Drag Force On Janus Sphere: Effect of Particle Position

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Drag on Janus Sphere in a Channel: Effect of Particle Position

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Potential use of Janus spheres in novel engineering applications is being explored actively in recent years. Hydrodynamics around Janus spheres is different from that around homogeneous sticky or slippery spheres. Instantaneous motion of a sphere in channel flow is governed by hydrodynamic force experienced by the sphere, which in turn depends on the particle to channel size ratio, its instantaneous position, hydrophobicity of its surface, and the particle Reynolds number. We investigate numerically the drag experienced by a Janus sphere located at different off-center positions in a square channel. Two orientations of Janus sphere consisting of a sticky and a slippery hemisphere with the boundary between them parallel to the channel midplane are studied: (1) slippery hemisphere facing the channel centerline and (2) sticky hemisphere facing the channel centerline. The flow field around Janus sphere is found to be steady (for $Re \leq 50$ investigated in this work) and asymmetric. Based on the data obtained, a correlation for drag coefficient as a function of particle Reynolds number and dimensionless particle position is also proposed. [DOI: 10.1115/1.4048928]

Keywords: Janus particle, square channel, drag coefficient, CFD, off-center

1 Introduction

Janus spheres are typically the particles which have hydrophobic as well as hydrophilic properties on its surface. These are named Janus after the Roman God having two faces [1]. Recently, these amphiphilic Janus spheres having both stick and slip boundary conditions on their two hemispheres have found applications as water repellent fibers in textile industry [2], switchable screens [3], and as self-propelling particles [4]. They are also used as stabilizers in Pickering emulsions for use in food and pharmaceutical industries [5]. The above-mentioned applications involve the hydrodynamics of Janus sphere in Stokes flow while there are also instances where understanding the hydrodynamics around such particles, at high Reynolds numbers is required. For example, the problem of drag reduction over bodies using hydrophobic or hydrophilic surfaces is studied in internal [6] as well as external flows [7–9].

The forces on Janus particles of the size of nanometer in a fluid stream were investigated using molecular dynamics by Safaei et al. [10]. They varied the orientation of the Janus sphere and suggested that the forces are function of orientation of the Janus sphere. Das et al. [11] observed self-propulsion of Janus sphere experimentally. They found that the Janus particles when moving in close proximity to a solid surface exhibited an arbitrary trajectory. The "self-motile" behavior of Janus particle is also observed when the chemical composition of the solution in which the particles are immersed is altered [12]. Recently, the quantification of forces and torques on different aspect ratios of rigid Janus particles and Janus droplets in a uniform flow field is studied [13,14]. The low Reynolds number hydrodynamics for a slip-stick sphere in a uniform as well as linear shear flow is investigated by Swan and Khair [15]. They suggested that the particle migrates parallel to the velocity gradient in a linear shear flow. Trofa et al. [16] predicted the trajectories of Janus particle by varying the position, orientation, slip parameter, and confinement ratio in a cylindrical microchannel. They observed two regimes: periodic oscillation for particle positioned far from the centerline and migration towards the tube axis for those near the centerline.

The brief review suggests that there is no study in the literature that investigates the drag on the Janus particles in a low to medium Reynolds number. Therefore, in our previous work [17], we investigated the flow field and drag over Janus sphere having sticky and slippery hemispheres placed at the centerline of a square channel. The effect of particle to channel size ratio (a/H) is explored, and it is observed that drag force on Janus sphere reduces when compared to that for stick sphere. We employ free-slip and no-slip boundary conditions on the slippery and sticky surfaces of the Janus sphere, respectively.

Therefore, the effect of wall on the hydrodynamics around off-centered Janus particles is investigated in this study. The remainder of this paper is organized as follows: In Sec. 2, we present the formulation of the problem. Section 3 describes the governing equations, boundary conditions and numerical schemes to solve the system of equations. In Sec. 4, we present the pressure and velocity distribution on and around the Janus sphere, and drag experienced by it. The drag coefficient obtained for Janus sphere is compared with that for no-slip homogeneous sphere and free-slip homogeneous sphere. Based on the data obtained from computational fluid dynamics (CFD) simulations, a correlation is proposed for the drag coefficient. Finally, in Sec. 5 we state our conclusions.

2 Problem Definition

Computational fluid dynamics simulations are performed in a channel of square cross section (yz plane) of side H as shown in Fig. 1. The Janus sphere of diameter a remains fixed in the channel and the liquid flows along positive x-direction. The Janus sphere is located at a distance Y from the channel centerline on the xy plane located in the middle of the channel for all the cases. The sphere is located sufficiently away from the inlet boundary so that the flow becomes fully-developed before it reaches the sphere. The length of the channel is $L = 400a$.

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Area Of Research :

- Fluid Mechanics (Chemical Engineering)

Specific Area Of Research :

- Study of Drag Force using Computational Fluid Dynamics Simulations.

Content

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- Methodology
- Novelty of Work
- Variables
- Result and Discussions
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Objective

To study hydrodynamics around Janus sphere by observing Instantaneous motion of sphere in channel flow.

To numerically investigate the drag force experienced by Janus sphere at different off centre position in square channel.

To study the effect of wall on hydrodynamics around off centred Janus particle.

Introduction

- Focuses on computer simulations of the flow around a Janus sphere.
- Examines the drag force acting on the sphere.
- Examines the effect of particle Reynolds numbers and flow characteristics.
- Explains the grid independence of the simulations, governing equations.
- Advances knowledge of flow behaviour and drag reduction.

Methodology

- CFD simulations for steady three dimensional flow are performed.
- Drag force at different off centre positions are analysed.
- The governing equations, boundary conditions and numerical schemes are analysed to solve system of equations.
- Pressure, Velocity and Drag characteristics of Janus Sphere is analysed.

Novelty of Work

Targeted Novelty

- Previously all work was done on slip stick sphere.
- Here a new type of body called Janus sphere was introduced.
- It consists of a slippery and sticky hemisphere with boundary between them parallel to channel midplane.

Subjective Novelty

- The hydrodynamic behaviour of slip stick sphere is uniform.
- In case of Janus particle it depends upon position, orientation, slip parameter and confinement ratio.
- Thus a research on hydrodynamic behaviour of Janus sphere was required.

Parameters

- Particle Reynold’s Number
- Particle to channel size ratio
- Janus particle position
- Density
- Dynamic viscosity

Dependent Variables

- Drag Coefficient
- Lift Coefficient
- Ratio of Drag to Lift

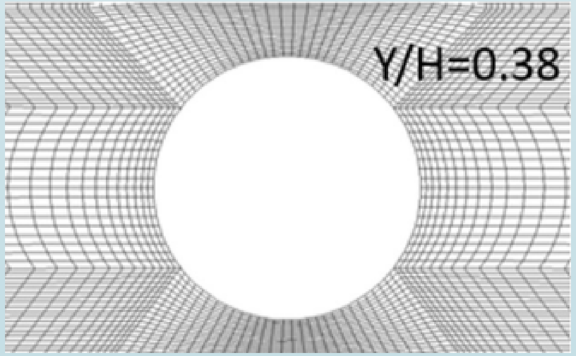
Independent Variables

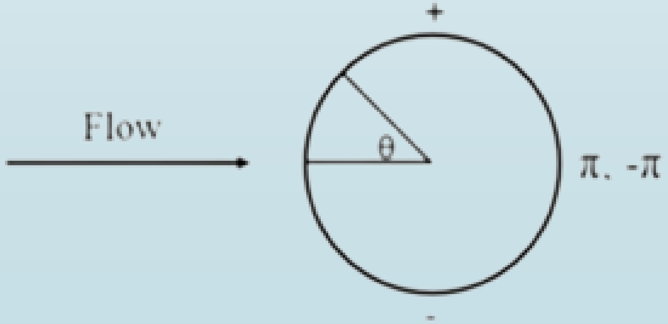
- Position of the Janus particle in channel.
- Particle Reynold’s Number

Result & Discussions

Pressure and Velocity Field

- Pressure gradient changes with changing location in the channel .
- CASE I : The free-slip hemisphere has a low-pressure area, with the least pressure at Y/H=0.38.
- CASE II : The pressure gradient differs depending upon whether a particle is placed near the centreline or away from it.





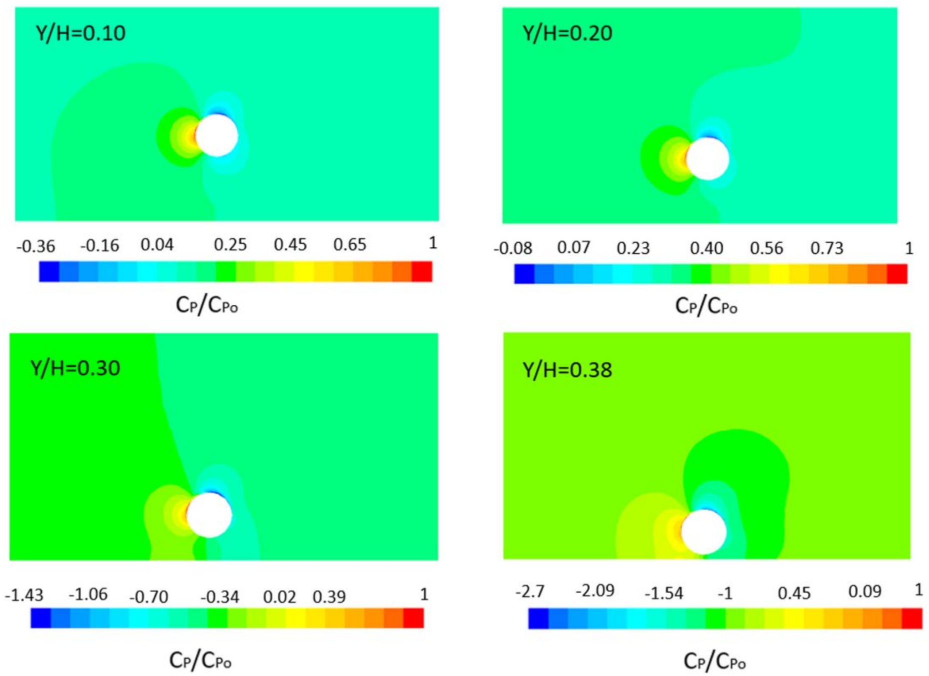


Fig. 3 Nondimensional pressure distribution $\left(\frac{C_p}{C_{p0}} = \frac{P-P_{exit}}{P_s-P_{exit}}\right)$ on the *xy* plane for $Y/H = 0.10$, 0.20, 0.30 and 0.38 at $Re_P = 10$ for case 1

Case I

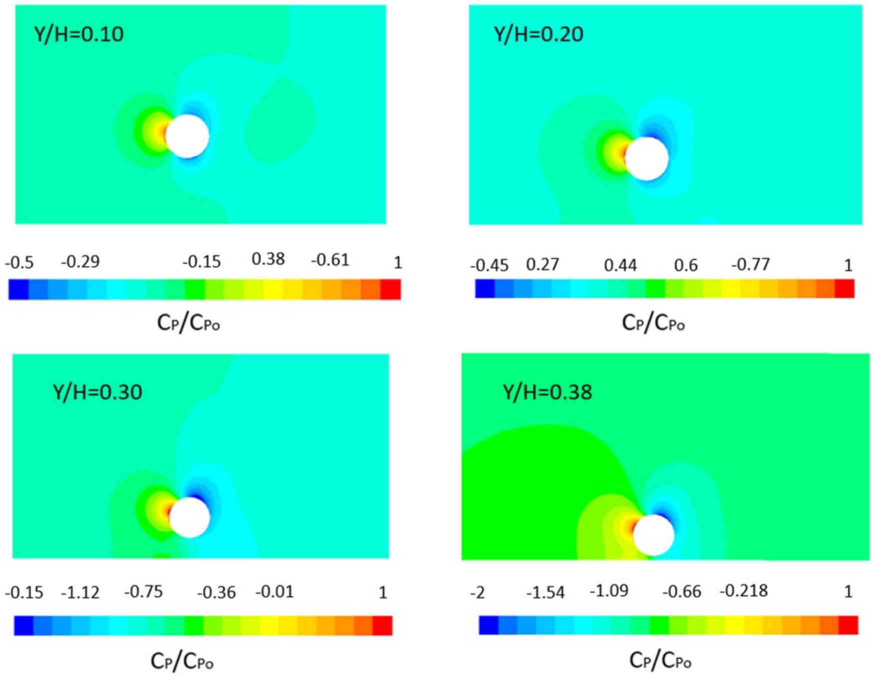
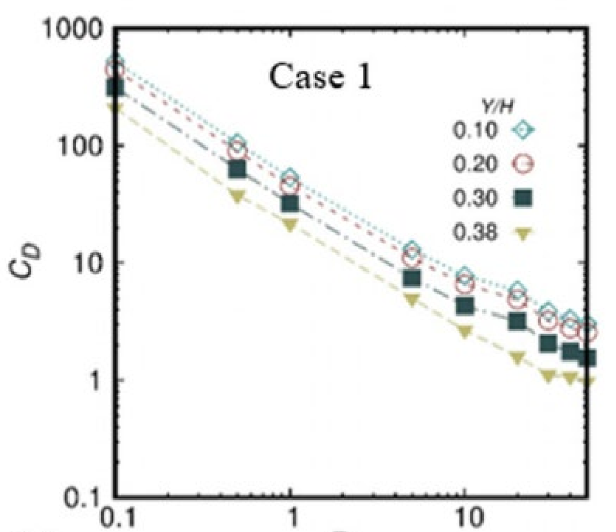


Fig. 4 Nondimensional pressure distribution $\left(\frac{C_p}{C_{p0}} = \frac{P-P_{exit}}{P_s-P_{exit}}\right)$ on the *xy* plane for $Y/H = 0.10$, 0.20, 0.30 and 0.38 at $Re_P = 10$ for case 2

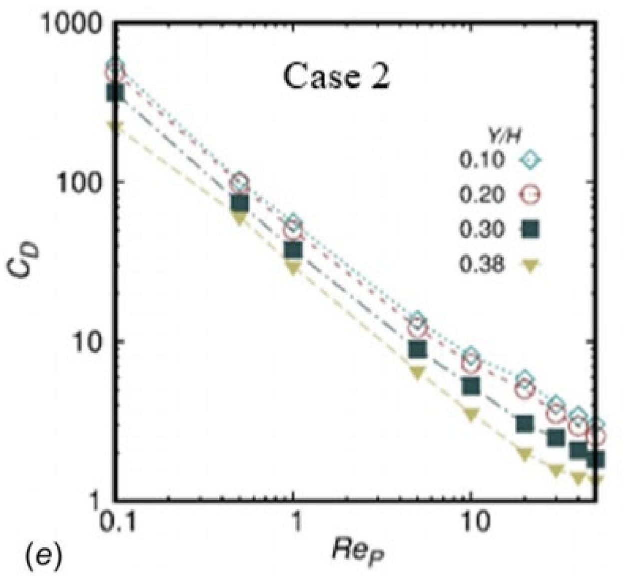
Case II

Drag Coefficient

- Drag coefficient decreases with increase in Reynolds number for both case 1 and case 2.
- The drag coefficient is higher for case 2.
- The local drag coefficient increases as the particle location is shifted closer to the wall.



(d)



(e)

Local Drag Coefficient

- Inversely proportional to the particle Reynolds number for Stokes flow.
- Based on the velocity at the streamline approaching the center of the Janus sphere.
- Variation of C D * Re P with Re P and Y/H is shown in Figure 12, indicating an increase in drag coefficient at near wall locations.

$$C_D = 13.4\,(Y/H)^{-0.73}\,Re_{\mathrm{P}}^{-0.84}$$

Case I

$$C_D = 22.69\,(Y/H)^{-0.50}\,Re_{\mathrm{P}}^{-0.85}$$

Case II

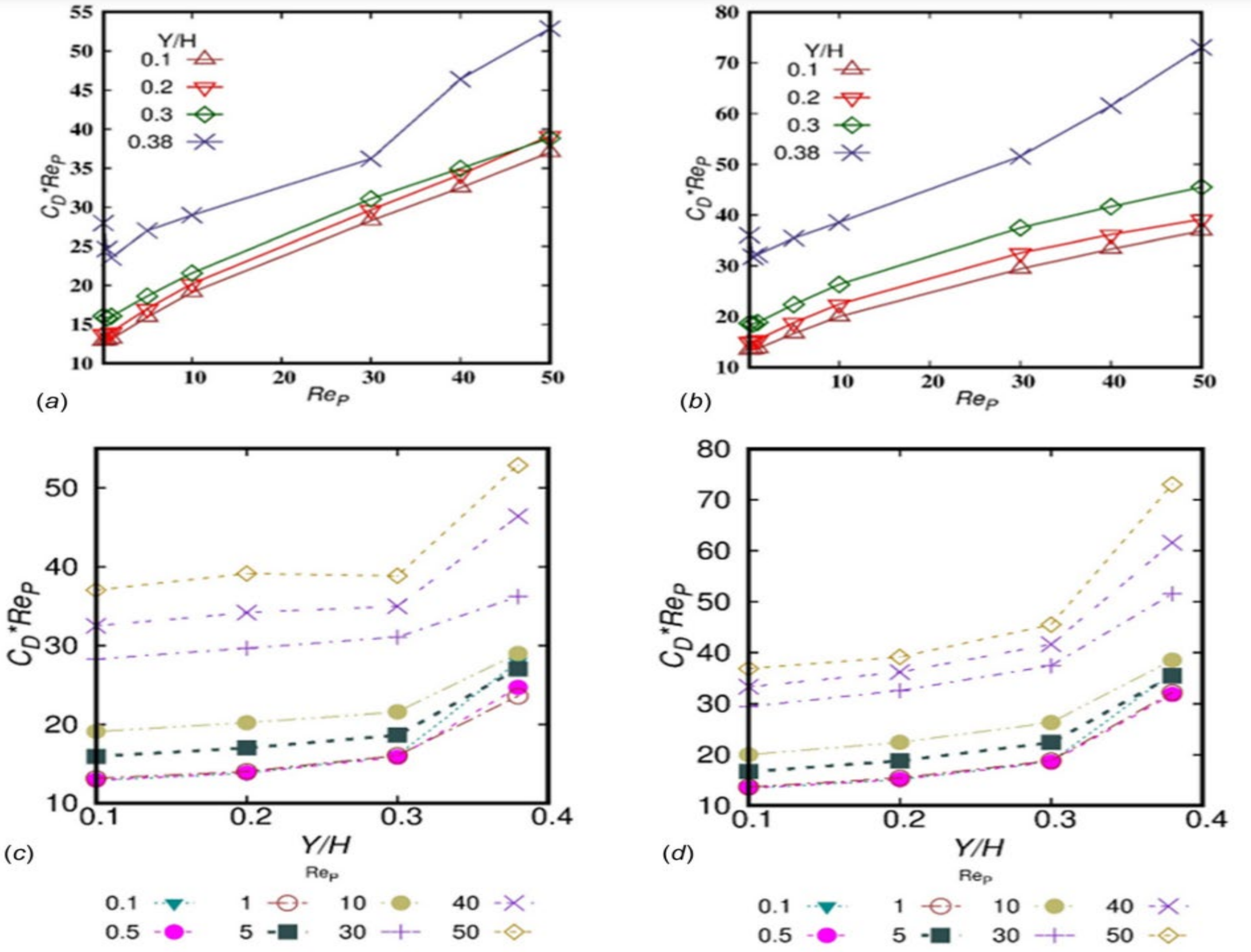


Fig. 12 Local drag coefficient variation; (*a*) and (*b*) for the orientation of Janus sphere as in case 1 and case 2, respectively, with Reynolds number and (*c*) and (*d*) with the varying Janus positions (*Y/H*)

Grid Independence

- A structured, hexahedral grid is used for the simulations.
- The grid independence is verified.
- Results are validated with experimental and numerical studies.

Conclusions :-

- Orientation has a significant effect on the flow field surrounding it.
- Drag force is lower than that of a stick sphere and higher than that of a slip sphere.
- Drag coefficient decreases with an increase in particle Reynolds number.
- Viscous and pressure contributions to the drag also decrease with an increase in particle Reynolds number.
- The local drag coefficient is almost independent of Y/H, except near the wall where it increases sharply.

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