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Single particle resuspension experiments in turbulent channel flows

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ABSTRACT

The resuspension of a monolayer of spherical glass and polypropylene particles from a channel floor by a dry and turbulent airflow was investigated. Special attention was given to the influence of the particle size, the particle and wall material, the wall surface roughness and the critical friction velocity. The experiments were performed in an air-driven small-scale test facility and the channel floor was made of interchangeable glass and steel wall segments. The turbulent channel flow was recorded using a planar Particle Image Velocimetry system. Prior to the experiments the spherical particles were classified using Scanning Electron Microscopy techniques. The particles on the channel floor were detected and classified by means of an optical microscope combined with a digital camera. A statistically sufficient particle monolayer was generated on the channel floor by dispersing the particles into the flow during a pure deposition regime. Afterwards, particle resuspension was induced by stepwise increase of the fluid velocity. The resuspension was quantified by the fraction of remaining particles against the friction velocity for a particle diameter range between 3 μm and 45 μm. It was found that particles instantly resuspend once a critical friction velocity is exceeded. Larger particles require lower fluid velocities for the removal than smaller particles. The wall surface roughness seems to scatter the resuspension process with respect to the friction velocity.

1. Introduction

Particle resuspension denotes the remobilisation of wall deposited particles by a turbulent flow and plays an important role in various industrial applications such as in building ventilation, semi-conductor fabrication and in the operation of nuclear installations. In particular, the removal properties of nano-particles influence the performance of the megasonic cleaning of wafers (Holsteyns et al., 2005). Particle resuspension from heating, ventilation and air conditioning systems may cause the inhalation of aerosol particles and respiratory diseases of the building inhabitants (Holopainen et al., 2002). This effect may also provoke the transmission of pathogens in hospitals. Furthermore, the particle resuspension behaviour in nuclear installations is of primary safety relevance for the operation and safety assessment of such facilities. Radio-contaminated particles were found in several fusion reactors which were formed as consequence of the interaction between

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Nomenclature

a	fit parameter [dimensionless]
b	fit parameter [dimensionless]
d	diameter [mm]
fr	fraction remaining [dimensionless]
N	number [dimensionless]
R	surface roughness [μm]
Re	Reynolds number [dimensionless]
u, v, w	Cartesian velocity components [m/s]
x, y, z	Cartesian coordinates [mm]
ρ	mass density [g/cm^3]
σ	standard deviation [dimensionless]

Indices and subscripts

a	arithmetic
d	diameter
$geom$	geometric
hyd	hydraulic
max	maximum
$mean$	mean
rms	root mean square
z	arithmetic depth of the single cavities
$\langle - \rangle$	time averaged
$*$	friction
$+$	non-dimensional
50	50%

the plasma and in-vessel materials (Grisolia et al., 2009; Rosanvallon et al., 2009). Likewise, carbonaceous dust was found in several high temperature reactors (HTR) (Kissane, 2009; Moormann, 2008) which probably arose due to friction between the graphite components and due to oxidation processes as consequence of coolant impurities. Seeger et al. (2012) investigated the diffusion processes in HTR fuel pebbles with respect to the temperature. It was found that fission products started to diffuse into the graphite matrix when the local temperature exceeded the design basis explaining the radioactive contamination of the graphite dust. In case of a depressurisation of the primary circuit the contaminated particles may be remobilised by the flow and become a considerable source term when they escape over the system boundaries.

In principle, the removal of single particles from a duct wall by a turbulent flow is affected by the adhesive forces which in turn depends on the particle-to-substrate material composition, the humidity, the presence of electrostatic forces and gravity, the size and the shape of the particle as well as the substrate surface structure and the turbulent boundary layer (Zimon, 1982). First theoretical considerations of particle resuspension go back to the mathematical modelling of the particle-to-wall contact. Johnson et al. (1971) and Derjaguin et al. (1975) developed the JKR and the DMT particle adhesion models to describe the contact of a sphere and a flat wall. Subsequently, two different particle resuspension model approaches were developed namely the force balance and the energy balance concept. Cleaver & Yates (1973) introduced a force balance on a wall attached spherical particle and considered the detachment taking place when the hydrodynamic lift force overcomes the adhesive forces. Braaten et al. (1990) implemented a Monte Carlo simulation in the force balance concept to account for the influence of the coherent flow structures in the turbulent boundary layer triggering the particle resuspension process. Hontañón et al. (2000) extended the force balance to a momentum balance on a wall attached particle suggesting that the inceptive particle detachment takes place when the hydrodynamic torque caused by the particle lift and drag force times a distance overcomes a critical value. Recently, Ahmadi et al. (2007), Guingo and Minier (2008), Goldasteh et al. (2012, 2013) and Fu et al. (2013) coupled the force/momentum balance concept with stochastic flow field models to numerically study the effect of particle size, material composition, surface roughness and/or capillary forces.

The second approach is the energy balance concept. Reeks et al. (1988) introduced a model based on an energy transfer from the turbulent flow to a wall attached spherical particle sitting in a potential well. The particle may be remobilised from the wall when it has received sufficient vibrational energy to escape this potential well. This approach was extensively developed by various scientists (Reeks & Hall, 2001; Vainshtein et al., 1997; Ziskind et al., 1997). Recently, Zhang et al. (2013) coupled the kinetic particle resuspension model of Reeks and Hall with turbulent flow field data obtained from a Direct Numerical Simulation (DNS). Despite the extensive modelling effort the correct prediction of particle resuspension suffers from the lack of high quality reference data obtained from experiments performed comparable to the supposed model assumptions. In detail, the size of the used particles in previous investigations was stated, but the deviation of the particle shape from the ideal spherical shape was not specified. The adhesive and aerodynamic forces acting on a non-spherical particle may be somewhat different from a spherical particle which may hamper the comparability of the experimental results. Particle shape classification based on scanning electron microscopy techniques may give an indication for the irregularity. Furthermore, the local fluid friction velocity was usually estimated using analytical equations based on averaged flow field values. The presence of a flow disturbance or an insufficient long flow formation zone upstream of the particle laden wall segment may lead to a somewhat different shape of the turbulent boundary layer which may also hamper the comparability of the particle resuspension rates with respect to the friction velocity. Highly resolved flow field data of the turbulent boundary layer over the wall segment of interest may be required for the verification of the determination of the correct fluid friction velocity.

First experimental studies on particle resuspension started with the investigation of the particle-to-wall adhesive forces (Boehme et al., 1962; Visser, 1970). The remobilisation of particles by a turbulent airflow was observed by various groups by