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Numerical investigation on particle deposition enhancement in duct air flow by ribbed wall

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ABSTRACT

This paper studied the particle deposition in turbulent duct air flows with smooth and ribbed walls numerically. The RSM model with turbulent fluctuation correction and Lagrangian track method were adopted to investigate the particle deposition enhancement by ribbed surface. The air flow velocity profiles for both smooth and ribbed-ducts as well as particle deposition velocity on smooth wall obtained in the present simulation were validated by agreeing well with the previous related study data. Particle deposition is significantly enhanced by surface ribs, especially in turbulent diffusion and eddy diffusion-impaction regimes. It is found that the captures of turbulent eddies induced by ribs and entrainments of large turbulent kinetic energy (T.K.E.) to the wall are the main mechanism for deposition enhancement of small particles. Moreover, pressure drop-weighted efficiency ratio of particle deposition enhancement for ribbed surface is evaluated in this study. The efficiency ratio for ribbed surface can reach more than 100 for particle sizes 0.2–3 μm but only about 2–3 for particle sizes 20–50 μm. This study shows that the repeated ribs on the surface could be an effective and efficient choice for particle deposition enhancement, especially for micron-meter particles.

1. Introduction

Air pollution has been becoming a serious problem in urban environment nowadays. Since people spend most of their time indoors, the particulate matter (PM) in the indoor environment can be a major threat to people's health. Therefore, effective and efficient particle removal devices become extremely necessary to improve indoor air quality (IAQ). It has been found that the repeated surface ribs can significantly increase the collection performance of the particle removal devices such as air electrostatic precipitators (ESP) [1,2]. This is because arrangement of repeated ribs on the ESP surface can intercept a large number of airborne particles. However, the extra pressure drop is also induced by the surface ribs for their form drag. Therefore, the comprehensive performance needs to be investigated and evaluated by considering the above effects. Moreover, Lai et al. [3,4] proposed that it may be an effective alternative to filtration through enhancing aerosol particle deposition by repeated surface ribs along the length of the ventilation duct. In fact, it had been found that plenty aerosol particles would be deposited in the ventilated bend according to the previous experimental studies by Sun and Lu [5,6]. If a large number of aerosol particles can be collected and deposited in a length of dismountable ventilation duct, the IAQ would be significantly improved which is favorable for people's health. Nevertheless, it is also conceivable that the pressure drop would be increased by the surface ribs, which should be considered for the comprehensive performance of particle deposition enhancement. Therefore, better understanding of particle deposition enhancement performance and mechanism in obstructed air flow is meaningful and valuable for IAQ and relative engineering designs and applications.

The previous studies of particle deposition enhancement performance by ribbed surface are limited. Lai et al. [3,4] studied the particle deposition enhancement in duct air flow by surface ribs experimentally. Their results indicated that particle deposition rate could be significantly enhanced by ribbed wall. Li et al. [7] numerically investigated the aerosol particle transport and deposition in a duct with an obstructing block. They found that large numbers of particles deposited on the blocks due to impaction and interception. Iacono et al. [8] predicted spherical and cylindrical particle motions in channel flow with one surface rib using large eddy simulation (LES). They found that spherical particles tend to

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accumulate on the windward rib surface while cylindrical particles don't. Hussein et al. [9] proposed a new particle deposition model for rough surface based on the three-layer deposition model [10–13]. Their results showed that the new model was capable to predict the deposition velocities on various rough surfaces. Recently, multilayer particle deposition in ribbed channel flow was investigated experimentally by Barth et al. [14] and numerically by Lecrivain et al. [15], however, the particle deposition enhancement was not investigated. In summary, it has been previously found that particle deposition velocity could be enhanced by ribbed surface. However, the studied particle sizes in the previous studies were mainly ranging from 0.7 to 7.1 μm. The other size particles from the turbulent diffusion regime to the inertia-moderated regime have been not examined. Furthermore, the interception of the ribs and the increase of deposition surface area have been found as the main mechanisms of such kind of enhancement [3,4,7]. However, the mechanisms from the view of the modification of flow structures and turbulent kinetic energy (T.K.E.) by ribbed surface are not well investigated. Therefore, particle deposition enhancement performance and mechanism by ribbed surface were not fully understood. Further investigation on the enhancement is recommended.

In general, experiment investigation and numerical simulation are the two main methods to investigate particle deposition on the wall. According to the review by Chen [16], numerical simulation method has been contributed about 70% of literature for the studies of ventilation performance prediction for buildings in 2007. This is because numerical simulation can predict the information of airflow, particle deposition and behavior in details [17,18]. Nevertheless, it is quite challenging to accurately measure and analyze particle deposition and movement in the near-wall region by experiments as many complex influencing factors are coupled together to affect particle behavior in practice. For numerical simulation, the Eulerian–Lagrangian methods have been considered as a powerful tool to investigate the particle deposition in turbulent flow by a number of studies such as Tian and Ahmadi [19], Zhang and Chen [20], Gao et al. [21], Jiang et al. [22–24], and Sun et al. [25–27]. In these methods, turbulent flow is treated as a continuous phase and simulated in the Eulerian frame while particles are considered as a discrete phase and the trajectory of each particle is tracked through solving the particle dynamic equation. It has been found that accurate prediction of turbulent air flow is very important for successfully simulating the particle deposition onto surface [19,20]. Tian and Ahmadi [19] numerically studied the particle deposition in duct flow by using different turbulence models. It was found that Reynolds stress model (RSM) with the correction of turbulent wall-normal velocity fluctuation can simulate the particle deposition velocity in turbulent channel flow more accurately compared with the other RANS models. This is because most eddy viscosity turbulence models such as k-ε and k-ω assume isotropic turbulence structures while RSM considers anisotropy of turbulence. Therefore, the RSM can predict the turbulent flow more accurately with strong anisotropy behaviors such as the flow over ribbed surface. Moreover, although direct numerical simulation (DNS) or large eddy simulation (LES) can obtain more accurate turbulent flow fields, it also needs much more computational costs compared with RANS. As RSM with velocity fluctuation correction can already accurately predict deposition velocity of particles with 0.1–50 μm in turbulent flow [19], it is unnecessary to use DNS or LES for large calculation amount. Therefore, RSM with turbulent fluctuation correction is employed to perform the simulations.

In the present study, particle depositions on both smooth and ribbed surfaces are investigated by RSM turbulence model with turbulent fluctuation correction and Lagrangian tracking method. This study aims to investigate the enhancement ratio and mechanism of particle deposition by ribbed surface with comparison with smooth surface case. Moreover, pressure drop-weighted particle collection efficiency by ribbed wall is defined and evaluated to provide guides for the relative engineering designs and applications. The particle sizes in this study are ranging from 0.1 to 50 μm including the turbulent diffusion regime to the inertia-moderated regime.

2. Numerical model and methodology

In the present study, the commercial software Ansys Fluent 13.0 implemented with user-defined functions (UDF) was employed for the simulation since its capacity and reliability have been widely proved in many studies [19–27].

2.1. Turbulent air flow model

The RSM model was adopted to deal with turbulent air flow because it accounts for the anisotropy of turbulence. The mean continuity and momentum equations are given to describe incompressible turbulent flow as follows.

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

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

where $\overline{u}_i$ is the time-averaged velocity, $\overline{p}$ is the time-averaged pressure, μ is the dynamic viscosity of air, and $\rho \overline{u_i' u_j'}$ is the Reynolds stress tensor. The transport equation of the Reynolds stress is given as follows,

$$\frac{\partial}{\partial t}\left(\overline{u_i' u_j'}\right) + \overline{u}_k \frac{\partial}{\partial x_k}\left(\overline{u_i' u_j'}\right) = \underbrace{\frac{\partial}{\partial x_k}\left(\frac{\nu_t}{\sigma_k}\frac{\partial \overline{u_i' u_j'}}{\partial x_k}\right)}_{D_{T,ij}=\text{Turbulent Diffusion}} \underbrace{-\left(\overline{u_i' u_k'}\frac{\partial \overline{u}_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial \overline{u}_i}{\partial x_k}\right)}_{P_{ij}=\text{Stress Production}} \underbrace{-C_1 \frac{\varepsilon}{k}\left[\overline{u_i' u_j'} - \frac{2}{3}\delta_{ij} k\right] - C_2\left[P_{ij} - \frac{2}{3}\delta_{ij} P\right]}_{\phi_{ij}=\text{Pressure Strain}} - \underbrace{\frac{2}{3}\delta_{ij}\varepsilon}_{\varepsilon_{ij}=\text{Dissipation}} \tag{3}$$

where the production term is given as

$$P_{ij} = -\left(\overline{u_i' u_k'}\frac{\partial \overline{u}_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial \overline{u}_i}{\partial x_k}\right), \quad P = \frac{1}{2}P_{ii}, \quad \delta_{ij} = \begin{cases} 1 \ (i=j) \\ 0 \ (i \neq j) \end{cases} \tag{4}$$

In the Eq. (3), empirical constants $\sigma_k = 1.0$, $C_1 = 1.8$ and $C_2 = 0.6$ [28]. Moreover, the turbulence dissipation rate ε is calculated by the following transport equation,