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Direct numerical simulation of free and forced square jets

Trushar B. Gohil, Arun K. Saha *, K. Muralidhar

Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208 016, India

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ABSTRACT

Direct numerical simulation (DNS) of incompressible, spatially developing square jets in the Reynolds number range of 500–2000 is reported. The three-dimensional unsteady Navier–Stokes equations are solved using high order spatial and temporal discretization. The objective of the present work is to understand the evolution of free and forced square jets by examining the formation of large-scale structures. Coherent structures and related interactions of free jets suggest control strategies that can be used to achieve enhanced spreading and mixing of the jet with the surrounding fluid. The critical Reynolds number for the onset on unsteadiness in an unperturbed free square jet is found to be 875–900 while it reduces to the range 500–525 in the presence of small-scale perturbations. Disturbances applied at the flow inlet cause saturation of KH-instability and early transition to turbulence. Forced jet calculations have been carried out using varicose perturbation with amplitude of 15%, while frequency is independently varied. Simulations show that the initial development of the square jet is influenced by the four corners leading to the appearance hairpin structures along with the formation of vortex rings. Farther downstream, adjacent vortices strongly interact leading to their rapid breakup. Excitation frequencies in the range 0.4–0.6 cause axis-switching of the jet cross-section. Results show that square jets achieve greater spreading but are less controllable in comparison to the circular ones.

1. Introduction

Jets emerging from noncircular cross-sections are of interest in many applications. The expectation from such configurations is in terms of reducing combustion instabilities and undesired emissions, noise suppression, and thrust vector control, enhanced entrainment and mixing properties relative to axisymmetric jets. Noncircular jets have been investigated by Tsuchiya et al. (1986), Quinn and Militzer (1988), Gutmark et al. (1989), Quinn (1992), and Grinstein et al. (1995). The measurements of Tsuchiya et al. (1986) and Gutmark et al. (1989) are for rectangular and triangular jets, respectively while other authors have examined jets from nozzles of square cross-section. Both circular and non-circular jets show similarity in evolution along the downstream direction in the following respect. The near-field is dominated by large coherent structures that stir and entrain pockets of the ambient fluid. Subsequently, large-scale fluctuations cascade energy to the small scales, creating steep velocity gradients, and accelerate mixing.

In noncircular jets, the deformation dynamics of asymmetric vortices play an important role in jet evolution. Asymmetric jets are naturally more unstable than their axisymmetric counterparts (Michalke, 1971). The locations on a non-circular jet with highest curvature, such as corners and major axis sections of elliptic jets, move downstream faster than points closer to the jet axis. Sections with lower curvature eventually develop higher curvature and move forward at an equal speed. The vortex ring then becomes essentially flat with its axes rotated by an angle depending on the initial jet cross-section (Grinstein et al., 1995).

Jets from non-circular nozzles entrain more ambient fluid than the corresponding round jets (Ho and Gutmark, 1987). The sharp corners of the nozzles lead to the appearance of azimuthal concentrations of small-scale motions within the ensuing large-scale vortical structures, with considerable enhancement of mixing (Gutmark et al., 1989). Grinstein et al. (1995) examined various parameters experimentally that affect the development of square subsonic jets. Axis-switching was found to be related to vortex deformation dynamics that are enhanced at low turbulence levels and in jets with a thin initial shear layer. It was found that the Reynolds and Mach numbers do not have a strong effect on jet deformation. High azimuthal coherence and a thin shear layer relative to the jet dimensions were found to be crucial to initiate vortex deformation and self-induction. In corner jets, an important parameter that governs self-deformation is the initial momentum thickness. If the ratio of the equivalent jet diameter and initial momentum thickness (D_e/θ_s) is small, Grinstein et al. (1995) showed that the jet does not experience axis-switching.

* Corresponding author. Tel.: +91 512 2597869; fax: +91 512 2597408.
E-mail address: aksaha@iitk.ac.in (A.K. Saha).

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Nomenclature

D	characteristic length – edge of the square nozzle cross-section (m)
f	preferred mode frequency (Hz)
p	pressure (N/m^2)
Re	jet Reynolds number, $U_{inlet}D/\nu$
S_{ij}	strain rate tensor, $\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$ (s^{-1})
St_D	Strouhal number, $\mathrm{St}_D = fD/U_{inlet}$
t	time (s)
$u_i^{noise}(r,t)$	noise content (velocity) in $i = x$, y, and z directions
u, v, w	velocity components in x, y, and z directions (m/s)
$\bar{u}, \bar{v}, \bar{w}$	time-averaged velocity components in x, y, and z directions (m/s)
U_{inlet}	time-averaged maximum inlet velocity (m/s)
U_C	time averaged centerline velocity (m/s)
W_n (%)	RMS velocity as a percentage of the average inlet velocity used to prescribe noise
x, y, z	Cartesian coordinates (m)

Greek symbols

Ω_{ij}	rotational tensor, $\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)$ (s^{-1})
θ_m	inlet momentum thickness, $\int_0^{D/2}\frac{\bar{u}}{U_{inlet}}\left(1-\frac{\bar{u}}{U_{inlet}}\right)dr$ (m)
θ_c	azimuthal direction in cylindrical coordinates
ν	kinematic viscosity (m^2/s)
ρ	density of the fluid (kg/m^3)

Abramovich (1983) and Koshigoe et al. (1989) respectively performed theoretical and stability analysis of non-circular jets. These authors showed that the shear layer has growth rates defined along characteristic directions leading to the axis-switching phenomenon. For rectangular jets (Tsuchiya et al., 1986) and elliptical (Ho and Gutmark, 1987; Hussain and Husain, 1989), axis-switching was observed farther downstream from the jet exit in comparison to the square.

Experiments on a free square jet by Quinn and Militzer (1988) found positive mean static pressures in the near field. A comprehensive numerical study for elliptic, rectangular, and triangular jets by Miller et al. (1995) revealed axis-switching phenomenon and higher entrainment rates. Grinstein (2001) performed large eddy simulation of compressible rectangular jets when the inflow is free of disturbances. Self-deformation and splitting of vortex ring were observed in the flow field.

The goal of the present work is to carry out DNS calculations of free and forced square jets using higher order spatial and temporal discretization within a finite difference framework. A Reynolds number range of 500–2000 has been considered and the flow is treated to be incompressible. The present study aims at (i) understanding the effect of varicose perturbation and (ii) a comparison of square and circular jets. For characterizing the resulting flow field, instantaneous as well as the time-averaged data along with the relevant statistics are presented.

2. Numerical methodology

Numerical simulation is performed by solving the unsteady three-dimensional incompressible Navier–Stokes equations written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j^2} \tag{2}$$

Eqs. (1) and (2) are non-dimensionalized using D, the edge of the square nozzle cross-section and velocity scale U_{inlet}. Time and pressure are non-dimensionalized by D/U_{inlet} and $\rho U^2{}_{inlet}$ respectively.

The numerical algorithm that solves Eqs. (1) and (2) utilizes the second-order Adams–Bashforth scheme in time for the convective terms. The diffusion terms are discretized using a Crank–Nicolson scheme. All the equations are spatially discretized on a staggered grid. The convective terms are discretized spatially using a weighted averaged 4th-order central difference and 5th-order upwind-biased schemes and diffusion terms are discretized using a 4th-order central difference scheme. Pressure–velocity coupling is treated on the basis of the Marker-And-Cell (MAC) formulation proposed by Harlow and Welch (1966). The pressure Poisson equation is solved using a GSOR approach. Code validation has been described in detail by the authors elsewhere (Gohil et al., 2010–2013).

On the inlet boundary, the instantaneous velocity profile is prescribed as

$$\begin{aligned} u_x^{inlet}(r,t) &= u_x^{profile}(r) + u_x^{noise}(r,t) + u_x^{forced}(r,t) \\ u_y^{inlet}(r,t) &= u_y^{noise}(r,t) \\ u_z^{inlet}(r,t) &= u_z^{noise}(r,t) \end{aligned} \tag{3}$$

Here $u_x^{inlet}(r,t)$ is the instantaneous inlet velocity vector and $r = \sqrt{y^2+z^2}$. The expression for $u_x^{profile}$ is given by Eq. (4) below while $u_i^{noise}(r,t)(i = x,y,z)$ and $u_x^{forced}(r,t)$ are components of random and large scale perturbations respectively. Subscript '*i*' refers to the x, y, and z coordinates.

The time-averaged streamwise velocity variation at the inlet proposed by Michalke and Hermann (1982) is used at the inflow plane. It is almost a flat distribution and is a good approximation of the measured velocity profiles in round jets at a location which is little away from the jet exit. When adapted for square cross-sections, profiles as shown in Fig. 1(b) are obtained. The modeled streamwise velocity on the inflow plane is given as

$$u_x^{profile}(r) = \frac{(U_{inlet})}{2}\left\{1+\tanh\left[\frac{R-r}{2\theta_m}\right]\right\} \tag{4}$$

In Eq. (4), distance r is either y or the z coordinate depending on the selected quadrant and $R = D/2$. The time-averaged cross-stream components are zero. The momentum thickness of the boundary-layer at the inflow plane, θ_m, is used to normalize the distance coordinate. A constant value (=20) of R/θ_m has been used for all simulations. In the present study, a few simulations are carried out by adding random perturbation $u_i^{noise}(r,t)$ with its RMS value varying in the range 0–5% of the space-averaged velocity to the velocity vector at the inflow plane. The perturbation is specified to have a Gaussian probability distribution.

Varicose excitation (VAR) refers to a finite amplitude axisymmetric perturbation in the streamwise direction and was developed originally for circular jets (Gohil et al., 2013). The oscillatory movement of the inlet velocity profile around its time average generates a pattern similar to loudspeakers in experimental studies of jets. As a result, a vortex ring rolls out and there are