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Lattice Boltzmann analysis of micro-particles transport in pulsating obstructed channel flow

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ABSTRACT

Dispersion and deposition of microparticles are investigated numerically in a channel in the presence of a square obstacle and inlet flow pulsation. Lattice Boltzmann method (LBM) is used to simulate the flow field and modified Euler method is employed to calculate particles trajectories with the assumption of one-way coupling. The forces of drag, gravity, Saffman lift and Brownian motion are included in the particles equation of motion. The effects of pulsation amplitude (*AMP*), Strouhal number and particles Stokes number (*Stk*) are rigorously studied on particles dispersion and deposition efficiency. Flow vortex shedding and particles dispersion patterns together with the averaged fluid–particle relative velocity and deposition efficiency plots are all discussed thoroughly. The results show that increment of pulsation amplitude enforces the vortices to form closer to the obstacle until their shape deteriorates as Strouhal number ratio (SNR) rises. The average recirculation length shrinks to its minimum at each studied Amp when SNR escalates to 2. Various behaviors are categorized for dispersion pattern of particles when Stokes number changes from 0.001 to 4. Deposition efficiency is indirectly related to Amp for $Stk \leq 2$ while for higher Stokes numbers ($2 < Stk \leq 4$) they show direct relationship. Deposition pattern becomes rather independent of SNR at $Amp = 0.1$. The grid independency test was performed for the LBM analysis, and simulation code was successfully verified against credible benchmarks.

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1. Introduction

Understanding and quantifying the behavior of particles such as dispersion, deposition, aggregation and sedimentation are crucial in various sectors of science, technology, environmental and biological systems. Numerous studies have been performed, namely, deposition of particles in channels [1], separation in cyclones [2], filters [3], flame propagation [4], fluidized beds [5] and aerosols transport in human respiratory tract [6]. A number of publications focused on the theoretical aspect of particulate suspensions, while many researched the application aspects of particulate flows. Moshfegh et al. [7,8] obtained a new expression for drag force of microparticles in the rarefied slip flow regime. The two-way coupling simulation of particulate flow in a transonic nozzle flow was performed by Moshfegh et al. [9]. Crowe et al. [10] introduced the Stokes number of particles and showed that particles dispersion is strongly dependent on this number. In the context of heat transfer, some researchers mainly focused on the forced convection in particle-laden turbulent flow [11,12], whilst others studied the particles behavior in natural and mixed convection flows [13–16].

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Nomenclature

B	Square side (m)
$\vec{C}_k$	Discrete lattice velocity in direction k (m/s)
C_s	Speed of sound in Lattice scale (m/s)
F_L	Saffman lift force (N/kg)
G	Gaussian random number
H	Channel height (m)
Kn_p	Particle Knudsen number
L	Channel Length (m)
N_d	Number of deposited particles
N_p	Number of injected particles
$S = \rho_p/\rho_g$	Particle specific density
SNR	Strouhal number ratio
STR	Strouhal number
T_p	Flow Period
V	Local velocity (m/s)
d_p	Particle diameter (μm)
f_k^{eq}	Equilibrium distribution function
g	Gravity coefficient (m/s^2)
m	Mass (kg)
t	Time
td	Deformation tensor
$\vec{x}$	the position vector

Greek symbols

ω_k	Weighting factor
τ	Relaxation time (s)
Δt	Time step (s)
ν	Kinematic viscosity (m^2/s)
λ	Gas mean free path (μm)
ρ	Density

Subscripts

lb	Lattice parameter
p	Particle
g	Gas
eq	Equilibrium

Superscripts

i, j, k, l	Tensor pair indices

Subscripts

i	Direction index

The dispersion and removal of micro and nano aerosol particles are investigated numerically in many works. Brandon and Aggarwal [17] simulated particles deposition in an obstructed channel subject to an unsteady flow. They studied the effect of Stokes and Reynolds numbers on particles dispersion and deposition. It was shown that the deposition efficiency of aerosols with large specific densities is not dependent on Reynolds number and specific density, while it is only affected by Stokes number. Salmanzadeh et al. [18] investigated the effect of blockage and aspect ratios of rectangular obstruction on the deposition efficiency of particles in a channel. For deposition of large particles on the front face of the obstacle, the impaction was identified as the dominant mechanism. For $Stk > 1$, the deposition efficiency was increased due to the inclusion of Saffman's lift force, whereas no significant effect on deposition efficiency was monitored as the result of changes in blockage aspect ratio. Moshfegh et al. [19] analyzed the dispersion and deposition of different particle clusters over two tandem squares. As their results showed, deposition rate is more influenced by changes in particles diameter than by alteration of particles density. The capture efficiency diagrams implied a direct relationship between particles mass and their unsuccessful transport to the channel outlet.

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