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Numerical study on particle deposition in rough channels with different structure parameters of rough elements

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ABSTRACT

This paper presents a study of the characteristics of particle deposition in rib-roughened channels. The gas-particle flow was numerically investigated by Reynolds stress model (RSM) with the discrete particle model (DPM). The particle deposition velocity and deposition ratio at different positions were numerically investigated in a channel where the relative roughness factor, e/D, were between 0.02 and 0.1, and the ratios of rough-element spacing to its height, p/e, were between 7 and 20. It is found that the eddy structures behind the rough-elements are changed by the increase of e/D. The windward surfaces are the main deposition regions and the cavities between the rough-elements are the secondary deposition regions. e/D contributes more to the increase of particle deposition velocity than p/e.

1. Introduction

With the rapid development of industry, increasing energy consumption and the rising number of vehicles, particle pollution (also known as particulate matter) in the atmospheric environment has become the leading cause of pollution in big cities [1]. According to investigation statistics, urban residents spend more than 20 h indoors. However, health problems resulting from indoor air quality (IAQ) have also become increasingly prominent; thus, the prevention and control of indoor air pollution have become an important health issue, especially for those with asthma and other respiratory problems. Atmospheric particulates not only enter houses through air conditioning and ventilation, but also deposits in the interior of the pipe, and provide nutrition for the breeding of bacteria and fungus. Microorganisms produce secondary suspension with the action of air flow, which spreads to the indoor environment, causing its air quality to deteriorate even further [2,3]. Roughness elements widely exist in ventilation ducts, air conditioner components, heat exchangers, and electrostatic precipitators. These elements not only improve the flow and heat transfer effect, but also intercept particulate matter effectively [4].

Particle transport and deposition has received extensive attention recently. Deshmukh et al. [5] used the high speed particle tracking velocimetry to measure particle velocity distribution, they found smaller particles to be the best choice for channel distribution and that better homogeneity in the flow could be achieved through a lower mass loading ratio and higher gas velocity. Laein et al. [6] used the PIV to investigate the TiO_2–water nanofluid free convection. They found that the nanoparticles will decrease the velocity boundary layer. Kussin and Sommerfeld [7,8] experimentally studied the wall roughness effects on particle behavior in duct flow by phase-Doppler anemometry (PDA). The deposition of micron-droplets in rectangular tubes was studied by Barth et al. [9], who also studied multilayer particle deposition in a channel arranged periodic steps by experiment [10]. Particle deposition in turbulent flow has been widely simulated by computational fluid dynamics (CFD) [11–13]. Moreover, it can provide more detailed information about the flow field and particle behavior than experimental measurements [14,15]. Abdolzadeh et al. [16,17] numerically analysed the deposition velocity of particles on tilted rough surfaces by a modified v2-f turbulence model with a two-phase Eulerian approach. They found that a thermophoretic force and tilt angle can have a significant effect on particle deposition velocity. De Marchis et al. [18] investigated the effect of roughness on particle distribution based on direct numerical simulation (DNS) and the Euler-Lagrange method. Li et al. [19] used the coupled discrete element method (DEM) and CFD approach to investigate the solid deposition in pipes. Lecrivain et al. [20,21] researched multilayer particle deposition in an obstructed channel by numerical simulation. They used a detached eddy simulation (DES) with self-organized criticality to reproduce the growth of a multilayer deposit. Because the direct numerical simulation (DNS) or large eddy simulation (LES) is too computationally expensive, it still

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Nomenclature

C_c	Cunningham slip correction factor
C_D	drag coefficient
D	channel diameter (m)
D_h	hydraulic diameter of channel (m)
d_p	particle diameter (m)
e	rough-element height (m)
fr_l	friction factor of the smooth channel
fr	friction factor of rib-roughened channel
L	the length of channel (m)
N_{dep}	particle deposition numbers to wall
N_{in}	incoming particle numbers
N_d	the number of deposited particles on surface
N_t	the number of particles that transited through the section upon the deposit surface
p	rough-element spacing (m)
R_d	particle deposition ratio
Re	Reynolds number
Re_p	particle Reynolds number
Re_y	Reynolds number of y-coordinate
S	ratio of particle-to-fluid density
U_0	average velocity of air (m/s)
u	velocity of fluid (m/s)
u_p	velocity of particle (m/s)
u^*	frictional velocity of air (m/s)
V_d^+	non-dimensional deposition velocity
V_d	particle deposition velocity (m/s)
Greek symbols	
ε	turbulence dissipation rate (J/(kg•s))
μ	dynamic viscosity of air (Pa•s)
ρ	air density (kg/m^3)
ρ_p	particle density (kg/m^3)
v	kinetic viscosity of air (m^2/s)
τ_w	shear stress on the wall (Pa)
τ_p^+	non-dimensional particle relaxation time

cannot be widely used for engineering applications. The Reynolds-averaged Navier-Stokes (RANS) model became the preferred choice. Different methods of simulating particle deposition in channel flow are compared by Tian and Ahmadi [22]. They found that compared with other RANS models, the Reynolds stress model (RSM) can calculate the particle deposition rate more accurately as it considers the anisotropy of turbulence. Recently, Lu and Lu [23] numerically studied the particle deposition characteristics in duct which arranged ribs on the underside. Moreover, the influence of rib shapes, rib spacing and height, and surface rib arrangements were also considered in their later researches [24–26]. However, previous research was mainly about overall particle deposition rate. Few study researched the particle deposition ratio on each rough element in the initial stage of gas-solid flow. The local particle deposition ratio and the effect of rib spacing and height have not been well investigated. Therefore, further study is recommended.

In this paper, particle deposition on surfaces with different spacing and height rough-elements was investigated by the RSM turbulence model with the Lagrangian tracking method. The purpose of this study is to investigate the effect of rough-element spacing and height on particle deposition and get the detail information of particle deposition ratio on each rough element in the initial stage of two phase flow. Moreover, the mechanisms of particle deposition by a rib-roughened surface and the characteristics of local deposition were also analysed. All findings are presented herein.

2. Physical model and computational cases

A schematic of this study's exemplary two-dimensional computational rough channel is shown in Fig. 1. The rough channel is 20 mm high and 400 mm long. To insure the full development of turbulent flow before the rough section, the first half of the channel is smooth. The second half of the channel underside has rough-elements uniformly arranged with identical spacing. The rough-element is characterized by p/e and e/D, which are the ratios of rough-element spacing to its height and rough-element height to channel diameter, respectively. Here, p is the rough-element spacing, e is the rough-element height and D is the channel diameter.

A variety of rough channel were simulated in this paper, and the parameters and layout of the rough-elements are shown in Table 1.

3. Numerical method and validation

3.1. Numerical model

3.1.1. Continuous phase

Since the velocity of the turbulent air flow is low, it can be considered an incompressible fluid. For turbulent air flow, the mean mass and momentum equations can be expressed as,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u'_i u'_j}\right) \tag{2}$$

where $\bar{u}_i$ is the time-average velocity, x_i is the space position, t is the time, $\bar{p}$ is the time-averaged pressure, ρ is the constant air density, and μ is the dynamic viscosity.

In this study, the individual turbulent was solved using the RSM model. The differential transport equation is given as,

$$\underbrace{\frac{\partial}{\partial t}(\overline{u'_i u'_j}) + \bar{u}_k \frac{\partial}{\partial x_k}(\overline{u'_i u'_j})}_{\text{convective transport}} = \underbrace{\frac{\partial}{\partial x_k}\left(\frac{v_t}{\sigma_k}\frac{\partial \overline{u'_i u'_j}}{\partial x_k}\right)}_{D_{T,ij}=\text{diffusive transport}} - \underbrace{\left(\overline{u'_i u'_k}\frac{\partial \bar{u}_j}{\partial x_k} + \overline{u'_j u'_k}\frac{\partial \bar{u}_i}{\partial x_k}\right)}_{P_{ij}=\text{stress production}} \times \underbrace{-C_1 \frac{\varepsilon}{k}\left[\overline{u'_i u'_j} - \frac{2}{3}\delta_{ij}k\right] - C_2\left[P_{ij} - \frac{2}{3}\delta_{ij}P\right]}_{\phi_{ij}=\text{pressure strain}} - \underbrace{\frac{2}{3}\delta_{ij}\varepsilon}_{\varepsilon_{ij}=\text{dissipation}} \tag{3}$$

where the σ_k = 1.0, C_1 = 1.8, and C_2 = 0.6 are the empirical constants [27]. The turbulence dissipation rate, ε, is as follow,

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(v + \frac{v_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_{\varepsilon 1}\frac{\varepsilon}{k}\overline{u'_i u'_j}\frac{\partial \bar{u}_i}{\partial x_j} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

where the empirical constants σ_ε = 1.3, $C_{\varepsilon 1}$ = 1.44, $C_{\varepsilon 2}$ = 1.92 [28].

3.1.2. Discrete phase

In this paper, particle phase is considered a discrete phase and its motion is simulated by the discrete particle model. Because the ratio of particle volume to air volume in the whole channel is 0.08% in this paper, far less than 5%, the influence of particles on turbulent air flow is ignored and so is the interactions between particles [29,30]. Moreover, the particle-to-gas density ratio is so

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