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Original Research Paper

Numerical simulation of multilayer deposition in an obstructed channel flow

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A B S T R A C T

Simulation of multilayer deposition of dry aerosol particles in turbulent flows has gained a growing interest in various industrial and research applications. The multilayer deposition of carbonaceous aerosol particles in a turbulent channel flow obstructed by a succession of square ribs is here numerically investigated. The multilayer particle bed growth on the various wall surfaces affects the air flow, which in turn affects the overall deposition rate. An iterative numerical procedure is therefore suggested to simulate the evolution of the graphite layer. The iterative process used to reproduce the layer build-up is decomposed as follows: Reynolds-Avergared Navier Stokes is employed to generate the flow field. The turbulent dispersion of the particles is reproduced through the use of a continuous random walk model. After statistically sufficient deposition of particulate matter, the layer build-up is computed using mechanics of dry granular material. The layer build-up model shows good agreement with data obtained from experimental tests carried out on-site.

1. Introduction

1.1. Motivation

The deposition of micrometre-sized aerosol particles spans across a wide range of applications such as to name a few examples, exposure to hazardous particulate matter, sedimentation of atmospheric particles and surface obscuration. The deposition of aerosol particles has also gained increasing interest in the field of nuclear safety research [1]. During operation of a graphite moderated high temperature pebble-bed reactor, the motion of the spherical fuel elements within the core initiates the production of carbonaceous dust. The graphite is then conveyed by the coolant gas and deposit in the primary circuit over the course of years. The dust layer build-up as a result of graphite deposition in the cooling system eventually becomes a major source of ionising radiation [2,3].

1.2. Particle deposition in a turbulent flow

Deposition denotes here the process of attaching suspended aerosol particles from a gas in turbulent motion to a surface. Friess and Yadigaroglu [4] distinguished two types of deposition: monolayer deposition and multilayer deposition. Monolayer deposition indicates that particles adhere directly to a wall surface and are not in contact with one another. Multilayer deposition indicates however that particles densely accumulate on the wall surface to form a multilayer particle bed henceforth referred to as dust layer.

Whether monolayer or multilayer, turbulent diffusion is a chief agent responsible for deposition of micrometre-sized aerosol particles. The results of deposition experiment are frequently plotted as curves of particle deposition velocity u_d against particle response time τ_p. The deposition velocity is defined by the surface particle mass flux J divided by the airborne particle mass concentration C_0. As illustrated in Fig. 1, two deposition regimes typically exist [5]. For fine particulate matter (diameter typically lower than 10 μm), the deposition velocity increases with particle size. Fine particles at the low end of the regime are stopped by strong drag forces in the viscous sublayer whereas fine particles at the very end of the regime possess sufficient energy to overcome the drag forces and eventually collide with the wall surface [6]. For large particulate matter (diameter typically greater than 10 μm), the regime becomes ballistic [7], i.e. large particles have greater inertia so that the trajectories are less affected by near wall turbulence. In this regime the deposition velocity reaches a maximum and remains fairly constant.

The diffusion of fine and large particulate matter is largely governed by the unsteady turbulent gas fluctuations. There are currently three well-established approaches to numerically reproduce the transport and deposition of particles. These are Direct Numerical Simulation (DNS), Large Eddy Simulation (LES)

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Nomenclature

Greek

α_d	dynamic angle of repose
α_p	drag correction factor
α_s	static angle of repose
δt_c	critical time step
δx	horizontal grid spacing
δy_c	critical height
ϵ	dissipation rate
η_d	deposited fraction
ν	fluid kinematic viscosity
ϕ	medium porosity
τ_p	particle response time
ξ_i	zero mean, unit variance distributed random number

Latin

C_0	particle mass concentration
d_p	particle diameter
dm/dt	particle mass flow
e	rib height
e_k	sharing coefficient
$\boldsymbol{g}$	gravitational acceleration
H	channel height
J	particle mass flux
k	turbulent kinetic energy
L	channel length
L_{Vi}	associated length of the recirculation zone Vi in the streamwise direction
p	rib pitch
Re^*	friction-velocity-based Reynolds number
Re_b	bulk Reynolds number
Re_p	particle Reynolds number
S	particle to fluid density ratio
t_c	critical time
$\boldsymbol{T_L}$	Lagrangian integral time scale
$\boldsymbol{u}$	instantaneous fluid velocity ($\boldsymbol{u} = \bar{\boldsymbol{u}} + \boldsymbol{u}'$)
$\boldsymbol{u}'$	fluctuating fluid velocity
u^*	friction velocity
$\boldsymbol{u^c}$	drift correction velocity
U_b	bulk fluid velocity
u_b	build-up velocity
u_d	deposition velocity
$\bar{u}_d^f$	mean deposition velocity on the floor
$\boldsymbol{u^p}$	particle velocity
$V1$	recirculation zone at downstream corner of the rib
$V2$	largest recirculation zone downstream of the rib
$V3$	smaller recirculation zone at upstream corner of the rib
y	distance to the nearest wall

Miscellaneous

X^+	superscript denoting the normalisation of arbitrary quantity X with wall scaling (u^* for velocity variables, ν/u^* for length variables, ν/u^{*2} for time variables and u^{*3}/ν for acceleration variables)
$\overline{X}$	overbar denoting time averaging of arbitrary quantity X

and Reynolds-Avergared Navier Stokes (RANS) simulations. While DNS can precisely resolve all turbulent features down to the smallest scales, its heavy computational cost makes inappropriate for turbulent particle-laden flows in complex geometries. Its use has therefore been largely limited to simple geometries such as channel flows [8]. In the LES approach, the large eddies are directly simulated whereas eddies smaller than the grid scale are modelled. Studies on particle deposition using LES have been performed in more complex turbulent flows such as flows in respiratory tract [9]. RANS simulations have gained a growing interest owing to its relatively small computational cost since only the mean flow field is computed. Information on the turbulence is only available in the statistical terms and therefore a dispersion model must be implemented beforehand to reproduce the turbulent diffusion of particles [10]. The deposition of particles using a turbulent dispersion model combined with a RANS simulation has proven successfully under various conditions. The continuous random walk model of Tian and Ahmadi [11] accurately predicted the deposition of nano- and micro-particles in a turbulent channel flow. The random walk model developed by Berrouk [12] has also shown some reasonable accuracy in predicting deposition rates in a curved piped. Li et al. [13] investigated the deposition of aerosol particles around a single obstruction placed in a two-dimensional channel. His findings showed that the particle deposition rate decreases as the shape of the obstacle becomes more streamlined.

1.3. Particle layer build-up in a turbulent flow

A few attempts have been made in the literature to predict layer build-up in turbulent flows. Sarimeseli and Kelbaliyev [14] derived empirical equations to reproduce the multilayer deposition of 10 μm size particles in a horizontal two-dimensional cylindrical pipe. As opposed to vertical flow, the distribution of the deposition velocity across the pipe circumference was included to account for gravity effects. Stempniewicz et al. [15] later estimated the layer build-up of carbonaceous dust in various parts of a pebble bed modular reactor. Through the use of a fairly simple one-dimensional code, the team simulated a build-up that reached, after years of sedimentation, a height of a few centimetres. In the study of Friess and Yadigaroglu [4], the two-dimensional clustering of micron-sized particles was investigated in greater detail. The deposition and re-entrainment of Lagrangian particles in the turbulent boundary layer over a flat plate was simulated. More recently Bozzi and Passoni [16] combined a two-dimensional LES with Lagrangian particles to reproduce the evolution of a sand heap in a two-dimensional turbulent flow.

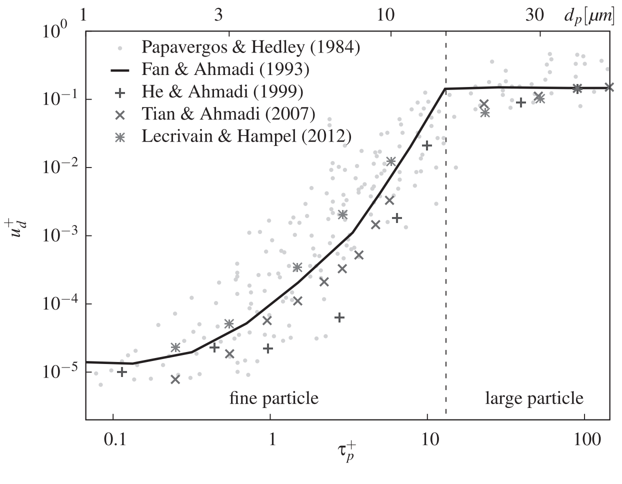

Fig. 1. Effect of the particle response time τ_p on the deposition velocity u_d.