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A numerical study of the impact of surface roughness on heat and fluid flow past a cylindrical particle

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A B S T R A C T

This work is devoted to a two-dimensional numerical study of the influence of surface roughness on heat and fluid flow past a cylindrical particle. The surface roughness consists of radial notches periodically distributed on the cylinder surface. The roughness was varied using different notch shapes and heights. The Navier–Stokes equation and conservation of energy were discretized using the Finite Volume Method (FVM) onto a fixed Cartesian grid, and the Immersed Boundary Method (IBM) with continuous forcing (Khadra et al. Int. J. Numer. Meth. Fluids 34, 2000) was used to simulate heat and gas flow past a cylindrical particle with a complex geometry. A polygon and the Sutherland–Hodgman clipping algorithm were used to immerse the rough cylindrical particle into a Cartesian grid. The influence of the roughness on the drag coefficient and the surface-averaged Nusselt number was studied numerically over the range of Reynolds numbers $10 \leq Re \leq 200$. Analyzing the numerical simulations showed that the impact of the roughness on the drag coefficient is negligible in comparison to the surface-averaged Nusselt number. In particular, the Nusselt number decreases rapidly as the degree of roughness increases. A universal relationship was found between the efficiency factor E_f, which is the ratio between Nusselt numbers predicted for rough and smooth surfaces, and the surface enlargement coefficient S_{ef}.

1. Introduction

Rough surfaces plays an important role in many engineering branches, e.g. from chemical engineering to aerospace engineering, due to their significant role in the heat and mass transfer between a fluid and the surface of a solid. In particular, the effect of surface roughness on the total heat transfer coefficient and the boundary layer characteristics has been studied in various experimental [1–4] and numerical works [5,6], respectively. It should be noted that these works are related to the influence of surface roughness on heat transfer. A recent review of pioneering works accounting for the surface roughness effect on hydrodynamic characteristics, e.g. pressure drop and drag coefficient, can be found in work by Taylor et al. [7].

An analysis of a large range of literature in this area shows that considerable efforts have been focused on the effect of roughness in the turbulent flow regime. Applied to a flow past a cylinder, in a series of works [1,3] Achenbach carried out experiments investigating the influence of surface roughness on the cross-flow and heat transfer around a circular cylinder for a range of Reynolds numbers. In the isothermal experiments described in [1] the roughness was represented by *emery paper* covering the cylinder. To characterize the roughness the so-called *roughness coefficient* k_s/D was utilized, where k_s is the height of the sand grain (Nikuradse roughness) and D is the cylinder diameter. In Achenbach's work the roughness coefficient was varied between 1.1×10^{-3} and 9×10^{-3}. Experiments showed that the subcritical flow regime was not influenced by the surface roughness. However, Achenbach found out that increasing the roughness parameter causes a decrease in critical Reynolds number. Here, following [1], the critical Reynolds number corresponds to the Reynolds number where the drag coefficient exhibits a minimum. In the follow-up experiment Achenbach [3] carried out an investigation into the effect of surface roughness on heat transfer between a cylinder and a gas flow. The roughness was reproduced using regular arrangements of pyramids, each with a rhomboidal base. Achenbach's experiments showed that, similar to the isothermal case, the roughness parameter did not play a significant role in the total heat transfer coefficient under subcritical flow conditions. However,

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Nomenclature

Roman symbols

A_s	area of the polygon (m^2)
A_A	area of the finite volume (−)
c_p	heat capacity (J kg^{-1} K^{-1})
C_D	drag coefficient (N kg^{-1} s^2)
c_u, c_T	constants
d	dimensionless height of the notch (−)
D	characteristic size, diameter (m)
R	radius (m)
E_f	heat transfer efficiency factor (−)
k_s	height of the sand-grain (Nikuradse roughness) (m)
K_R	roughness coefficient (−)
K	permeability coefficient
$\vec{F}_{IBM}$	IBM forces (N m^{-3})
F_D	drag force (N)
g	gravitational constant (m s^{-2})
$\vec{n}$	surface normal (−)
Nu	Nusselt number(−)
$\mathcal{P}_i$	polygon
p	pressure (N m^{-2})
Pr	Prandtl number (−)
Sr	Strouhal number (−)
S_{ef}	surface enlargement (−)
$\dot{Q}_{IBM}$	IBM source term for energy equation (W)
t	time (s)
T	temperature (K)
T_s	cylinder surface temperature (K)
T_∞	free stream temperature (K)
$\Delta T = T_s - T_\infty$	temperature difference (K)
$\vec{u}$	velocity vector (m s^{-1})

Greek symbols

ε	volume fraction of gas (−)
λ	heat conductivity (W K^{-1} m^{-1})
ν	kinematic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

av	averaged
s	surface
in	inflow

for the transcritical flow range, the increase in the roughness parameter led to an increase in the heat transfer by a factor of about 2.5 [3].

Numerical efforts to reproduce the effect of roughness on a flow past a rough cylinder were reported by Kawamura et al. [5] and Lakehal [6]. In particular, Kawamura et al. [5] carried out direct numerical simulations of the flow around a circular cylinder with a roughness parameter of about 5×10^{-3}. The Reynolds number was varied between 10^3 and 10^5. The total number of mesh points was 80×80. Following Kawamura et al. [5] reasonable qualitative agreement was achieved between numerically predicated results and results by Ashebach et al. [4]. Lakehal [6] performed two- and three-dimensional RANS simulations of turbulent flows past rough-walled circular cylinders. A rough-wall model was utilized within the $k - \varepsilon$ RANS model. The calculations provided close agreement with experimental data published. However, in the two works cited above no heat transfer was included into considerations.

An analysis of the literature indicates that the basic issue in early investigations concerned the effect of roughness on relatively high *Re* flows. In the laminar flow region, the roughness was shown to have very little effect on the drag coefficient. In spite of extensive research on the role of the laminar flow in heat transfer near the cylinder, e.g. see Lange et al. [8], Shi et al. [9], Juncu [10], so far, however, there has been little discussion about the influence of surface roughness on heat transfer on bluff body wakes for laminar flow regimes. At the same time it should be noted that, recently, with considerable development in microfluidic devices, where the flow is laminar due to the small scale of the geometry, researchers have shown an increased interest in the role of surface roughness on the heat transfer in laminar flow regimes, e.g. see the works [11–14]. Basically in these works the surface roughness is modeled directly using blocks of different shapes periodically distributed on the plane walls. From this point of view the work by Abu-Hijleh [15], who carried out numerical investigation into the influence of radial fins around the cylinder on the enhancement of heat transfer, has some similarities to studies on the effect of roughness. Abu-Hijleh [15] reported that short fins reduce the heat transfer from the cylinder surface. This effect is reversed for long fins, where the enlargement of the surface can compensate for the effect.

Parallel to the direct modeling of roughness, various models have been proposed to account for the effect of roughness on laminar flows. In particular, Koo and Kleinstreuer [16] introduced the concept of an equivalent porous medium layer to model the rough near-wall region. Using a similar approach, Bhattacharyya and Singh [17] carried out numerical investigation into the influence of a porous layer around the cylinder on the enhancement of heat transfer. In particular, Bhattacharyya and Singh [17] showed that a thin porous wrapper which has the same thermal conductivity as the cylinder can significantly reduce the heat transfer between the cylinder and flow. To model the gas flow inside the porous layer they used the Dupuit–Forchheimer relationship, which states that the velocity inside the porous medium is proportional to the bulk velocity multiplied by the porosity. The use of this or the Darcy flow assumption when modeling particle roughness is questionable due to the fact that the convection may not be negligible within the roughness region.

All the studies reviewed so far relating to the effect of roughness on heat transfer, however, suffer from the fact that they directly model the influence of surface roughness on heat transfer between the cylinder and gas flow. Motivated by this fact the present work investigates the flow and heat transfer from a rough, solid cylinder placed horizontally in a cross-flow with an uniform stream of air. The main motivation of this study is to estimate the influence of the thickness of the roughness layer on the heat transfer and on the drag coefficient for a cylindrical particle. The practical context of this study is to contribute to understanding and developing closure relations for the drag coefficient and the Nusselt number, which can be used in the so-called subgrid models when modeling particulate flows in chemical reactors or coal gasifiers.

2. Problem formulation and governing equations

2.1. What is roughness?

Before we proceed with a description of the setup under investigation and the model we use, let us specify what roughness is. Following recent work by Taylor et al. [7] the term roughness is short for '*the finer irregularities of surface texture that are inherent in the materials or production process, i.e. the cutting tool, spark, grit*