjected to an acoustic excitation, and showed, for a large broad frequency band, that the sound fields produce changes in the mean flow structure. For some frequencies, it was possible to increase the turbulent intensities and Reynolds stresses in the jet initial region, and these effects decrease for distances far from the nozzle. Thomas and Goldschmidt [15] studied experimentally the same flow type as Chambers et al. in the initial and similarity regions. They found that the increase of the expansion rate is larger for Strouhal numbers (St) ranging between 0.29 and 0.48. This increase can go up to 45%

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Nomenclature

b	nozzle thickness, m
g	gravity constant, m s^{-1}
D	diffusion coefficient, m^2 s^{-1}
C_p	specific heat at constant pressure, J kg^{-1} K^{-1}
C_v	specific heat at constant volume, J kg^{-1} K^{-1}
R	ideal gas constant, J mol^{-1} K^{-1}
P	pressure, Pa
m	mass fraction
M	molecular mass, g mol^{-1}
u, v	velocity components, m s^{-1}
U, V	dimensionless velocity components
x, y	longitudinal and transverse coordinates, m
X, Y	dimensionless longitudinal and transverse coordinates
f	pulsation frequency, Hz
F	dimensionless mass fraction
t	time, s
T	temperature, K
T_f	period, s
Ga	Galileo number $\left(\frac{gb^3}{v_0^2}\right)$
Re	Reynolds number $\left(\frac{u_0 b}{v_0}\right)$
Sc	Schmidt number $\left(\frac{\mu_0}{\gamma_0}\right)$
St	Strouhal number $\left(St = \frac{b}{T_f u_0}\right)$
Pr	Prandtl number $\left(\frac{\mu_0 Cp_0}{\lambda_0}\right)$
w	initial densities ratio $\frac{\rho_\infty}{\rho_0}$
X_F	dimensionless concentration core length

Greek symbols

ρ	density, kg m^{-3}
θ	dimensionless temperature
Γ	diffusion term, kg m^{-1} s^{-1}
σ	collision diameter, Å (10^{-10} m)
ω_D	collision integral of molecular dynamic viscosity
ω_n	collision integral of molecular diffusivity
ω	angular velocity $\omega = 2\pi$f, rd s^{-1}
ε_K	collision temperature, K
μ	molecular dynamic viscosity, kg m^{-1} s^{-1}
λ	thermal conductivity, w m^{-1} K^{-1}
τ	dimensionless time

Indices

0	nozzle exit
1	gas resulting from nozzle
$2, \infty$	gas of ambient middle (air)
C	jet axis (jet center)
mn	mean

compared to the non-pulsed jet. Farrington and Claunch [16] showed that the pulsed jet involves the surrounding fluid more quickly than a non-pulsed jet, and consequently, the pulsed jet dissipates more quickly. Hussain and Rayclark [17] confirmed the results of Farrington and Claunch. In the case of a pulsed plane jet, they found very high entrainment rates in the first diameters compared to the non-disturbed case. These authors observed also that the influence of the excitation on the mean and fluctuating velocity fields is much weaker than in the case of the circular jet studied, respectively, by Zaman et al. and Hussain et al. [18,19]. In a former study, Hussain and Zaman [20] showed that controlled excitations at low amplitude in a circular jet do not affect only the turbulence structure and the swirls pairs but also parameters such as the mass flow, momentum quantity and entrainment rate.

Numerical studies conducted on jet type flows subjected to periodic disturbances are rare [21,22]. In the laminar mode, Marzouk et al. [22] showed that the development of a pulsed jet depends on the pulsation amplitude and Strouhal number and that it is difficult to separate their respective influences, but in all cases, the pulsed jet reached the same balance mode as the non-pulsed jet in the plume region. In the turbulent mode, Mankbadi [21] studied numerically a circular jet subjected to a periodic disturbance. They found that the forced oscillation makes possible an increase or reduction in shear layer thickness and the velocity according to the Strouhal number values. For $St < 0.5$, the mixture rate grows with the pulsation amplitude, but this is definitely observable only if the pulsation amplitude is higher than 0.5% of the ejection velocity. For Strouhal numbers going from 0.6 to 1, the dynamic boundary layer thickness increases even for low pulsation amplitudes. For excitation levels larger than 10%, the dynamic boundary layer thickness increases considerably.

To our knowledge, the pulsation effect on a jet type flow with variable density was not examined. However, according to the studies conducted on simple jets with constant density, the pulsation accelerates the initial development of the jet and improves considerably the diffusion and the drive and, consequently, the mixture in the first diameters of the jet. Thus, the pulsation effect proves to be interesting to increase the mixture degree of jets with variable density. In this context, the objective of this work is to study the characteristic parameters of a jet flow with variable density in the laminar mode subjected to a sinusoidal disturbance.

2. Assumptions

We consider a vertical flow of a gas (argon) ejected from a plane nozzle emerging into an atmosphere constituted of a fluid of different density (air). The dimensions of the nozzle