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REMOVAL OF PARTICLES FROM A POWDERY FOULED SURFACE DUE TO IMPACTION

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ABSTRACT

Particulate fouling is defined as the unwanted deposition of particles on heat exchange surfaces. The fouling layer reduces the heat transfer rate and leads to inefficient operation. The net fouling rate is the result of the difference between the deposition rate and the removal rate of particles. One of the mechanisms that contribute to the removal of particles from powdery fouled surfaces is the collision of an incident particle with the fouled surface. In the present study, removal of particles from powdery fouled surfaces due to an incident particle impact is studied numerically and experimentally.

A numerical model is developed to study the interaction of an incident particle with a bed of particles. The numerical model is based on the molecular dynamic theory of granular matter. The numerical model is tested for an incident copper particle hitting a bed of particles at different impact speeds. The numerical results are verified experimentally. An experimental setup has been built to study the removal of particles from powdery fouling layers due to an incident particle impact. It is shown that depending on the impact speed, zero, one, two or three particles are ejected from the powdery layer. By comparing the numerical results with the experimental measurements it is shown that the numerical results fit in the measured range of impact mentioned above. The numerical model will be used further to characterize the removal of particles from powdery fouling layers as function of particle size, material, incident particle impact speed and the bed of particles porosity.

INTRODUCTION

Fouling of heat transfer surfaces introduces a major uncertainty into the design and operation of heat exchange equipment. The first derivation of a fouling model was by Kern and Seaton (1959) who made the important suggestion that the net fouling rate was the result of the difference between the deposition rate and the removal rate. Attention has been given to the deposition of particles (see, e.g. Abuzeid et al, 1992 and van Beek, 2001) but hardly to removal of particles. Samples of fouling layers were taken from a Dutch waste incineration boiler (van Beek et al., 2001). The layers on the tube bundle of the superheater are thick and sintered whereas the layers on the tube bundle of the economizer are found to be thin and powdery. In this paper, removal of particles from powdery fouled surfaces due to an incident particle impact is studied numerically and experimentally.

In the present study a numerical model is developed to study the interaction of an incident particle with a bed of particles. The numerical model is based on elastic (Hertz, 1896) and plastic deformations (Johnson, 1987) between two particles in contact. These models are used to calculate the particle motion of the bed particles. The numerical model is tested for an incident copper particle hitting a bed of copper particles at impact speeds of 0.2 and 0.6 m/s. An experimental setup has been built to study the removal of particles from powdery fouling layers due to an incident particle impact. A set of experiments is done to study the influence of the impact speed on the removal of particles from powdery layers. A comparison is made between the numerical model results and the experiments.

NUMERICAL MODEL

The numerical model developed is based on molecular dynamic theory of granular matter (Duran, 2000). In this model rotational motion of particles is not taken into account. Particle displacement and velocity are calculated explicitly through a given time step Δt,

$$\vec{x} = \vec{x}_\circ + \vec{v}_\circ \Delta t \qquad (1)$$

$$\vec{v} = \vec{v}_\circ + \dot{\vec{v}}_\circ \Delta t \qquad (2)$$

where the subscript (o) denotes the initial value and the superscript (˙) denotes a time derivative. $\vec{x}$ and $\vec{v}$ are the position and velocity vectors of the concerned particle, respectively. If two particles approach each other such that Ian overlap (deformation) occurs between the particles, a contact force is developed. The contact force is divided into a normal force $\vec{F}_{cn}$, and a tangential force $\vec{F}_{ct}$, fig. 1. If the overlap between the particles does not exceed the elastic yield limit y (Mavko et al, 1988 and Rogers et al, 1984) of the interacting particles, an elastic normal contact force is developed which is given by the Hertz equation:

$$\vec{F}_{cn} = \left| k\delta^{\frac{3}{2}} \right| \vec{n} \,. \tag{3}$$

The normal unit vector $\vec{n}$ is defined in fig. 1 and is given by:

$$\vec{n} = \frac{\vec{x}_2 - \vec{x}_1}{\left|\vec{x}_2 - \vec{x}_1\right|} \tag{4}$$

with $\vec{x}_1$ and $\vec{x}_2$ the position vectors of the interacting particles. δ is the overlap between the interacting particles as shown in fig. 2 and k is equal to:

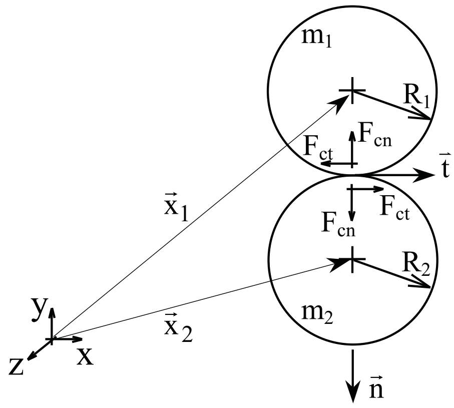

Fig. 1 Contact forces between particles during contact.

$$k = \frac{4}{3} E^* \left(R^*\right)^{\frac{1}{2}} \tag{5}$$

with R^* the reduced radius equal to:

$$R^* = \frac{R_1 R_2}{R_1 + R_2} \tag{6}$$

R_1 and R_2 are the radii of particles 1 and 2, respectively. E^* is a material parameter defined by:

$$\frac{1}{E^*} = \frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2} \,. \tag{7}$$

where σ_i is the Poisson ratio and E_i the Young's modulus of particle i. The elastic deformation limit δ_{el} and the elastic limiting force F_{el} are given by the Hertz theory to be equal to:

$$\delta_{el} = \left(\frac{\pi}{2}\right)^2 \frac{R^* y^2}{E^{*2}} \tag{8}$$

$$F_{el} = \frac{1}{6} (\pi y)^3 \left(\frac{R}{E^*}\right)^2 \tag{9}$$

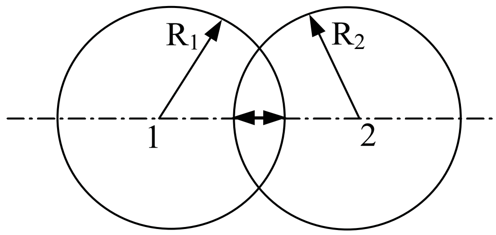

Fig. 2 Interpenetration of two spheres during frontal collision.

If the overlap between the interacting particles exceeds the elastic deformation limit δ_{el} of the interacting particles' material, plastic deformations occur and the normal contact force in that case is different from the one calculated with the Hertz equation. The contact force in case of plastic deformation is given by Johnson (1987):

$$\vec{F}_{cn} = \left| F_{el} + F_p \right| \vec{n} \tag{10}$$

where F_p is equal to:

$$F_p = \pi R^* y \left(\delta - \delta_{el}\right) . \tag{11}$$

When particles get in contact an adhesion force appears acting in the normal direction. The adhesion force is given by Johnson et. al. (1971) to be equal to:

$$\vec{F}_{adh} = \left| \frac{3}{2} \pi R^* \Gamma \right| \vec{n} \tag{12}$$

with Γ the surface energy between the interacting particles. The tangential force $\vec{F}_{ct}$ due to the normal force is equal to:

$$\vec{F}_{ct} = -\mu \left| F_{cn} + F_{adh} \right| \vec{t} \tag{13}$$

where μ is the coefficient of friction and $\vec{t}$ is the unit vector in the tangential direction.

Due to the interaction between an incident particle and a bed of particles, interpenetration occurs causing contact forces to develop. The contact forces can be calculated using equations 3, 10, 12 and 13. The contact forces influence the velocity of the particles. According to

Newton's second law, the change in the particle translational velocity is equal to:

$$\dot{\vec{v}} = \vec{F} / m + \vec{g} \tag{14}$$

where $\dot{\vec{v}}$ is the acceleration of the particle, m is the particle mass, $\vec{F}$ is the sum of forces acting on the particle and $\vec{g}$ is the gravity acceleration vector. The new positions and velocities for the particles after a certain time step Δt are calculated explicitly by equations 1 and 2 respectively. To follow the particles' motion for a certain period of time t, the previous procedure is repeated several time steps for all the interacting particles until the final simulation time T is reached. The cycle of calculations is shown in fig. 3.

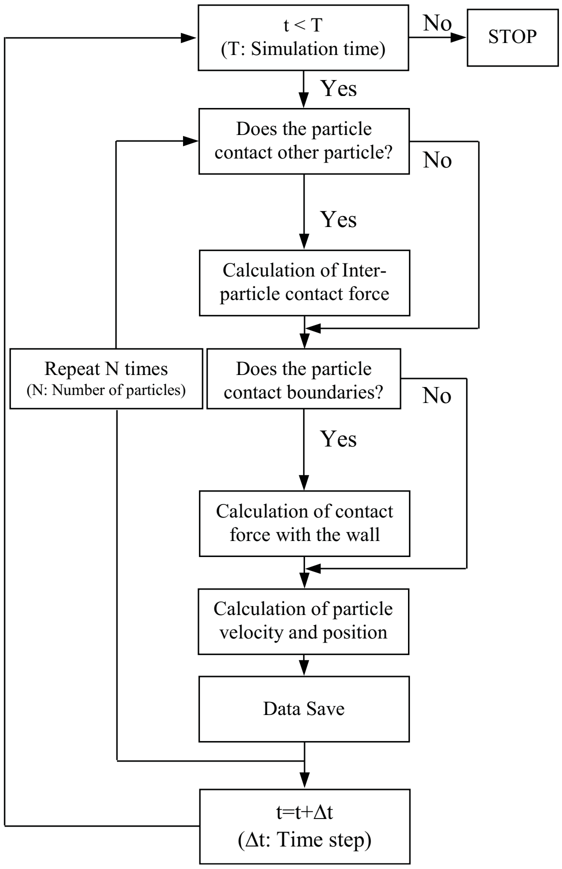

Fig. 3 A Flow-chart of the numerical model.

The model has been run for two cases. In the first case an incident spherical bronze particle at a speed of 0.2 m/s hits a bed of particles. In the second case the incident bronze particle speed is 0.6 m/s. The bed's particles and the incident particle are made from the same material and of a diameter equal to 54 μm. The bed of particles contains 1000 particles arranged in a cubic lattice 10×10×10 as shown in fig. 4. A time step of 1E-12 s has been used in both cases.

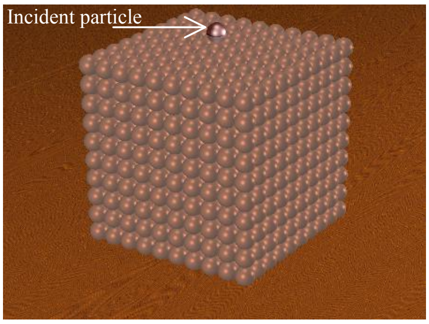

Fig. 4 The bed of particles and the incident particle at the beginning of a simulation. The bed consists of 1000 particles, arranged in a cubic lattice 10×10×10.

Preliminary Numerical Results

Simulation results of the above mentioned two cases are shown in fig. 5. Fig. 5 shows the incident particle displacement with respect to time for both cases. During approach, the incident particle dives into the bed till all its kinetic energy is absorbed into elastic and plastic deformation. At the end of the approach phase the elastic energy stored in the form of elastic deformation is recovered and the particle starts to rebound, this is known as the restitution phase. For the first case, the ejection speed of the incident particle is so small that the particle falls back to the bed's surface due to gravity very fast. For the second case the particle ejection speed is high that it continues ejection out of the surface.

EXPERIMENTAL WORK

An experimental setup has been built to study removal of particles due to an incident particle impact. The setup consists of a vacuumed column in which particles impact on a well-defined surface. The impact of the particles is recorded using a digital camera system. A pulsated light sheet illuminates the particle several times in one camera image. For each particle the impact velocity is determined from the average distance between two successive illuminations (blobs) and the rate of pulsation of the laser sheet. Further details about the measurement procedure and analysis can be found in van Beek (2001). At the bottom of the column, the powdery layer is installed on an object table. With this object table the surface on which the particles impact can be rotated in a vertical plane to investigate the influence of the impact angle. Fig. 6 shows the experimental setup and a typical recorded image.

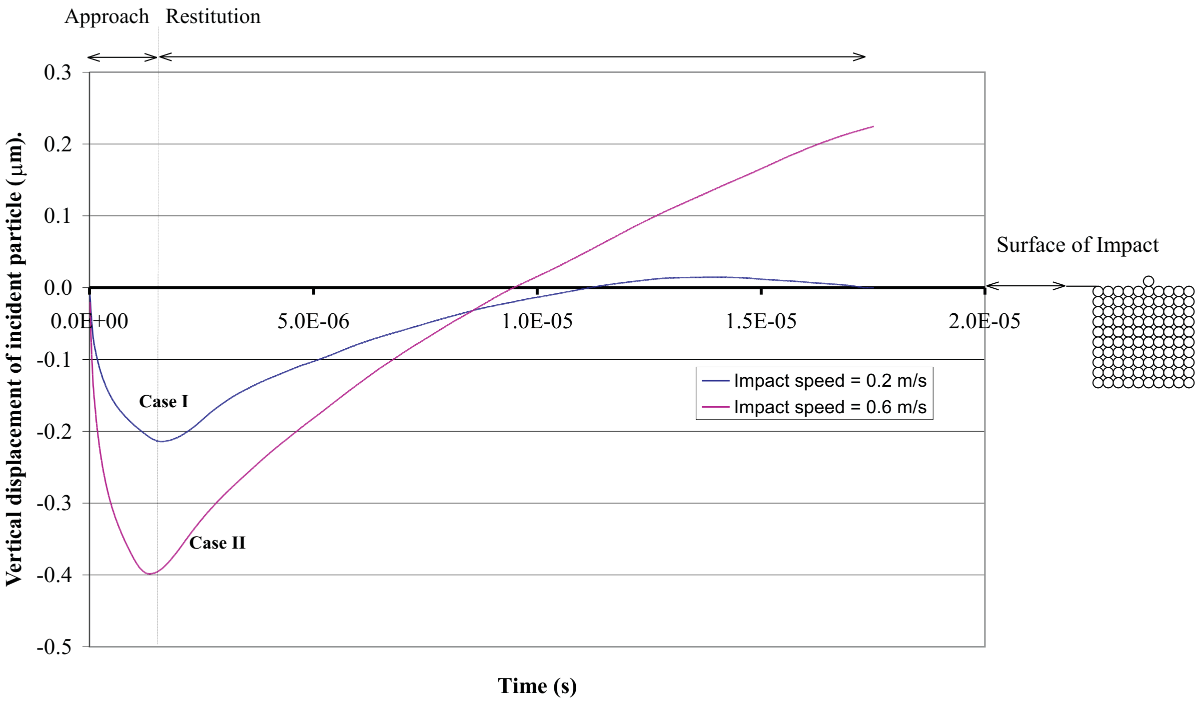

Fig. 5 Vertical displacement versus time for the incoming particle for two impact speeds

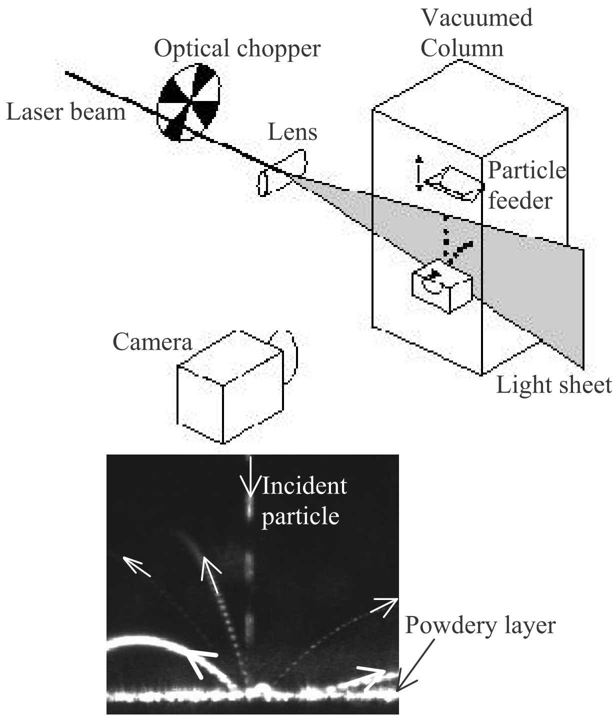

Fig. 6 The experimental set-up (top) and a typical recorded image (bottom).

Sample Preparation

A powdery layer is prepared from spherical bronze particles of average diameter of 55 μm. The standard deviation of the particles size distribution from the average is 6 μm. The porosity of the layer is adjusted to be equal to 0.48. Figure 7 shows a schematic of the press and the preparation steps taken to prepare the porous powdery layer. A certain mass m of powder is poured into the press cavity. The powder is pressed to a final volume V. The average porosity P of the prepared tablet is determined from the following equation:

$$P = 1 - \frac{(m/V)}{\rho_p} \qquad (15)$$

where ρ_p is the density of the layer's particles. By changing the amount of powder pressed for constant volume, the porosity of the formed tablet can be changed. The amount of mass m pressed is measured with an accuracy of $\pm$ 0.001 grams while the final volume V of the press is measured with an accuracy of $\pm$1E-6 m^3. An error analysis shows that the uncertainty in the calculated porosity by using Eq. 15 is $\pm$ 0.001.

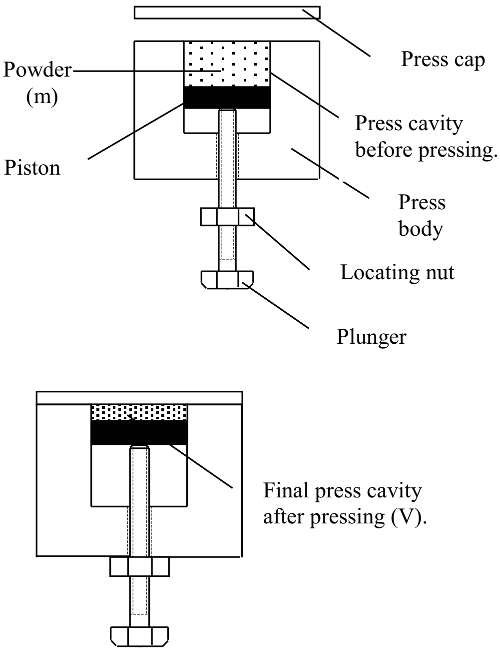

Fig. 7 A schematic diagram showing the steps of preparation for the powdery layers used. Top: Insertion of powder into the press. Bottom: Powder after pressing.

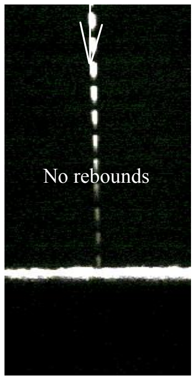

Fig. 8.a

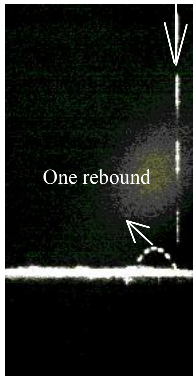

Fig. 8.b

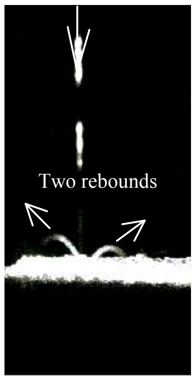

Fig. 8.c

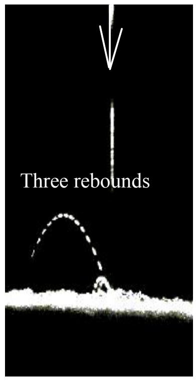

Fig. 8.d

Fig. 8 a) Impact speed is 0.2 m/s. No particles evolve. b) Impact speed is 0.5 m/s. One particle evolves. c) Impact speed is 1.3 m/s. Two particles evolve. d) Impact speed is 2 m/s. Three particles evolve.

Experimental Procedure

The objective of the experiment is to determine the number of particles, which evolves from a powdery layer as function of an incident particle impact speed. The prepared powdery layer is installed on the table in the vacuum column. Spherical bronze particles of average diameter 54 μm, similar to the bed's particles are dropped on the powdery layer. Varying the height of drop (height of the vacuum column) can vary the incident speed. The impact speed of the incident particle is varied from 0.1 to 2 m/s. The impact speed, impact angle and the number of particles that evolves due to impact are measured.

EXPERIMENTAL RESULTS

Figures 8.a to 8.d show typical recorded images of particles ejecting from a powdery layer as function of the incident particle impact speed. It is shown that as the impact speed increases more particles are ejected from the powdery layer.

Figures 9.a to 9.c shows the variation of impact speed with the number of particles ejected. From Fig. 9.a it can be concluded that an incident bronze particle of diameter 55 μm hitting a bed of particle of the same material and porosity 0.48 at a speed of 0.24 m/s will stick to the bed. If the impact speed increases to 0.52 m/s the particle will rebound from the surface, fig. 9.b. If the particle speed goes higher to 1.27 m/s, the incident particle will rebound from the surface and in the mean time it ejects another particle from the surface, fig. 9.c. If the speed increases to 1.73 m/s, the incident particle rebounds and ejects two particles from the surface, fig. 9.d.

It can be also concluded from figures 9.a to 9.c that there is a range of impact speeds at which the same number of particles is ejected from the powdery layer.

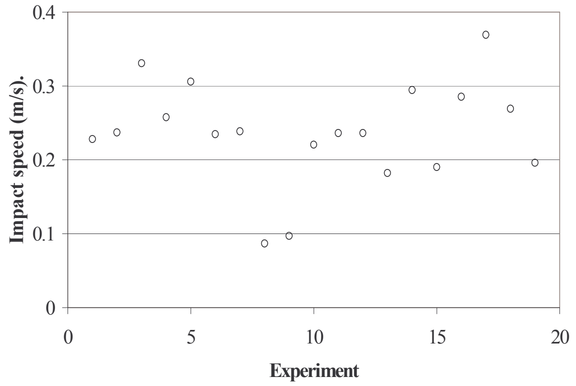

Fig. 9.a No particles are ejected from the fouling layer. (Average speed =0.24 m/s and S.D. = 0.07 m/s)

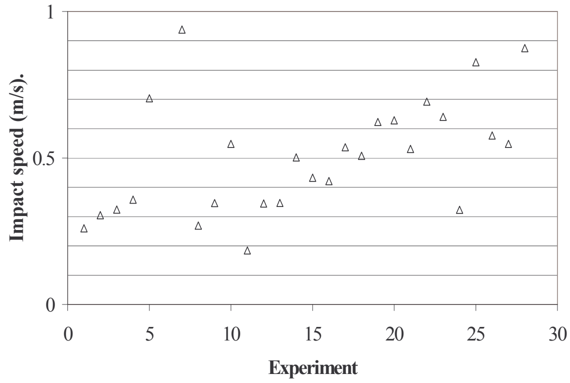

Fig. 9.b One particle is ejected from the fouling layer. (Average speed =0.52 m/s and S.D. = 0.22 m/s)

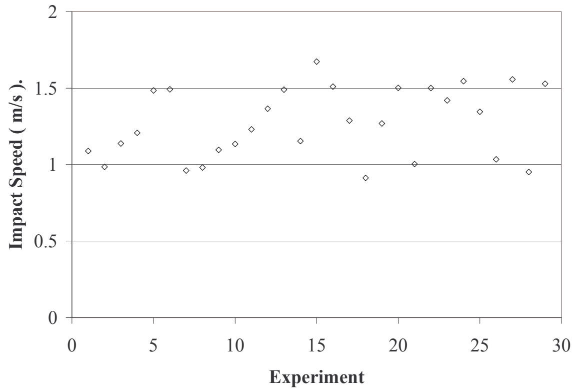

Fig. 9.c Two particles are ejected from the fouling layer. (Average speed =1.27 m/s and S.D. = 0.23 m/s)

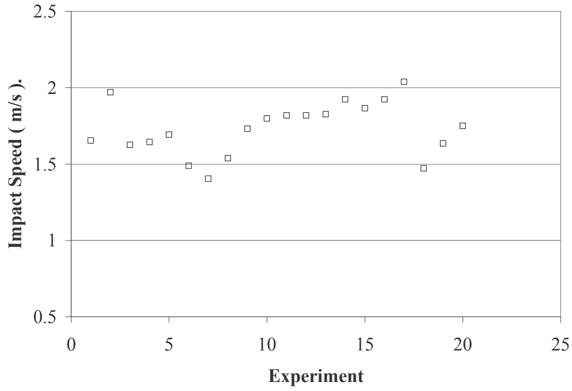

Fig. 9.d. Three particles are ejected from the powdery layer. (Average speed =1.73 m/s and S.D. = 0.17 m/s)

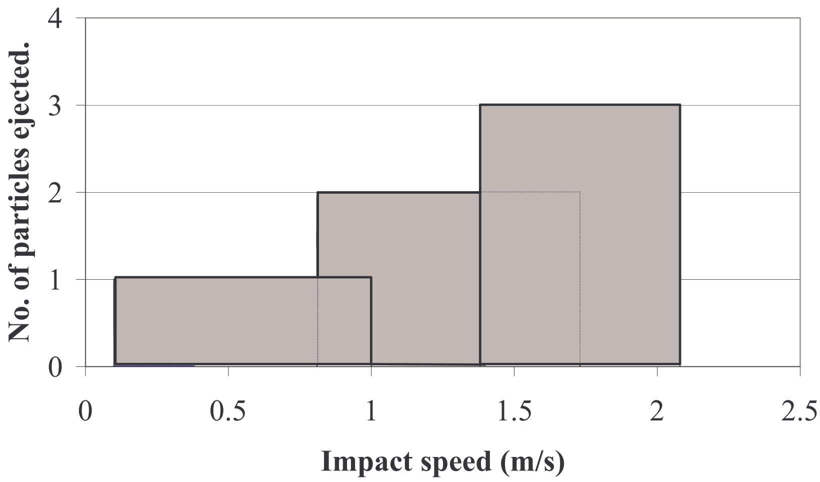

Fig. 10 Number of particles ejected versus impact speed

This trend is summarized in fig. 10. The overlapping in the measurements is due to the change in impact position with respect to the impacted particle in each measurement.

DISCUSSION AND CONCLUSION

The numerical model shows that an incident spherical bronze particle sticks to a bed of particles of porosity 0.48 if it hits at a speed of 0.2 m/s and rebounds if the impact speed is 0.6 m/s. In both cases the bed of particles consists of particles similar to the incident particle. This result complies with the experimental work. From the experimental study it is shown that incident particles stick if the impact speed is below 0.24 m/s and rebounds if it is higher than this value.

A numerical model has been developed which models the interaction between an incident particle and a bed of particles. The numerical model can predict the removal of particles from powdery layers due to an incident particle impact. An experimental study has been done. Experiments show that as the impact speed of the incoming particle increases more particles are ejected from powdery surface. The numerical model predictions comply with the experimental measurements. The numerical model will be used further to characterize the removal of particles from powdery fouling layers as a function of particle size, material, incident particle impact speed and the bed of particles' porosity. By integrating the numerical model with developed deposition models more insight can be attained about the fouling process.

NOMENCLATURE

E Young's modulus, N/m^2.
F_{adh} Adhesion force, N.
F_{el} Elastic limiting force, N.
F_{cn} Normal contact force, N.
F_{ct} Normal tangential force, N.
F_p Plastic deformation, N.
$\vec{g}$ Gravity acceleration vector, m/s^2.
m Mass of the particle, kg.
$\vec{n}$ Unit vector in the normal direction, dimensionless.
P Porosity, dimensionless.
R Radius of particle, m.
R^* Reduced radius $\frac{R_1 R_2}{R_1 + R_2}$, m.
S.D. Standard deviation, dimensionless.
T Total simulation time, s.
t Instantaneous simulation time, s.
$\vec{t}$ Unit vector in the tangential direction, dimensionless.
V Volume, m^3.
$\vec{v}$ Velocity vector, m/s.
$\vec{x}$ Position vector, m.
y Yield stress, N/m^2.
δ Overlap between interacting particles, m.
σ Poisson's ratio, dimensionless.
δ_{el} Elastic deformation limit, m.
Γ Surface energy, J/m^2.
ρ_p Density of the particle, kg/m^3.
Δt Time step, s.

Subscript

1, 2. Particle 1 and particle 2 respectively.
i. Particle number.

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