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Deposition and dispersion of aerosols over triangular cylinders in a two-dimensional channel; effect of cylinder location and arrangement

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ABSTRACT

The deposition and dispersion of particles with diameters in the range of 0.45 μm to 55 μm in a channel over a Q4 triangle obstacle are studied. The lattice Boltzmann method (LBM) is used to obtain the fluid velocity in a two-dimensional channel at Reynolds number of 200. The effect of position and arrangement of triangular cylinders on the deposition and distribution of particles and relative profiles and physical parameters is studied. To obtain the particle location and velocity a Lagrangian method is used. All affected forces in particle motion such as Q5 Brownian, gravity, drag and lift forces are considered in this investigation. The results are shown in terms of instantaneous plot of particle location and the profiles of deposition efficiency over the upstream and downstream cylinders. Decreasing the gap ratio restricts the movement of particles toward the region between the two cylinders except for Stk = 0.001.

1. Introduction

The study of dispersion and deposition of aerosols has attracted considerable attention due to its importance in numerous industrial applications. Particle transport and deposition play a major role in filtration, combustion, air and water pollution, coal transport and cleaning, chip fabrication, and many other industrial processes. One of the most attracting topics is investigation of the effects of exposure to particles on human health [1]. The deposition of drugs and harmful substances in the nasal and respiratory tracts in medical science and engineering is another important usage of investigation of particle deposition and dispersion. Most of the articles about aerosols and their movement have focused on the investigation of particle deposition and dispersion on smooth or non-smooth surfaces in pipes and channels. Li et al. [2] investigated aerosol particle deposition in turbulent duct flow obstructed with rectangular and trapezoidal blocks. In their study, the capture efficiency of rectangular and trapezoidal blocks for different Stokes number were simulated and their results showed that the deposition rate decreases as the shape of the obstruction becomes more streamlined. Sippola and Nazaroff [3] measured particle deposition from fully developed turbulent flow in ventilation ducts experimentally. It was observed that in steel ducts, deposition rates were higher to the duct floor than to the walls, which were, in turn, greater than to the ceiling. Moreover, in insulated ducts, deposition was nearly the same to the duct floor, wall and ceiling for a given particle size and air speed. Q7 (See Tables 1 and 2.)

Tian and Ahmadi [4] compared different model predictions for particle deposition in turbulent duct flows. The results indicated that turbulence diffusion significantly affects particle deposition rates in the "Brownian" and "transition" size regions. Thus, for accurate evaluation of the deposition rate, the turbulence fluctuations need to be properly modeled.

Afshar et al. [5] examined micro-channel heat transfer and dispersion of nano-particles in slip flow regime with constant heat flux. The Navier–Stokes and energy equations for fluid flow in a micro-channel in slip flow regime were solved analytically and temperature and velocity profiles were evaluated. Their results showed that by decreasing the particle diameter, the surface to volume fraction increases and so heat transfer can be increased by using nanoparticles. Akbar et al. (2009) investigated particle transport in a small square enclosure in laminar natural convection. The air flow was simulated in Eulerian frame using commercial CFD software. Their results confirmed the important role of thermophoresis and Brownian dispersion, in particular for submicron size particles. Brandon and Aggrawal (2001) investigated deposition of particles in a channel obstructed with square cylinder. Their results showed that the Reynolds number for laminar and transitional regimes has a negligible effect on deposition rate. Some investigations related to particle transport and deposition in obstructed duct was performed by Suh and Kim (1996), Goharrizi et al. (1998), and Yu et al. [6]. Salmanzadeh et al. [7] investigated particle deposition in a channel with a built-in cylinder numerically. They used finite volume method with the staggered grid to simulate duct flow. They studied the effects of blockage ratio and aspect ratio on deposition efficiency at Re = 200. The results showed that the aspect ratio has negligible effect on the cylinder front side deposition but the increase of blockage ratio

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Table 1
Grid study against the drag coefficient.

Grid	Re	C_D
600 × 80	200	2.12
900 × 120	200	2.48
1200 × 160	200	2.68
1500 × 200	200	2.73

increases deposition efficiency. Jafari, et al. [8] studied deposition of particles in a channel with rectangular obstacle and their results showed that deposition at the back side of the block occurs when the particle is sufficiently small as the Brownian force is more considerable and causes the particles to diffuse into the wake region.

In this investigation, particle deposition inside a two-dimensional channel in the presence of one and two triangular obstacles for four different cases is studied. In addition, the effects of distance between the cylinders and channel's wall and the gap between the two triangular cylinders are investigated. All effective forces on the particle motion are considered such as lift force, drag force, gravity and Brownian force. The flow field is simulated by the lattice Boltzmann method (LBM) at Re = 200.

2. Numerical procedure

A two-dimensional nine-velocity (D2Q9) LBM model (Mohamad [9]) is applied to the computational domain to obtain the flow field in the present work.

2.1. Lattice Boltzmann equation of velocity field

The Bhatnagar et al. [10] approximation of lattice Boltzmann equation without external forces can be written as,

$$f_\alpha(x + e_\alpha \delta t, t + \delta t) - f_\alpha(x, t) = \Omega_\alpha \qquad (1)$$

where f_α is the particle distribution defined for the finite set of the discrete particle velocity vectors e_α ($\alpha = 0,1,...,8$). The collision operator, Ω_α, on the right hand side of Eq. (1) uses the BGK approximation. For single time relaxation, the collision term Ω_α will be replaced by:

$$\Omega_\alpha = -\frac{[f_\alpha(x, t) f_\alpha^{eq}(x, t)]}{\tau_v} \qquad (2)$$

where $\tau_v(\tau_v = 1/\omega_\alpha)$ is the relaxation time and $f_\alpha^{eq}(x, t)$ is the equilibrium density distribution function. Therefore, the BGK lattice Boltzman equation can be written as:

$$f_\alpha(x + e_\alpha \delta t, t + \delta t) - f_\alpha(x, t) = -\frac{1}{t_v}[f_\alpha(x, t) - f_\alpha^{eq}(x, t)]. \qquad (3)$$

The equilibrium density distribution function is defined as:

$$f_\alpha^{eq}(x, t) = \omega_\alpha \rho_{lbm}\left[1 + 3\frac{e_\alpha \cdot u}{c^2} + \frac{9}{2}\frac{(e_\alpha \cdot u)^2}{c^4} - \frac{3}{2}\frac{u \cdot u}{c^2}\right], \qquad \alpha = 0, 1, 2, ...8 \qquad (4)$$

where u and ρ_{lbm} are the macroscopic velocity and density, respectively, and ω_α is the constant factor. In the D2Q9 model:

$$\omega_\alpha = \begin{cases} 4/9 & \alpha = 0 \\ 1/9 & \alpha = 1, 3, 5, 7 \\ 1/36 & \alpha = 2, 4, 6, 8 \end{cases} \qquad (5)$$

In the D2Q9 model shown in Fig. 1, e_α denotes the discrete velocity set, namely,

$$e_\alpha = \begin{cases} (0, 0), \alpha = 0 \\ (\cos[(\alpha-1)\pi/4], \sin[(\alpha-1)\pi/4]) & c, \alpha = 1, 2, 3, 4 \\ \sqrt{2}(\cos[(\alpha-1)\pi/4], \sin[(\alpha-1)\pi/4])c, & \alpha = 5, 6, 7, 8 \end{cases} \qquad (6)$$

where the streaming speed, $c = \Delta x/\Delta t$ is the particle velocity and Δx and Δt are the lattice grid spacing and the lattice time step size, respectively, which are set to unity. The macroscopic hydrodynamic quantities, such as density ρ and velocity u, are evaluated, respectively, as:

$$\rho_{lbm}(x, t) = \sum_\alpha f_\alpha(x, t) \quad, \rho_{lbm}u(x, t) = \sum_i e_\alpha f_\alpha(x, t). \qquad (7)$$

The macroscopic viscosity v and pressure P are determined by

$$v = [\tau_v - 0.5]c_s^2 \delta t \qquad (8)$$

$$\rho = \rho_{lbm} c_s^2 \qquad (9)$$

where c_s is the speed of sound equal to $c/\sqrt{3}$.

For momentum equation we have,

$$\frac{1}{t_v} = \frac{1}{3 \cdot v_{lbm} + 0.5} \qquad (10)$$

where v_{lbm} is the kinematic viscosity. Eq. (3) is usually solved in the following two steps. The collision step is:

$$\widetilde{f}_\alpha(x, t + \delta t) = \widetilde{f}_\alpha(x, t) - \frac{1}{t_v}[f_\alpha(x, t) - f_\alpha^{eq}(x, t)]. \qquad (11)$$

The streaming step is:

$$f_\alpha(x + e_\alpha \delta t, t + \delta t) = \widetilde{f}_\alpha(x, t + \delta t) \qquad (12)$$

where $\widetilde{f}_\alpha$ denotes the post-collision states of the distribution function of density.

3. Curved boundary treatment

3.1. Treatment curved boundary for velocity

To deal with the velocity on the curved boundaries, the method proposed in Yan & Zu [11] has been implemented. Fig. 2 shows an arbitrary curved wall separating a solid region from the fluid.

Table 2
Comparison between the present work with the previous numerical study of flow over triangular cylinder.

Geometry	Re	Strouhal number		C_D	
		Present study	Farhadi et al. (2010)	Present study	Farhadi et al. (2010)
Triangular cylinder	100	0.201	0.187	1.915	1.84