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Original Research Paper

On the enhancement of particle deposition in turbulent channel airflow by a ribbed wall

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A R T I C L E I N F O

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A B S T R A C T

The particle deposition at a vertical wall roughened by transverse square bars placed at a small spacing between them is investigated using large-eddy simulation of the turbulent flow in a ribbed channel with the gravity aligned in the flow direction together with Lagrangian particle-tracking. It is found that the particle deposition coefficient is substantially increased in the presence of roughness elements, exhibiting a weaker dependence on the variation of particle response time relative to the case of smooth channel. The enhancement ratio of particle deposition varies from three for the larger size particles to about 400 for the smaller particles examined here. The friction-weighted enhancement ratio of particle deposition is higher than unity for all particle sets, indicating that the present ribbed channel configuration efficiently increases particle deposition with respect to the increase in energy losses. The rise in the particle deposition coefficient at the rough surface is closely related to the direct inertial impaction and interception mechanisms. The population of particles depositing at the rear surface of the square bars is very small, revealing that an enlargement of the effective deposition area is not necessarily translated to a similar augmentation of particle removal.

1. Introduction

Several human health problems associated with heating, ventilation, and air conditioning (HVAC) systems are caused by the pollution of ventilation ducts. Particle deposition onto duct surfaces is a critical factor, which influences size distributions, concentrations, and fate of indoor aerosols. Re-suspension of the deposited particles in a ventilation duct may also take place, resulting in polluted indoor environment and adverse health effect. It has been found that the removal of particles is significantly increased by a rough wall consisting of elements with various sizes and shapes placed on the solid surface in various arrangements and combinations, improving the collection efficiency of electrostatic precipitators [1] and the air filtration in ventilation ducts [2–4]. However, the total energy losses are usually increased in such geometric configurations, and the trade-offs between those losses and particle removal need to be clarified. Therefore, it is important to advance our knowledge and understanding of the complicated processes occurring in particulate flows and particularly in particle deposition on rough surfaces, in order to maintain and improve indoor air quality (IAQ).

Relatively few studies have been performed on the particle deposition enhancement by a rough wall. The effect of surface roughness on the particle deposition has been quantified in several experimental works by using irregular size materials or well-defined large scale obstructions [2–5]. Particle deposition was measured rather indirectly by calculating the particle mass rate, while certain details were not provided. Nevertheless, all these works indicate that the amount of particles depositing on rough walls is higher than that on smooth walls. Moreover, the significance of the interception mechanism for the augmentation of particle deposition observed at the rough walls is clearly highlighted.

Several aspects of the transport and deposition of aerosol particles in turbulent channel flows with surface ribs have been investigated mostly based on Reynolds-averaged Navier-Stokes (RANS) models together with Lagrangian particle-tracking [6–12]. In accordance with the experimental observations, the numerical studies predict an increase of particle deposition at the rough surface. The differences in the dynamic behavior between spherical and cylindrical particles in a channel flow with one surface rib were discussed by Lo Iacono et al. [13], who used large-eddy simulation (LES) coupled with Lagrangian particle-tracking. They showed that spherical particles were concentrated mostly at the frontal surface of the rib, while cylindrical particles didn't exhibit

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Nomenclature

A_d	deposition area
C	LES parameter
c_D	drag coefficient
C_f	viscous shear stress
d_p	particle diameter
f	friction factor
$f^n_{D,i}$	drag force acting on particle
F_d	friction drag
f_G	gravity force acting on particle
Fr	Froude number
f_{rough}	friction factor of the rough channel
f_{smooth}	friction factor of the smooth wall
g	gravity
h	half distance between the right smooth wall and the crest of the left rough wall
k	dimension of the square bar
k_d^+	normalized particle deposition coefficient
l	distance from the vertical crests of the rough wall
L_{ij}	LES quantity
L_x, L_y, and L_z	dimension of the channel in the streamwise, wall-normal and spanwise direction, respectively
M_{ij}	LES quantity
m_p	the spherical particle mass
$\boldsymbol{n}$	unit vector normal to the wall contour
n_d	number of deposited particles
$n_{\delta V}$	initial number of particles
$\overline{p}$	pressure
$\overline{P}$	non-dimensional pressure
P_d	form drag
Re	Reynolds number
Re_p	particle Reynolds number
$\boldsymbol{s}$	unit vector parallel to the wall contour
$\overline{S}_{ij}$	resolved strain-rate tensor
$\lvert\overline{S}\rvert$	magnitude of resolved strain-rate tensor
S_{pf}	particle-fluid density ratio
St^+	non-dimensional particle response time
t, T	time (non-dimensional)
t_c	contact time
$\overline{u_i}$	component of the filtered velocity in the i-direction
$\overline{U_i}$	non-dimensional component of the filtered velocity in the i-direction
$\tilde{u}^n_{@p,i}$	undisturbed fluid velocity at the particle position
$\overline{U}$	mean fluid velocity in the streamwise direction
u_b	bulk velocity
$U_{p,d}$, $V_{p,d}$, and $W_{p,d}$	non-dimensional components of the wall-impact velocity in the x, y, and z directions, respectively
$u^n_{p,i}$	velocity of the n particle
U_{rms}, V_{rms}, and W_{rms}	non-dimensional rms fluid velocity fluctuations in the x, y, and z directions, respectively
$u_{\tau,0}$	wall friction velocity at $w/k = 0$
U_τ	non-dimensional wall friction velocity
W	cavity width
$\boldsymbol{X}$	unit vector in the x-direction
$x(X)$, $y(Y)$, and $z(Z)$	coordinates (non-dimensional) in the streamwise, wall-normal and spanwise direction, respectively
$X_u(nbl)$, $X_l(nbl)$, Y_{in}, Y_{out}	planes of the upper and lower horizontal surfaces of the nbl square bar and planes of the inner and outer vertical surfaces of the rough wall, respectively
$x^n_{pc,i}$	particle position at contact with the planes of the rough wall
$x^n_{p,i}$	particle position
y^+	non-dimensional distance
y^+_0	origin of distribution of correction 2
Greek	
Γ	enhancement ratio of particle deposition
$\overline{\Delta}$	characteristic length scale
δ_{ij}	Kronecker delta
δt_d	time interval
δV	volume
Δx, Δy, and Δz	grid spacing in the x-, y-, and z-directions, respectively
η	friction-weighted enhancement ratio of particle deposition
λ	streamwise wavelength
ν	air kinematic viscosity
Π	extra pressure gradient
ρ_f	air density
ρ_p	particle density
τ^r_{ij}	subgrid scale stress tensor
τ_p	particle relaxation time
τ_w	wall stress
Symbols	
$-$	filtered LES quantities
$\wedge$	variables calculated on a test filter
$\langle\rangle_{z,t}$	denotes averaging over the z-direction and time

such tendency. Lo Iacono et al. [14] showed that the mass-sink concept could be employed in engineering practice, even though it could not capture the microphysics of the interaction of the suspended particles with the roughness element. The effect of the subgrid scale fluid motions on the particle trajectories in turbulent channel flows with one surface rib was investigated by Khan et al. [15]. They concluded that their effect is rather small on the motion of particles with high response times in well-resolved LESs. On the other hand, the model impact could be non-negligible at different flow regimes, such as higher Reynolds number of the flow, insufficient grid resolution, and/or low particle inertia.

In the present study, the effect of roughness elements on the particle deposition is investigated by using LES of the downward turbulent flow in a vertical channel with one wall consisting of square bars separated by a cavity, as shown in Fig. 1. The combination of numerical methods (LES/immersed boundary method/Lagrangian particle-tracking) has not been utilized previously for the in depth investigation of particle deposition enhancement by a rough wall, which so far is based on RANS simulations. This work differs form previous LES studies [13,14] in several aspects, as for example, in the size and arrangement of roughness elements, the Reynolds number of the airflow, the gravity orientation, and the particle response time, indicating that a different parameter space is examined here. Moreover, the main objective of this work is focused on addressing the impact of square bars on the particle deposition enhancement and quantifying it properly based on measures, such as the deposition enhancement ratio and the friction-weighted efficiency factor. To the best of the author's knowledge, this is performed for the first time by using LES results. LES can provide a reliable representation of the turbulent flow fields, and several quantities required for the description of particle deposition onto rough walls can be obtained accurately, such as