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Numerical investigation of parallel plane jets at low Reynolds number

Li-Qing Zhao *, Xiao-Chun Wang

School of Marine Sciences, Nanjing University of Information Science & Technology, No. 219, Ningliu Road, Nanjing, 210044, China
Jiangsu Research Center for Ocean Survey Technology, No. 219, Ningliu Road, Nanjing, 210044, China

HIGHLIGHTS

- Low Reynolds number parallel plane jet is studied using lattice Boltzmann method.
- In converging region, steady and periodically unsteady flow states are demonstrated.
- The periodically unsteady flow state is found to have faster mean maximum streamwise velocity decay in converging region.
- This study provides some flow physics to control mixing based on parallel jets.

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ABSTRACT

Two parallel plane jets with various jet spacing between two jet centerlines, defined as s, are numerically simulated using lattice Boltzmann method. The Reynolds number based on jet-exit-width d is set to be $Re = 56$ and the jet spacing is set to be less than or equal 8 times the jet-exit-width. Generally, there exist three distinct regions, a converging region, a merging region and a combined region. When the jet spacing is in the range of $s/d < 7$, the flow field displays periodic oscillation in the combined region, while it remains steady in the converging region with two counter-rotating vortices. When $7 \leq s/d \leq 8$, the whole flow field reveals periodic vortex shedding, even in the converging region close to the nozzle plate, and the non-dimensional periodic oscillation frequency (Strouhal number) is nearly one order of magnitude larger than that in the cases of $s/d < 7$, indicating the scale of the oscillation for $7 \leq s/d \leq 8$ is smaller than that of $s/d < 7$.

1. Introduction

Parallel jets are important in a variety of engineering applications, such as entrainment and mixing processes in microcircuit cooling system, ventilation system, waste disposal, and fuel injection systems [1–3]. The interaction of parallel jets with adjacent jets or with their surroundings plays a crucial role in the effectiveness of the interacting flow. For example, an optimum jet spacing between two jet centerlines can enhance fluid interaction and improve diffusion of pollutants in waste disposal system.

Fig. 1 shows the schematic diagram of two parallel plane jets. As shown in Fig. 1, there exist three distinct regions, a converging region, a merging region and a combined region. A sub-atmospheric pressure zone close to the nozzle plate causes the individual jets to curve towards each other in a region known as the converging region. The two jets merge together at some downstream distance along the symmetry plane, known as the merging point (mp) where the mean streamwise velocity is zero. Downstream from the merging point in the merging region, the two jets continue to interact with each other up to the combined point (cp) where the mean streamwise velocity attains its maximum value. Downstream from the combined point in the combined region, the two jets combine to form a single jet flow.

While a considerable number of studies have been conducted on the mean flow characteristics of parallel plane jets [4–8], including mean velocities, turbulent intensities, and Reynolds shear stress, only little work has focused on unsteady behavior of the flow, especially the periodic vortex shedding phenomenon. Anderson et al. [9] observed periodic vortex shedding in near-field region between parallel plane jets when the jet-exit-widths are greater than 0.5 times the separation distance between two jets. Recently, Mondal et al. [10] numerically investigated the periodic vortex shedding of two parallel plane jets. Results revealed that when nozzle separation distance, defined as w, was in the range of $0.6 \leq w/d \leq 1.4$, the flow field demonstrated periodic vortex shedding close to the nozzle plate. On the contrary, for $w/d = 0.5$ and 1.5, the near flow field region remained to be steady with two counter-rotating vortices in the recirculation zone. The unsteady

* Corresponding author at: School of Marine Sciences, Nanjing University of Information Science & Technology, No. 219, Ningliu Road, Nanjing, 210044, China.
E-mail address: zhaoliqing@nuist.edu.cn (L.-Q. Zhao).

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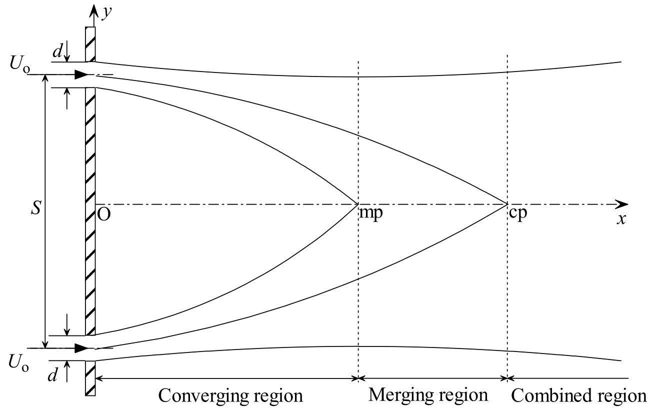

Fig. 1. Schematic diagram of two parallel plane jets. s is the spacing between two jet centerlines, d the jet-exit-width, and U_o the jet-exit-velocity.

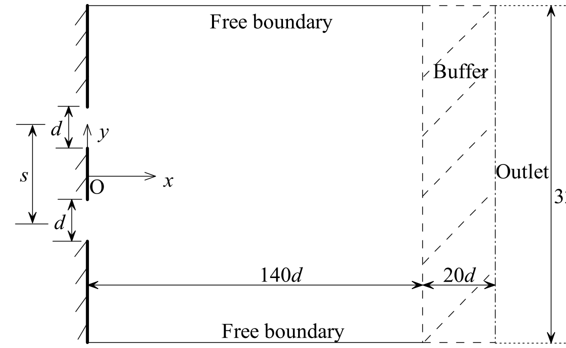

Fig. 2. Sketch of computational domain.

periodic vortex shedding phenomenon could also be observed for turbulent parallel jet consisting of a wall jet and an offset jet [11]. It has been reported that periodic oscillation of parallel jets can enhance mixing between two jets with the ambient and have the advantages of both passive and active mixing control [1].

The literature above mainly focused on high Reynolds number parallel plane jets, i.e. $Re > 10^3$. However, in microelectronic cooling systems, the air velocities are small, hence, low Reynolds number jets are more relevant. However, low Reynolds number parallel plane jet (i.e. $Re < 10^2$) have not been well documented in the literature. In previous studies [12,13], single plane jets over a range of Reynolds numbers from 16 to 65 have been investigated using numerical modeling. Results show that there exist two flow states dependent on a critical Reynolds number Re_{cr}. One is a stable flow state when $Re < Re_{cr}$, and the other is a flow state with periodic oscillation in the far field region when $Re \geq Re_{cr}$. The present study is an attempt to investigate the flow characteristics of two parallel plane jets at low Reynolds number. The periodic vortex shedding phenomenon is also examined based on the instantaneous flow field. More in-depth study on low Reynolds number parallel plane jet is also useful to provide improved fundamental understanding of the jet stability and transition to turbulence. In most numerical solvers, the flow field is obtained by solving the Navier–Stokes equations. As an alternative computational technique to Navier–Stokes equations, the lattice Boltzmann method (LBM) [14] is employed to investigate the parallel plane jets. The simulation methodology is described in Section 2. The mean flow characteristics of the jets are examined in Section 3.1. The instantaneous vortex structures are visualized in Section 3.2, which displays the existence of periodic vortex shedding, followed by a quantitative analysis of oscillation frequency and oscillation stresses in Section 3.3. The effect of vortex shedding on the flow field is discussed in Section 3.4 and the conclusions are presented in Section 4.

2. Simulation methodology

2.1. Set-up of problem

As shown in Fig. 2, two jets enter into the computational domain of $160d \times 320d$ from two jet nozzles, where d is the jet-exit-width. The x axis is in the symmetry plane bisecting the distance between the two jets. The origin is located where the symmetry plane intersects the jet plane. The parallel plane jet, assumed as a two-dimensional, incompressible flow, is influenced by two dimensionless parameters. One is the Reynolds number, defined as $Re = U_{oc}d/\nu$, where U_{oc} is the maximum jet-exit-velocity and ν the kinetic viscosity. Another parameter is the jet spacing s/d, where s is the spacing between two jet centerlines. In the present study, the Reynolds number is set to be $Re = 56$ and the jet spacing is set to be $s/d \leq 8$.

2.2. Governing equations and boundary conditions

The governing equations of the jet flow are incompressible Navier–Stokes (N–S) equations, shown as

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

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j}\right), \tag{2}$$

where u_i is the velocity, p the pressure field, ν the kinetic viscosity, x_i the spatial coordinate, and the subscripts i and j represent the spatial directions.

At each jet exit, a fully developed parabolic velocity profile is prescribed as

$$u(y) = U_{oc}\left[1 - (2y/d)^2\right], v = 0. \tag{3}$$

On the free boundaries, as shown in Fig. 2, the pressure is prescribed as the ambient pressure p_∞ and the other variables are extrapolated from the interior solution, allowing for entrainment. A convective boundary condition [15] is adopted at outlet boundary, shown as

$$\frac{\partial \hat{u}_i}{\partial t} + U_{con}\frac{\partial \hat{u}_i}{\partial n} = 0, \tag{4}$$

where $\hat{u}_i$ is the target velocity at outlet boundary, and U_{con} a pre-selected convection velocity in the normal direction (n) respect to the boundary. The pre-selected convection velocity is chosen to be 0.5 in the streamwise boundary [16] in the present study. In addition, a buffer zone is employed near the downstream end of the computational domain with a length of $20d$, as shown in Fig. 2, in order to isolate the interior of the domain from the effects of the boundary condition. Inside the buffer zone, a fringe function term [16] is added into the right-hand-side of Eq. (2), and then we have

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \sigma(n)\left(u_i - \hat{u}_i\right), \tag{5}$$

where u_i is local velocity of fluid and $\hat{u}_i$ is the velocity at outlet boundary obtained from the convection boundary condition Eq. (4). $\sigma(n)$ is the damping term, and its function has an exponential form [16] with streamwise position dependent part that contains the start and end position of the damping zone x_s and x_e, that is

$$\sigma(n) = \alpha\left(\frac{x - x_s}{x_e - x_s}\right)^{\beta}. \tag{6}$$