CRITERIA FOR MINIMUM PARTICLE DEPOSITION ONTO A CYLINDER IN CROSS-FLOW

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ABSTRACT

Flow around a single cylinder is the elementary model for the fibrous filter and is also the geometry of interest for deposition on pipes, wires, and other such objects in a dusty fluid flow. The flow pattern at low and high Reynolds numbers differ significantly and this affect deposition efficiency. Flow of gases across obstructions is a common phenomenon in heat recovery units. If the gas contains particulate matter, it is likely that they will deposit on the obstruction. The amount deposited or captured will depend, among other things, on the characteristics of the particulate matter, the deposit surface and the fluid dynamics. The net deposition can be expressed as function of the deposition and re-entrainment rates respectively.

Deposition occurs due to inertial impaction, interception, fluid forces or a combination of these. Inertial impaction is characterised by Stokes number ($= \tau_p \cdot 2U/D$ where U is the fluid approach velocity, D is the cylinder diameter, τ_p ($= Cc \cdot \rho_p \cdot d_p^{\,2} / 18 \cdot \mu$) is the particle relaxation time, d_p is particle diameter, ρ_p is the particle density, μ is the fluid dynamic viscosity and Cc is the Cunningham-Stokes correction factor) whereas interception is explained by interception parameter. The Reynolds number explains the magnitude of the fluid forces. Particle deposition due to interception occurs if the ratio of the particle diameter to that of the obstruction is significant. As reported by Friedlander[1] and others inertial impaction is significant if the Stokes number is above a certain critical value (Stk_{crt}) that varies with the geometry of the obstruction. For inviscid flow around a cylinder and negligible interception effect, Stk_{crt}=0.125.

Capture efficiency is a function of Stokes number; Reynolds number based on the obstruction's characteristic diameter and interception parameter. A lot has been written about dependence of capture efficiency on those parameters but only above the critical Stokes number. For this reason it is the objective of this work to investigate the effect of Reynolds number on deposition where interception effect is negligible and Stokes number is below the critical value.

Deposition for constant particle size while varying fluid velocity and hence the Reynolds number has been simulated for a cylinder of 36 mm diameter mounted in a channel of 100 mm width. Flow-3D code was used for the simulations. Figure 1 shows the capture efficiency, which is the fraction of the particles supplied that deposit, as a function of Stokes number for different particle sizes. The figure presents that with a single particle size one could obtain three distinct deposition regimes by just varying the Reynolds number. It is also evident from the figure that there exists a critical velocity (or Reynolds number), for each particle size, giving a minimum deposition. Above this velocity inertial effect increases thus increasing deposition and below it fluid forces increase leading into increased deposition.

Vincent and Humphries[2] investigated, experimentally, the effect of velocity on capture efficiency on a circular plate in cross-flow. In their experiment they mounted a 50 mm diameter plate in 300 mm wide channel. By maintaining the particle size they varied the fluid (air) velocity and obtained results shown in Figure 1. Their results have the same trend as what we simulated for a cylinder in cross-flow. The large difference in magnitude can be associated with lack of similarity – geometric, kinematic and dynamic. Because Vincent and Humphries particles were not monodispersed and no detailed particle size distribution given, this discrepancy might also be explained by the effect of particle size distribution.

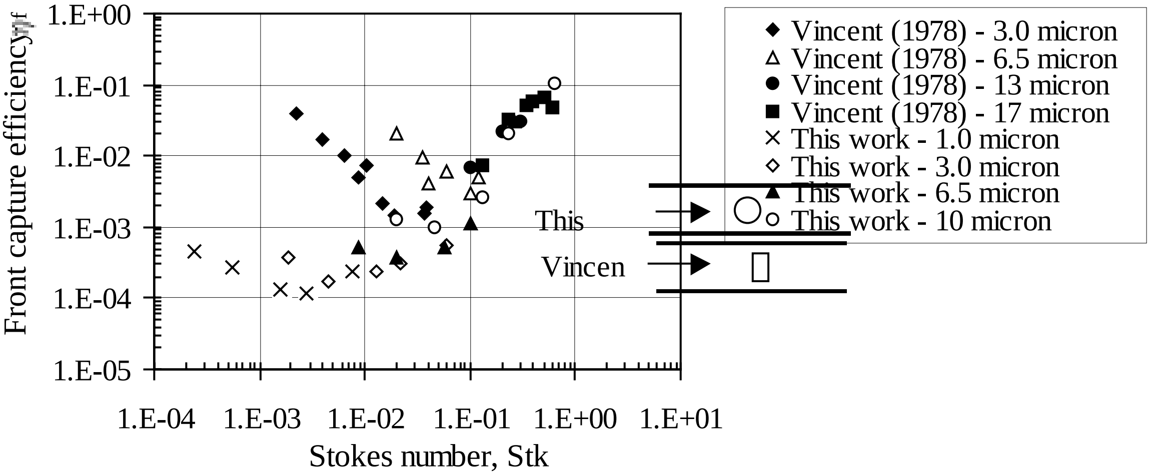

Figure 1 Capture efficiency as a function of Stokes number

Existence of a critical Reynolds number is more evident when the capture efficiency is plotted against the Reynolds number as shown in Figure 2.

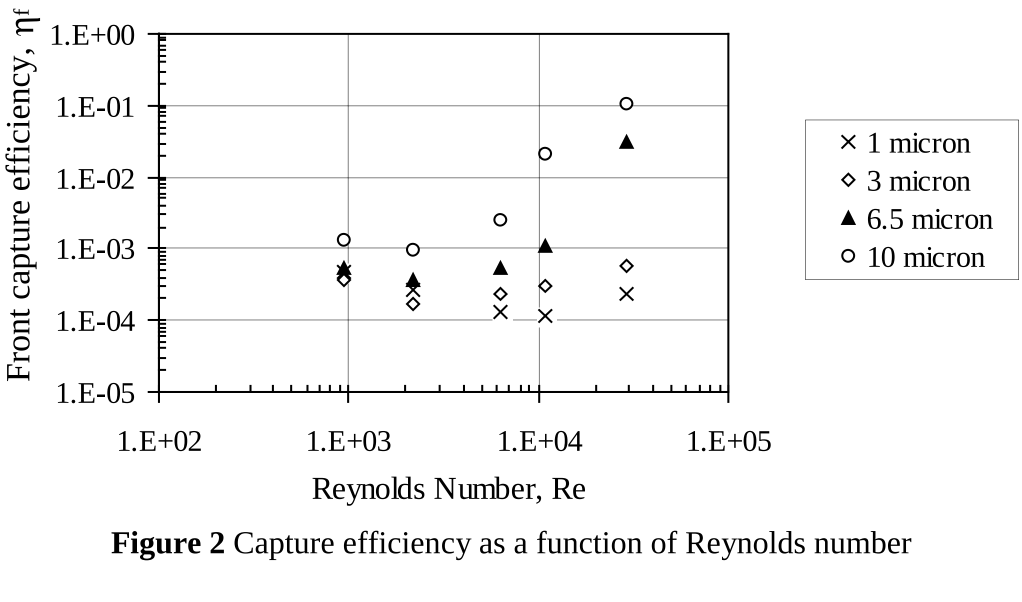

Figure 2 Capture efficiency as a function of Reynolds number

The observed trend is substantiated by force magnitude analysis. Take a 6.5 μm particles for instance. In absence of thermal effect, forces contributing to their deposition are mainly inertia, lift, electrophoresis, diffusion, and gravity. The variation of inertial effect can be looked at using the concept of stopping distance as advanced by Friedlander and Johnstone[3], which asserts that the larger the stopping distance the more inertia a particle has. The stopping distance is expressed as:

$$S_d = v_{p,o} \cdot \tau_p \quad (1)$$

where $v_{p,o}(= 0.9 \cdot u_\tau)$ is the free flight particle velocity, u_τ is the shear velocity. If the stopping distance is commensurate with the concentration boundary layer thickness, it means a particle can deposit by inertia alone. Because concentration boundary layer thickness is directly proportional to the hydrodynamic boundary layer thickness, we use the latter in the comparison.

Figure 3 shows the difference between boundary layer thickness and stopping distance for different velocities. It is clear form this figure that at high velocities the particle can deposit only by inertia while at lower velocities it can not.

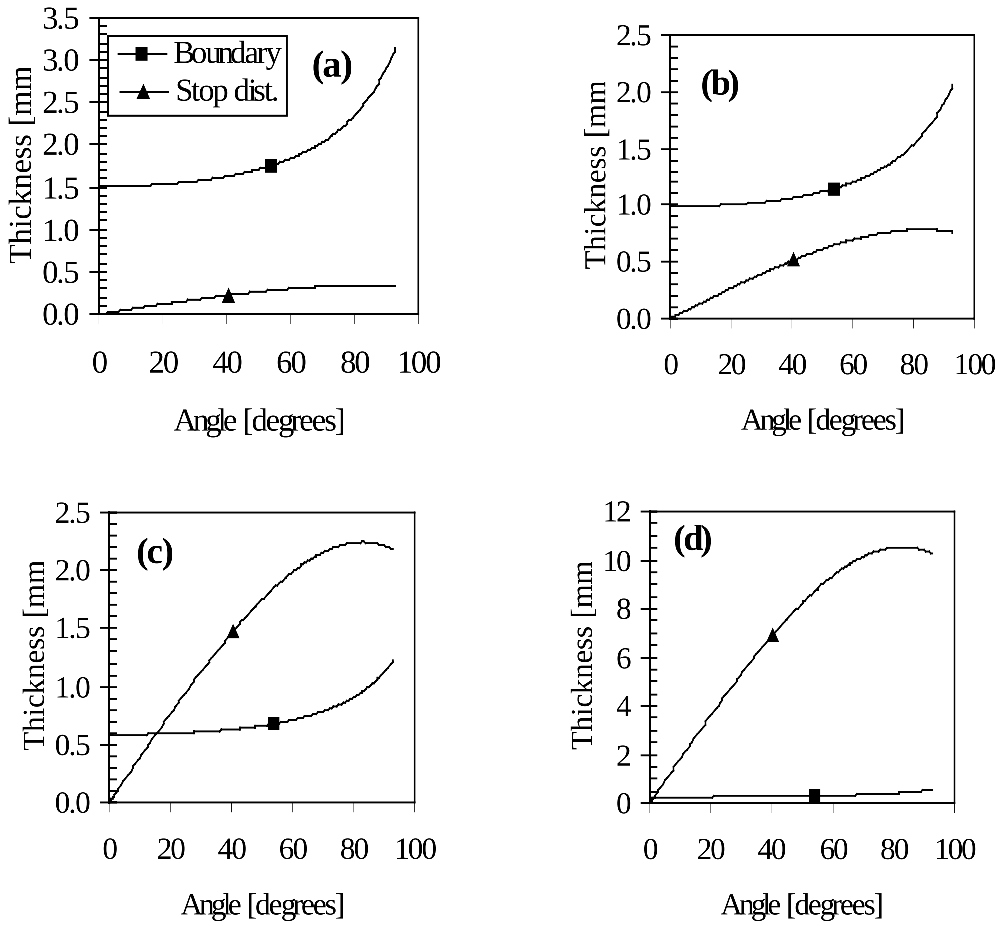

Figure 3 Variation of stopping distance for a 6.5 µm particle and hydrodynamic boundary layer thickness at different velocities in m/s (a) 0.6 (b) 1.4 (c) 4.0 (d) 18.8

For 6.5 µm particles, not only is electrophoretic effect insignificant but also it does not depend on Reynolds number. Gravitational force also does not depend on Reynolds number. This leaves lift and diffusion as the main forces due to the fluid. Near the wall both lift and diffusion forces increase with decreasing fluid velocity. However, they impart opposing effects on the particle deposition whereas diffusion improves deposition lift force, in most cases, impairs deposition. Figure 4 shows this variation close to the front stagnation point. These results show that as velocity decreases more particles will be deposited because of diffusion dominance.

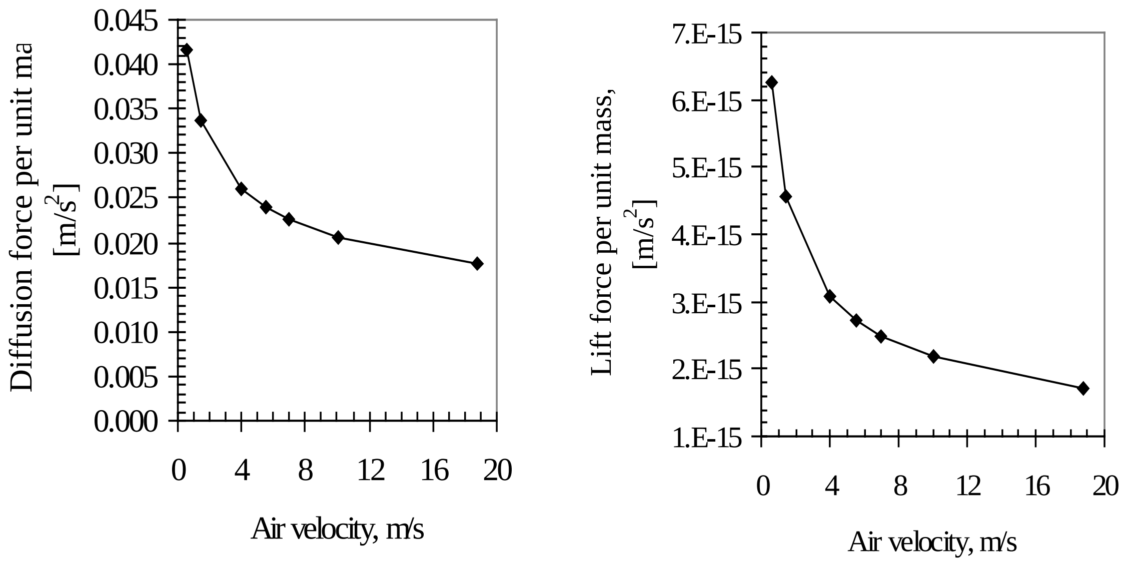

Figure 4 Variation of diffusion and lift forces for different velocities.

Low velocities means particles have to spend more time going around an obstacle. Because of long residence time the inertia effect can make the particle travel longer distance and hence deposition. Hence residence time might be another explanation for the trend shown in Figure 1.

CONCLUSION

Deposition varies with particle size and Reynolds number. For each Reynolds number there is a critical particle size giving minimum deposition. For each particle size there exists a critical Reynolds number giving a minimum particle deposition onto a cylinder in cross-flow.

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