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Janus surface concept for three-dimensional turbulent flows

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ABSTRACT

Three-dimensional numerical simulations of turbulent flow over a partial super-hydrophobic cylinder, hereinafter referred to as the “Janus cylinder”, are performed using large-eddy simulation (LES) with OpenFOAM solver. The slip-wall velocity at the super-hydrophobic surface is evaluated from a third-type (Robin) boundary condition whose coefficient is adjusted based on the available experimental data. Compared to no-slip smooth cylinder, the Janus cylinder has a lower drag coefficient and a lower root-mean-square (rms) lift coefficient, whereas its dominant vortex shedding frequency is higher. The power density distribution of the oscillations, obtained from the Fourier transform of the time-history of the lift coefficient, of the Janus cylinder has a less-sharp and broader distribution compared to the one of the smooth cylinder. No significant difference is observed between the wall shear stress distributions of a Janus cylinder, where super-hydrophobic surface covers only the frontal half of the cylinder, and a totally super-hydrophobic cylinder. This helps the potential manufacturers to reduce the manufacturing costs by partially processing the surface while achieving the highest possible drag reduction.

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1. Introduction

The flow past the circular cylinder is a well-known benchmark problem in fluid dynamics and has been the subject of numerous experimental and numerical studies in the past decades (see, e.g., Williamson [1] for a review of early developments). Achenbach [2] conducted a series of experiments for a large range of Reynolds numbers and reported on the distribution of skin friction and pressure, and on the location of separation point at different flow regimes. Since then, numerous numerical studies have been conducted on the subject using large-eddy/direct numerical simulation (LES/DNS), Reynolds-Averaged Navier–Stokes (RANS), and sub-particle scale (SPS) model [3–6]. Different techniques for the drag reduction have also been tested such as the in-line and cross-flow oscillations, or the installation of attached/detached splitters (see, e.g., [7–9]).

Recently, the use of super-hydrophobic surfaces has attracted considerable attention as a new method of drag reduction. This concept was initially inspired by high water repellency of the lotus leaf [10]. In super-hydrophobic surfaces the water droplet contact angle generally exceeds 150° [11], which results in a good corrosion resistance and self-cleaning property of the surfaces. Super-hydrophobic surfaces are made either by coating the surface by water-repellant materials [12], or by inserting micro/nano-scale ridges over the surface [13–16].

Ambrosia et al. [17] and Sun et al. [18] performed molecular dynamics simulations to obtain equilibrium states of water droplets on groove/ridge textured surfaces with different ridge heights and groove widths. The Cassie–Baxter (Fig. 1a) and the Wenzel (Fig. 1b) theories explain the correlation between the surface roughness and its degree of wettability. In the Wenzel theory of hydrophobicity [19], the liquid phase completely penetrates into the roughness grooves, and creates a water-water interface, whereas in the Cassie–Baxter theory [20], the air (or another gas) is trapped underneath the liquid, inside the roughness grooves, and a water-air interface appears. The robustness of a super-hydrophobic surface is commonly defined based on the time needed to complete the transition between these two states. In a series of experimental studies on super-hydrophobic cylinders with ridges on their surfaces, it was found that the super-hydrophobicity shifts the onset of vortex shedding to higher Reynolds numbers, increases the length of the recirculation region in the wake of the cylinder and it increases the Strouhal number, but it reduces the rms of the lift force [21–23]. Mastrokalos et al. [24] reported on the stabilizing effect of increasing the non-dimensional slip length in their numerical study for low Reynolds number flow over circular cylinder. Huang et al. [25] investigated the influence of super-hydrophobicity on the viscous and pressure drag coefficients at different slip lengths and Reynolds numbers (up to $Re = 180$). They found that at small

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Fig. 1. Schematic of a super-hydrophobic surface. (a) Cassie–Baxter state of super-hydrophobicity with the air trapped into the grooves. (b) Wenzel state of super-hydrophobicity with the water penetrated into the grooves.

Reynolds numbers (Re $\leq$ 100) and small slip lengths the viscous drag is dominant, whereas at higher Reynolds numbers and slip lengths the total drag mainly depends on the pressure drag, and viscous drag has a smaller contribution.

Rastegari and Akhavan [26] used DNS and lattice Boltzmann method to investigate the effect of super-hydrophobicity on the drag reduction of a channel flow with longitudinal microgrooves and riblets. They found that super-hydrophobicity can significantly reduce the rms of streamwise vorticity fluctuations. They also studied the impact of the longitudinal microgrooves and riblets on the Reynolds shear stresses, and concluded that the longitudinal microgrooves have a dominant role in the reduction of Reynolds shear stresses. Same observations about the Reynolds shear stresses have been reported by Zhang et al. [27] at the Reynolds numbers up to 1220.

Legendre et al. [28] numerically studied the two-dimensional flow past a circular cylinder as a prototypical transitional flow, and investigated the influence of a generic slip-boundary condition on the wake dynamics. They showed that the slip condition significantly delays the onset of recirculation and vortex shedding in the wake behind the cylinder, which is in line with the above-mentioned experimental results. Kim et al. [29] presented the effect of rough hydrophobic surfaces on the flow separation, and their subsequent effects on the vortical structures in the wake of the cylinder.

The research focus of Khojasteh et al. [30] was on the impact of water droplets on hydrophobic surfaces. They performed three-dimensional numerical simulations to study the impact of water droplet on curved/flat super-hydrophobic surfaces, and they concluded that the contact area is higher for curved surfaces compared to the one of flat surfaces.

The main objective of the present paper is to further explore the idea of reducing the drag and the rms of lift force by making the surface super-hydrophobic, and to find how the drag reduction can be achieved by having, not a full, but a partial super-hydrophobic surface (Janus cylinder) in order to reduce the manufacturing cost of super-hydrophobic bodies. Due to high manufacturing cost and complexities of super-hydrophobic surface production, especially at large industrial scales, it is crucial to identify the most effective segments of the cylinder surface which plays a dominant role in drag reduction.

In the present study, the LES results of flow past a smooth no-slip three-dimensional circular cylinder are first validated against the existing experimental data. Then, based on the experimental data of Daniello et al. [21] for a super-hydrophobic cylinder, the super-hydrophobicity factor of the third-type (Robin) boundary condition is calculated for the numerical model and the slip-velocity is estimated. The rest of the paper reports on the variations of drag and rms of lift coefficient, as well as Strouhal number at different Reynolds numbers for full and partial (Janus cylinder) super-hydrophobic cylinders. The paper is organized as follows. Section 2 presents the details of geometry and physical boundary conditions, and the numerical framework of the method using the OpenFOAM codes. Section 3 describes the computational results, and Section 4 concludes the paper.

2. Mathematical formulations and numerical models

The non-dimensional form of the equations governing the conservation of mass and momentum may be written as,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$
$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i \bar{u}_j) + \frac{\partial \bar{p}}{\partial x_i} = \frac{2}{Re}\frac{\partial \bar{S}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}^r}{\partial x_j} \quad (1)$$

where $\bar{p}$, $\bar{u}_i$, $\bar{S}_{ij}$, and t denote the filtered pressure field, the filtered velocity, the strain rate tensor, and time, respectively. τ_{ij}^r is the residual subgrid-scale (SGS) stress tensor, which represents the motion of fluid at scales smaller than the filter width. The principal idea behind the LES model is to reduce the computational cost by ignoring the smallest length scales of the flow. For the SGS model, the one equation eddy-viscosity model is used, where the eddy viscosity is calculated from the SGS turbulent kinetic energy equation [31].

In order to mathematically model the super-hydrophobicity of a solid wall, a third-type mixed (Robin) boundary condition is introduced and implemented into the OpenFOAM codes. Eq. (1) is solved with respect to the following super-hydrophobic boundary condition,

$$u^*_{\text{slip}} + (1-\beta)\left(\frac{\partial u^*}{\partial y^*}\right)_{\text{wall}} = 0, \quad (2)$$

where u^*_{slip} is the fluid's relative velocity at the wall, and β is an adjustable coefficient, which will be computed by curve-fitting through the existing experimental data. The graphical illustration of this boundary condition is presented in Fig. 2. Hereinafter, this coefficient is called the super-hydrophobicity factor (SHF). The cuboid domain size and the cylinder's diameter are shown in Fig. 3. The two-dimensional mesh is extruded in the spanwise direction to produce the three-dimensional mesh. To assess the convergence of the solution, the mesh-independence study is carried out using different grid sizes, and the results are shown in Table 1.

Furthermore, a time-step-independence study is conducted at the Reynolds number of 830, and the results are shown in Table 2. The table concludes that with a non-dimensional time-step of 0.83 the Courant number stays below one and the results are independent of the time-step. The time-steps in Table 2 are made non-dimensional by the inflow velocity ($u_{\text{ref}} = 1.53$ m/s) and the cylinder diameter ($D = 0.0127$ m).

The velocity-slip condition is integrated into the open-source OpenFOAM C++ libraries. The PisoFoam solver is chosen as the basic solver [32]. The PISO (pressure implicit with splitting of operators) algorithm is an efficient method to couple the pressure and the velocity in unsteady problems. The time derivatives are discretized by the Crank-Nicolson scheme, and the gradients with the second-order Gauss-linear scheme. For the divergence terms, the bounded Gauss upwind is used. Finally, the Laplacian terms are discretized by the second-order Gauss-linear corrected method. The iterative linear algebraic solver is the preconditioned biconjugate gradient with the diagonal incomplete-Cholesky as a preconditioner. The number of iterations for the pressure equation

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