Powder Technology 263 (2014) 142–150

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Simulation of multilayer particle resuspension in an obstructed channel flow

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ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form 16 April 2014
Accepted 5 May 2014
Available online 14 May 2014

Keywords:
Multilayer particle resuspension
Large Eddy Simulation
Discrete Element Method
Obstructed channel flow

ABSTRACT

The present work deals with the multilayer resuspension of solid aerosol particles off a multilayer deposit exposed to a sudden gas flow increase. The heavy detachment of particles spans a wide range of industrial and non-industrial applications. It is used extensively in applications dealing with the resuspension of dust by wind, the resuspension of particles in ventilation ducts and the resuspension of radioactive graphite particles in high temperature reactors. A new numerical approach is suggested to simulate the particle resuspension off a multilayer deposit initially at rest in the cavity of horizontal obstructed turbulent channel flow. The present resuspension model is based on alternating iterations of a Large Eddy Simulation (LES) for the gas flow and of a Discrete Element Method (DEM) for the particle detachment. The combination of LES and DEM simulates the effect of a sudden increase in the turbulent gas flow on the topology of the granular interface, i.e. the surface separating the multilayer deposit from the turbulent gas phase. After tuning two parameters of a simple cluster re-entrainment criterion, results show good agreements with experimental data performed on-site. Both the shape and the wall roughness of the granular interface are predicted with a good level of accuracy. Findings from this study also confirm that the friction velocity is a major resuspension agent.

1. Introduction

The term resuspension, used here synonymously with re-entrainment, denotes the detachment of solid aerosol particles off a wall surface back into the flow. Resuspension of solid aerosol particles, whose size typically varies from 1 μm to 20 μm, spans a wide range of applications. Typical areas of investigations include the resuspension of dust by wind off grass and concrete surfaces under atmospheric conditions [1], the resuspension of particles in ventilation ducts [2] and also the resuspension of radioactive dust in nuclear reactors causing the release of fission products during an accident scenario [3]. Similar to particle deposition, particle resuspension can either be monolayer [4] or multilayer [5,6]. Monolayer resuspension indicates that all deposited particles only adhere to a wall surface whilst multilayer resuspension indicates a more complex particle arrangement: particles either sit on a wall surface or on top of other particles and form a multilayer particle bed, henceforth referred to as the multilayer deposit. Existing monolayer resuspension models are capable of predicting with reasonable accuracy the remaining fraction of a monolayer deposit. Two kinds of resuspension model have emerged from the literature [7]: the force-balance model [8,9] and the energy-balance model [10,11]. The force-balance model assumes particle detachment whenever the hydrodynamic effort overcomes the adhesion bonds. The energy-balance model is based on the resonance of the particle–wall system that could lead to the breaking of adhesion bonds. Whilst the development of monolayer resuspension models has seen an increasing interest over the past few decades, the same cannot be said for multilayer resuspension [12]. The complexity of the several effects that do not occur in monolayer deposits, such as mutual obstruction of particles and clustering effect [13], renders the development of multilayer resuspension model difficult. To date, only a handful of studies have attempted to numerically predict the remaining fraction of a multilayer deposit [13,14]. The simulations usually reproduce the "flat plate experiment", in which particles are placed on the bottom surface of a wind tunnel and are subsequently subject to a sudden flow increase [15]. The boundary conditions of such simulations are simple. A constant value of the mean friction velocity u_τ for each resuspension experiment and a well-defined wall roughness are assumed, notable examples include for instance the simulations of Guingo and Minier [9] and Fu et al. [16]. The instantaneous fluid velocity "seen" by the particle is then

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http://dx.doi.org/10.1016/j.powtec.2014.05.009
0032-5910/

Nomenclature

Acronyms

DEM	Discrete Element Method
LES	Large Eddy Simulation

Greek symbols

ΔP	pressure drop
Δ	filter width
δ	arbitrarily small distance
κ	von Karman constant
ν	kinematic fluid viscosity
ν_t	eddy viscosity of residual motions
ρ	fluid density
τ^s	subgrid scale tensor
τ_w	wall shear stress

Latin symbols

u_τ^0	pick-up velocity
C_f	friction coefficient
C_s	Smagorinsky constant
d	particle diameter
e	obstacle height
H	channel height
L	channel length
p	channel pitch
R_a	arithmetic wall roughness
Re_b	bulk Reynolds number based on channel height H and bulk velocity of the fluid U_b
S	strain rate tensor
t_0	adaptable time constant
t_r	resuspension time
u	instantaneous fluid velocity
U_b	bulk velocity
u_τ	friction velocity

Miscellaneous

$\widetilde{X}$	tilde-like overbar denoting the filtering operation of the arbitrary quantity X

artificially reconstructed using a continuous random walk model [17]. Whilst this approach may be acceptable in the flat experiment, it will likely fail when the geometry becomes complex. In an obstructed channel flow, as is the case here, some areas are more propitious for particle resuspension because of the large and instantaneous changes in the fluid velocity. The development of multilayer resuspension models is still in a very early stage of development. As indicated previously, resuspension models, be it multi- or monolayer were developed with the ultimate goal of predicting the remaining fraction as a function of the friction velocity. No attempts have yet been made to predict the evolving shape of the multilayer deposit in an obstructed channel. In this paper, a new numerical approach is suggested to simulate the particle resuspension off a multilayer deposit initially at rest in the cavity of horizontal obstructed turbulent channel flow. The present resuspension model, which is the first of its kind, combines a Large Eddy Simulation (LES) and a Discrete Element Method (DEM) to simulate the effect of a sudden increase in the turbulent gas flow on the topology of the granular interface. LES is employed to solve the instantaneous flow field and DEM to build a Lagrangian representation of the two-dimensional cross-sectional section of the multilayer deposit.

2. Methods

2.1. Experimental reference

The present work seeks to develop a novel approach for the numerical simulation of multilayer particle resuspension. The multilayer resuspension experiment performed by Barth et al. [18] is presently used for model validation. In an obstructed horizontal turbulent channel flow, whose schematic is illustrated in Fig. 1, the wall surfaces were subject to a lengthy deposition of carbonaceous dust for a period of about 4 h. The channel height, the rib height and the rib pitch are denoted by H, e and p, respectively. The rib pitch, defined as the distance from one leading edge of the rib to the next leading edge, is set to $p = H$. The height of the rib obstructs the channel height by $e/H = 10\,\%$. Particle size analysis of the airborne particles revealed a minimum equivalent aerodynamic diameter of 1 μm, a mean diameter of about 5.3 μm and a maximum diameter of 20 μm. Throughout the deposition process, it was ensured that the fluid velocity was low enough to avoid particle detachment. After formation of a multilayer deposit in the cavity, the inlet velocity of the gas phase (air) was suddenly increased. The increased inlet velocity was kept constant for a long period of time, after which particle detachment off the multilayer deposit could no longer be detected. The shape of the granular interface, i.e. the surface separating the multilayer deposit from the turbulent gas phase was measured with a laser scanner. The resuspension experiment was conducted for increasing bulk Reynolds numbers ranging from approximately $Re_b = 10{,}000$ to about 50,000.

2.2. Assumptions of the resuspension model

The simulation of the detachment of polydisperse particles off a multilayer deposit by an instantaneous turbulent flow field can be computationally expensive, especially when it involves the coupling of a LES and a DEM, which respectively require a fine mesh of the computational domain and a large number of particles. For a reasonable simulation time, the following assumptions are therefore made.

2.2.1. Particles are spherical

The original experiment was performed with graphite dust. The solid aerosol particles were not spherical but "cornflake"-like when placed under the microscope. Whilst the amorphousness of the particles may affect the adhesion force and the inceptive detachment motions [19], previous-published resuspension models assumed the sphericity of graphite particles [9]. The present assumption should therefore not

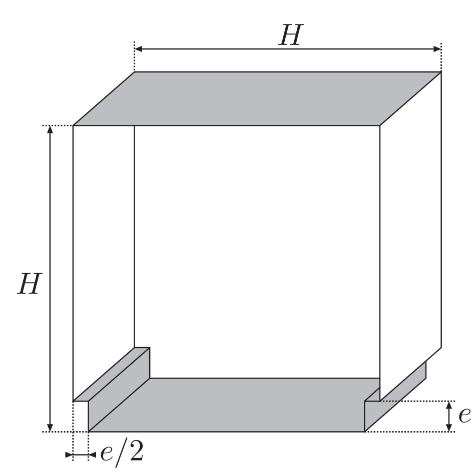

Fig. 1. Schematic of the obstructed channel flow without the multilayer deposit. A wall boundary condition and a periodic boundary condition are respectively enforced on the grey and on the transparent surfaces.