



Simulation of particle deposition on the tube in ash-laden flow using the lattice Boltzmann method[☆]



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ARTICLE INFO

Available online 25 October 2016

Keywords:

Lattice Boltzmann-Lagrange tracking method
Gas-solid two-phase flow
Deposition
Circular tube
Elliptical tube

ABSTRACT

The LBM-Lagrange tracking method with multiple relaxation time (MRT) model has been developed to predict the flow field and particle deposition a circular or elliptical tube in ash-laden gas turbulent flow with Re of 10,229. The model can be used for predict particle deposition effect on thermal resistance or fouling factor of heat exchangers mostly operating in turbulent flow.

Particle deposition morphology on the circular and the elliptical tubes were obtained with the lattice Boltzmann method (LBM). The particle deposition mechanism has been investigated. The dominating mechanism of particle deposition on the circular tube is Brownian diffusion for the Stokes number of 0.002, whereas the dominating mechanism of particle deposition is drag inertia for the Stokes number larger than 0.031. When the long axis of the elliptical tube is parallel to the flow, both the collision efficiency and the deposition efficiency for the elliptical tube are fewer than those of the circular tube which means less particle deposition. It also can be concluded that both ratios of the collision efficiency and the deposition efficiency decrease with increasing axial length ratio of the elliptical tube. The elliptical tube is better than the circular tube as heat transfer surface in the aspect of preventing ash particle deposition.

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1. Introduction

A typical cement plant process is characterized by significant heat losses in the flue gas. A waste heat recovery system could be used to increase the energy efficiency. However, ash concentration in the flue gas is much higher than that in the coal-burning boiler, which can even reach 100 g/m^3 [1]. Ash deposits on the heat exchanger tube increase heat transfer resistance and pressure drop. Normally, heat exchangers use circular tube. However, recent studies suggest that an elliptical tube performs better than the circular tube in the aspect of heat transfer and ash deposition inhibition [2,3]. There has been experimental research into the characteristics of particle deposition on the tube surface [4–6]. Fouling factors are often used and the additional surface areas are added to the design as compensation. However, most of the fouling factors are based on experience. At present, there exist many thermal calculation standards of different countries to choose a suitable fouling factor. The fouling factors in the standards are based on semi-empirical relations according to coal and its ash quality or on the experience of different boiler manufactures. Therefore, there should be a dramatic difference between the design result and operation data due to coal and its ash characteristics. Moreover, waste heat recovery

systems are widely used in different applications. For example, in a cement plant, characteristics of clinker particles are quite different with that of coal ash particles. Therefore, it is necessary to obtain a method to predict fouling factor in this application. The deposition morphology, including its shape, thickness, particle diameter as well as the particle physical characteristics have effects on the fouling thermal resistance. If the evolutions of the shape of the fouling layer are known, the fouling factors can be determined more precisely. Therefore, it is important to study the deposition mechanism, the deposition morphology, and to predict how the parameters influence the deposition efficiency.

It is difficult to simulate the complex gas-solid flow and morphology evolution of particle deposition with the traditional computational dynamics (CFD) algorithm because of their low scalability and low parallel efficiency [7]. Recently, the lattice Boltzmann method (LBM) has become a popular approach to simulate complex gas-solid flow thanks to its inherent parallelism, capability of dealing with complex boundary and simplicity of implementation [8,9].

Jafari et al. [10] numerically investigated particle dispersion and deposition over a square cylinder in a channel flow with LBM. Simulations were performed for particles of 0.01 to 10 and Reynolds numbers of 120, 200. The drag force, the Saffman lift force, the gravity, and the Brownian force were considered. They concluded that the Brownian diffusion affects the deposition rate of ultrafine particles on the block and the motion of particles behind the obstacle is greatly influenced

[☆] Communicated by W.J. Minkowycz.

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Nomenclature

C_c	stokes-Cunningham slip correction factor
C_D	drag coefficient
c	lattice velocity
d_p	particle diameter, m
D	tube diameter, m
E	Composite Young's modulus, Pa
E_p	Young's modulus of particle, Pa
E_s	Young's modulus of the wall surface (sediment), Pa
$\mathbf{e}$	velocity vector, m/s
$\mathbf{F}$	force vector, N
$\mathbf{FF}$	force vector, N
f	particle distribution function
f^{eq}	particle equilibrium distribution function
$\mathbf{G}$	gravity, N
g	acceleration of gravity, 9.8 m/s^2
H	channel length, m
K	effective stiffness coefficient
k_s	factor in effective stiffness parameter for surface, m^2/N
k_p	factor in effective stiffness parameter for particle, m^2/N
k_B	Boltzmann constant, $1.380662 \times 10^{-23} \text{ J/K}$
L	channel width, m
$\mathbf{m}$	moment vector
$\mathbf{m}^{\text{eq}}$	equilibrium moments vector
$\mathbf{M}$	transformation matrix of velocity space to moment space
p	pressure, Pa
Re	Reynolds number
R	kinematic restitution coefficient
$\mathbf{S}$	relaxation matrix
Sr	Strouhal number
St	Stokes number
t	time, s
δt	discrete time step
Δt	time step, s
T	temperature, $^\circ\text{C}$
u	velocity, m/s
$\mathbf{u}$	velocity vector, m/s
v	velocity, m/s
v_w	wall friction velocity, m/s
V_{cr}	particle critical velocity, m/s
$V_{\tau cr}$	critical wall shear velocity, m/s
w	width, m
W_A	adhesion work, J/m^2
x	coordinate, m
δx	lattice spacing
y	coordinate, m

Greek letters

ζ	zero-mean unit-variance independent Gaussian random number
η	efficiency, %
λ	gas molecular mean free path, m
μ	gas dynamic viscosity, $\text{Pa}\cdot\text{s}$
ν_s	Poisson's ratio on the deposition wall surface
ν_p	Poisson's ratio of particle
ρ	density, kg/m^3
σ	ratio of the long axis to the short axis of the elliptical tube
θ	peripheral angle of the cylinder, $^\circ$
τ_p	particle relaxation time, s
Ω	collision matrix

Subscripts

1	Wall surface
2	Sediment surface
B	Brownian
c	collision
d	deposition
D	drag
g	gas phase
in	inlet
p	particle
s	surface
w	wall
x	x-direction
y	y-direction
α	direction of lattice discrete velocity
∞	infinite

by the vortex shedding. Zhou et al. [11] investigated vortex structures and particle dispersion in the flow around a circular cylinder using LBM. They found that both the Reynolds number ($Re = 40\text{--}100$) and the Stokes number ($St = 0.01, 0.1, 1$ and 10) influence the particle distribution. Tehrani and Moosavi [12] studied particle transportation and deposition in a channel flow with elliptic obstruction using two-dimensional lattice Boltzmann method, while one-way coupling Lagrangian method for particle tracing for particle of $0.01\text{--}10$ and Reynolds number of $10, 50, 100, 200$. The influence of fluid flow properties as well as the particle size and the obstruction geometry has been studied. They concluded that large particles are highly influenced by drag force and gravity, whereas, ultrafine particles are mainly affected by drag and Brownian forces. Using the LBM, Lin et al. [13] numerically investigated a laminar ($Re = 1, 10, 100$) free-stream flow laden with aerosol particles of 20 nm to $5 \mu\text{m}$ over a semi-infinite array of staggered obstructions at the Stokes numbers of 0.1 to 13.7 applicable to the conditions of woven-wire screens. They analyzed the effects of Reynolds number, particle diameter, Stokes number, the obstruction geometric parameters, and the arrangement on the flow structures and the vortex shedding. Ghafouri et al. [14] studied deposition and dispersion of particles of 0.45 to 55 in a channel over a triangle obstacle with LBM. The Reynolds number is 200 , and the Stokes numbers are $0.001, 0.2, 1$, and 5 . The effects of the position and arrangement of triangular cylinders and the Stokes number on the deposition, the distribution of particles and the relative flow profile were observed. All forces in particle motion such as the Brownian force, the gravity, the drag force, and the lift force were considered. Afrouzi et al. [15] investigated dispersion and deposition of micro particles in a channel in presence of a square obstacle and inlet flow pulsation. The LBM method was used to simulate the flow field and modified Euler method was employed to calculate particles trajectories with the assumption of one-way coupling. The force of drag, gravity, Saffman lift and Brownian motion were included. The flow Reynolds number in their study is 150 .

The above studies mainly focused on aerosol technology where the Reynolds number is low (less than 200). This is not suitable for application of waste heat recovery system where the Reynolds number may be more than $10,000$. BGK collision operator was used in the above studies that are not applicable for high Reynolds as proposed by Zou et al. [11]. Moreover, the above simulations only gave the particle dispersion distribution or deposition efficiency of different obstacles. The shapes of the fouling layer were not considered. Tong and He et al. [16] simulated the particle transport in the flow field and the particle deposition on the tube surface of the aligned and staggered circular tube bundle using LBM and the lattice gas automata (LGA). The results showed that deposition occurred only on the leeward side of the front row of the tubes, while occurred on both the windward and leeward sides of the other rows.

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