Development of flow control methods in free and impinging jets

A K Shevchenko¹, S N Yakovenko¹

¹Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Sciences, Novosibirsk 630090, Russia

E-mail: shevchenkoanthony@gmail.com, s.yakovenko@mail.ru

Abstract. Submerged and impinging jets with harmonic perturbations added to the inlet velocity profile and with nozzle vibrations are simulated numerically at different Reynolds (Re) and Strouhal (St) numbers by solving the Navier–Stokes equations. The effects of Re, St and forcing amplitudes on flow behavior and jet splitting phenomena are studied.

1. Introduction

Study of jet flows is relevant in energy issues, such as the flow control in various burner nozzles, for transport applications, where jets are used to reduce engine noise, aircraft drag, fuel consumption. The present computation of free and impinging round jets is performed by the OpenFOAM software with the rhoPimpleFoam solver. The two active flow control methods are explored, i.e. the axial and helical harmonic oscillations (with frequencies 2f and f, amplitude A) of the inlet velocity distribution [1, 2],

\[ u(x = 0, r < R) = u_0(r, \theta, t) = U + A[\sin(4\pi f t) + \sin(2\pi f t + \theta)\sin(2\pi f R)], \quad u(x = 0, r \geq R) = 0, \quad (1) \]

the transverse vibration of the nozzle (with \( A = 0 \), frequency \( f \), transverse velocity \( v \), amplitude \( Z \)) [2],

\[ u(x = 0, y < [R^2 - (z^*)^2]^{1/2}) = u_0(y, z^*, t), \quad u(x = 0, y \geq [R^2 - (z^*)^2]^{1/2}) = 0, \quad (2) \]

\[ v(x = 0, t) = \omega Z \cos(\omega t), \quad \omega = 2\pi f, \quad z^* = z - Z(t), \quad Z(t) = Z_0 \sin(\omega t), \]

and their combinations. The axial oscillations promote the generation of ring vortices due to Kelvin–Helmholtz instability, and the helical oscillations direct the vortices away from the jet axis. Different parameters of Reynolds (\( Re = UD/\nu \)) and Strouhal (\( St = fD/U \)) numbers, where \( U \) is the mean inlet velocity, \( D = 2R \) is the nozzle diameter, \( \nu \) is the molecular viscosity, are considered.

2. Computation set-up

To simulate a homogenous submerged jet, the unsteady Navier–Stokes equations are solved at wide range \( 50 \leq Re \leq 23\,000 \). DNS is utilized at \( Re \leq 3000 \), whereas LES with the eddy-viscosity subgrid-scale model and subgrid-scale turbulent kinetic energy equation is used at \( Re > 3000 \). A jet enters the cylindrical or rectangular computational domain through a round orifice in the inlet wall. The top-hat inlet velocity profile, \( u(x = 0, t) = U \), is chosen. In the orifice proximity, the uniform fine mesh is arranged, and it coarsens in transverse and axial directions away from the nozzle. For impinging jet, the round nozzle is replaced by a pipe segment with mesh resolution increased near the pipe wall as well as the colliding wall. The domain sizes and mesh resolutions vary from case to case and have been chosen based on a series of preliminary runs. Further details of computation set-up are given in [2].
3. Results for free jets
As in [3, 4], the jet branching is obtained in wide ranges of amplitudes of oscillations of the inlet velocity profile \(0.01 \leq A/U \leq 0.2\), nozzle \(0.05 \leq Z/D \leq 0.5\), the Reynolds numbers \(Re > 50\), and the Strouhal numbers \(St = fD/U\) (Figure 1). We should note, in previous studies, computation results for excited jet splitting at \(Re < 500\) have not been reported yet. Only the measurements were done [3] where the jet bifurcation caused by acoustic forcing is observed at \(Re \geq 20\). The nozzle vibration (2) here has the similar effect to that of transverse acoustic field in [3, 4]. It was also found that at low Reynolds number \((Re \sim 50)\), the perturbations introduced at the inlet section quickly decay downstream of the nozzle exit, so even high-amplitude nozzle vibration is not enough to split a round jet (Figure 2).

The mechanism of interaction of vortex structures leading to the jet splitting is studied [2, 4]. The performed estimates of the expansion angle in the bifurcation plane showed [2] its growth with \(Re\).

Calculations of free jets at \(50 \leq Re \leq 3000\) demonstrate that in order to obtain and enhance the splitting effect, optimization of the forcing parameters (type, frequency and amplitude of disturbances) is required, and the transverse mechanical oscillation (2) of the nozzle turns out to be a more effective method of flow control, than the axial-helical excitation (1) of the inlet velocity profile.

Figure 1. Three-dimensional vortex structure \(\lambda_2\), distributions of instantaneous \((u/U)\) and average \(<u>/U\) velocities in the bifurcation plane of the jet \((y = 0)\) with nozzle vibration at \(St = 0.10\) which is optimal for bifurcation at \(Re = 100\) (a), 250 (b); forcing amplitude \(Z = 0.5D\); \(\lambda_2D/U = 500\) (a), 0.5 (b).
The mixing enhancement (which is important for applications and produced by the jet excitation) can be parameterized by the typical jet thickness $d$ or the expansion angles $\alpha$ in the bifurcation plane, as well as by centerline values of the mean velocity or the mean scalar [1, 4-6]. It is evident that mixing efficiency increases for the stronger jet expansion with larger $d$ and $\alpha$, resulting in larger spreading area and smaller centerline values of $\langle u \rangle$ and $\langle c \rangle$.

Figure 3 demonstrates that at the same nozzle vibration parameters ($Z = 0.5D$, $St = 0.1$) more efficient mixing is possible for higher Reynolds number $Re = 250$ than that for $Re = 100$. The stronger molecular viscosity effects at $Re = 100$ lead to faster decay of perturbation downstream of the nozzle exit and give the larger centerline mean velocity and the smaller expansion angle $\alpha = 39^\circ$ at $Re = 100$ (versus $\alpha = 57^\circ$ at $Re = 250$) estimated from the typical jet width $d(x)$ in Figure 3(b) at $6 \leq x/D \leq 9$ where $d(x)$ is close to a linear function, and where the round jet bifurcation usually occurs [1, 2, 4].

This trend is the same as that discovered earlier [2] for the wider range $50 \leq Re < 5000$. The larger values of the angle $\alpha$ than those shown in [2] for $Re < 500$ are related to the much larger excitation magnitude ($Z = 0.5D$) chosen in the present numerical simulations at low Reynolds numbers.
4. Results for impinging jets

Effective flow and heat transfer control is also possible using the passive methods, for example, by introducing various grids and screens near the nozzle exit [7] and by combining active and passive methods of forcing. The present LES calculations reproduce the conditions of a number of physical experiments [7-9] in a non-isothermal turbulent impinging jet flowing normally onto a plate placed at distance $2 \leq x/D \leq 10$ downstream from the inlet. The preliminary results of simulating the dynamics of a passive scalar (temperature, concentration) show (Figure 4) the jet splitting into several branches with implementation of more efficient mixing and intensification of heat and mass transfer.

![Figure 4](image)

Figure 4. The passive scalar contours for a round jet at $Re = 23000$: the instantaneous scalar $c(x, z)$ at splitting plane $y/D = 0$ with impingement plane placed at $x/D = 6$ (a), $10$ (b) with combination of axial and helical inlet excitation (a), with nozzle vibration only (b); the mean scalar $\langle c \rangle (y, z)$ at impinging plane $x = 10D$ for a jet with combination of nozzle vibration, axial and helical inlet excitation (c).

5. Conclusions

The study of active flow control methods reveals the jet splitting in wide ranges of Strouhal numbers, helical and flapping oscillation amplitudes at Reynolds number $Re > 50$. The effect of transverse nozzle vibration is similar to that of acoustic forcing. Both ways are shown to be effective for flow control, and lower Re cases have the smaller expansion and bifurcation angles. The results for the passive scalar dynamics in the laterally excited turbulent impinging jet show more efficient mixing and scalar transfer intensification. This can be further used for heat transfer enhancement in cooling devices.

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