THE EFFECT OF TURBULENCE ON PARTICLE IMPACTION ON A CYLINDER IN A CROSS FLOW

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Abstract Particle impaction on a cylinder in a cross flow is investigated with the use of Direct Numerical Simulations (DNS), with a focus on the effect of turbulence on the impaction efficiency. It is found that for particles with Stokes numbers in the boundary stopping mode there is up to ten times more front side impaction for turbulence with a large integral scale, than for a corresponding laminar flow. The back side impaction efficiency is also found to be influenced by the turbulence. The highest back side impaction efficiency is found for turbulence with small integral scales.

MOTIVATION

Particle-laden fluid flows are common both in nature and in a large number of industrial applications. Particles impacting on a solid object in the flow lead to the build-up of a deposition layer on the solid-fluid interface, or erosion of the solid object. For several industrial applications the solid objects in question may be approximated by a cylinder. Due to this, and to the simplicity of the cylindrical geometry, determination of particle impaction efficiency on a cylinder in a cross flow has become a benchmark case.
Using potential flow theory for the fluid flow is a commonly used method to find impaction efficiency for this flow problem, even though potential flow theory assumes infinite Reynolds numbers, yet do not account for turbulence. Alternative approaches focusing on experimental fluid dynamics, CFD and phenomenological modelling, can also be found in the literature. Few studies do, however, focus on the effect of turbulence on the impaction efficiencies. One exception is the study by Douglas & Ilias [1] that considers a cylinder situated within a channel affected by wall induced turbulence. The study presented here differs from the work of Douglas & Ilias as the cross flow is not restricted by channel walls. Instead, isotropic homogeneous turbulence is generated outside the computational domain, and introduced in the flow upstream of the cylinder. Reynolds numbers large enough for turbulence to be generated in the boundary layer around the cylinder has not been considered.

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If the turbulence is generated upstream of the cylinder there are several possible scenarios. Three scenarios have been considered:
Large eddy Stokes numbers. If the eddy turnover time of the integral scale eddies (τ_e) is much shorter than the particle Stokes time (τ_p), such that the eddy Stokes number $\mathrm{St_{eddy}} = \tau_\mathrm{p}/\tau_\mathrm{e}$ is much smaller than unity, the particles are too slow to be affected by the turbulent eddies. When this is the case the turbulence has no effect on the particles or the impaction efficiency.
Large scale turbulence. When the eddy turnover time is equal to or larger than the particle Stokes time the particles will follow the turbulent eddies. Consequently, the particle velocities will deviate from the mean flow velocities. This yields a modified Stokes number for turbulence scales that are comparable to the size of the cylinder. This effective Stokes number is proportional to the instantaneous mean flow velocity in the turbulent flow, thus the Stokes number becomes a stochastic variable ($\mathrm{St_{eff}} = \frac{\mathrm{St}}{\mathrm{U_0}}\mathrm{U}$, with mean flow velocity U_0 and flow velocity U). As the impaction efficiency in a laminar flow can be determined by the Stokes number [3], the impaction efficiency in a turbulent flow will clearly be effected by this change to an effective Stokes number. An expectation value for the impaction efficiency in the flow can be found from $\mathrm{St_{eff}}$. This requires the variance of the effective Stokes number (σ^2_{St}) to be found. For non-zero Stokes numbers σ^2_{St} must be found from the simulations.
Small scale turbulence. If the turbulent eddies are very small they may penetrate the boundary layer around the cylinder. If this happens the particles can impact the cylinder surface due to turbophoresis. Due to the rapid decay of small turbulent scales, this is, however, probably not practically feasible unless the Reynolds number is very large or the source of turbulence is very close to the cylinder.

SIMULATIONS AND RESULTS

The particles in the direct numerical simulations have been tracked individually in a Lagrangian manner, and the flow field has been computed by a Eulerian approach. Two different Reynolds numbers have been used in the simulations, namely 420 and 1685. The isotropic turbulence is created inside a cubic domain, a turbulent box, where statistically stationary turbulence is achieved by the use of external forcing, as described in [2]. The forcing ensures that the turbulent energy is put into the system at the spatial scale correponding to the forcing wavenumber, k_f, which in this manner determines the behaviour of the turbulence. Three different forcing wavenumbers have been used ($k_f/k_0 = 1.5, 5, 15.$, where k_0 is the wavenumber corresponding to the size of the simulation box. The turbulence is inserted into the domain with a mean flow velocity U_0, together with the particles, at a position $x = 0$. The particles are removed when they impact with the cylinder or reach the right boundary. Periodic boundary conditions are used in all but the streamwise direction (x-direction).

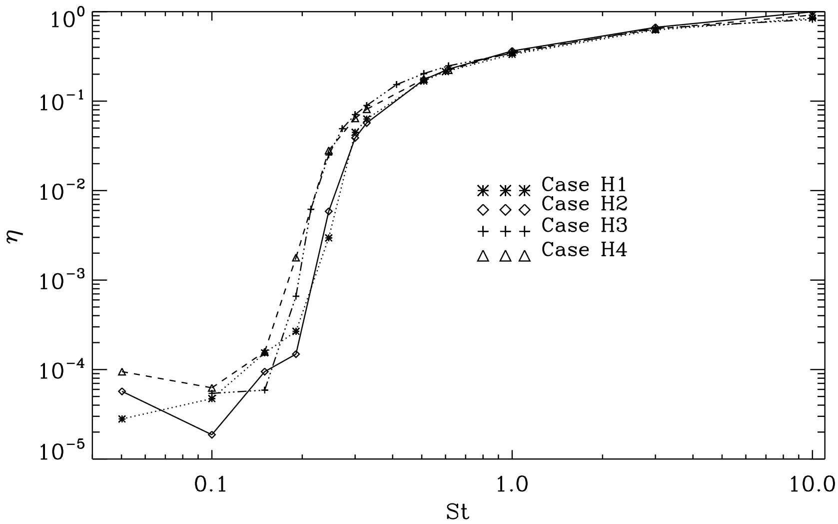

Figure 1. Front side impaction efficiencies, η, at $\mathrm{Re} = 1685$, for the laminar reference case (H1) and three simulations with forced turbulence. Forcing wavenumbers are 15 (H2), 5 (H3) and 1.5 (H4).

The impaction efficiency of particles on the cylinder front side can be seen to be greater for turbulent cases, compared to laminar reference cases in the boundary stopping mode. Figure 1 depicts the front side impaction efficiencies for the turbulent flow at different forcing wavenumbers, as well as a laminar reference case. The largest peak in relative difference is found at $\mathrm{St} \simeq 0.24$ for the three turbulence cases. As expected, the increase in the front side impaction efficiency is stronger for the larger forcing length scales. For $\mathrm{St} = 0.24$ the impaction efficiency is almost ten times higher for a turbulent flow with integral scale at $k_f = 1.5$ than for laminar flow. As the Stokes number increases towards unity, the effect of the turbulent flow decreases, and all cases approach the laminar case. Similar results are found for simulations with $\mathrm{Re} = 420$, yet the effect of turbulence is smaller than for the high Reynolds number case.
Particle impaction efficiency on the backside of the cylinder for $\mathrm{Re} = 1685$ is quite large. This is particularly true for the turbulence with the smaller integral scale, which, due to its strong vorticity, have the largest backside impaction efficiency.

References

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