Drag on Janus Sphere in the Channel: Effects of Particle Positions

1 Introduction

The possible uses of Janus spheres in innovative engineering scenarios have been the subject of intense research. When these spheres move across a channel, their hydrodynamics are different from that of uniform sticky or slippery spheres. The sphere's instantaneous movement depends on a few characteristics, such as its Reynolds number, hydrophobicity of surface, position inside the channel, and size in relation to the channel. Our numerical analysis focuses on the drag experienced by a Janus sphere positioned at various off-centre points within a square channel. We specifically look at two Janus sphere orientations: one with a slippery hemisphere facing the centreline of the channel and one with a sticky hemisphere facing the centreline. The resulting flow field around the Janus sphere is observed to be both stable (for Reynolds numbers within the range of this investigation) and asymmetric. Drawing from the available data, we suggest a relationship between the drag coefficient and the dimensionless particle position in the channel as well as the Reynolds number of the particle. Particles exhibiting both hydrophobic and hydrophilic qualities on their surfaces are known as Janus spheres, named after the two-faced Roman god. Recently, they have been used in several disciplines. They are employed as self-propelling particles, in the construction of switchable screens, and as water-repellent fibres in the textile industry. In addition, they function as stabilizers in Pickering emulsions used in the pharmaceutical and food sectors. In some of these applications, the operation of Janus spheres at low Reynolds numbers is examined; however, in other scenarios, a deeper understanding of their behaviour at higher Reynolds numbers is required. In both inner and outer flows, for example, researchers are attempting to determine how to reduce the likelihood that Janus spheres may drag across surfaces with hydrophilic or hydrophobic qualities. Molecular dynamics was used by Safaei et al. to study the forces acting on nanometre-sized Janus particles in a fluid stream. They looked at how the Janus sphere's orientation changed and proposed that the forces were dependent on the sphere's orientation. Das et al. observed Janus sphere self-propulsion experimentally in a different investigation. When these Janus particles moved near a solid surface, they showed random trajectories, they observed. Furthermore, when the surrounding solution's chemical composition changed, Janus particles' self-motile behaviour was seen to vary. Researchers have recently calculated the stresses and torques acting on rigid Janus particles and Janus droplets of varying aspect ratios in a uniform flow environment. Swan and Khair investigated low Reynolds number hydrodynamics by investigating the behaviour of slip-stick spheres in uniform and linear shear flows. They argued that in a linear shear flow, particles prefer to move parallel to the velocity gradient. This brief review shows the scarcity of research in the available literature that investigate the drag forces on Janus particles with Reynolds numbers ranging from low to medium.

2 Problem Definition

As shown in Figure, we used a square cross-section channel (in the YZ plane) with a side length of H in our computational fluid dynamics simulations. A Janus sphere with diameter a remains motionless within this channel, while liquid flows in the positive x-direction. This Janus sphere is positioned Y starting from the channel's centreline, precisely across the plane XY , which is always positioned within the channel's centerer placed the sphere far enough away from the edge of the inlet to ensure that prior to reaching the sphere, the flow develops entirely. The channel's total length is L, which is 400 times the diameter of the sphere (L = 400a). Reynolds Number = (a * * V) / is the particle Reynolds number. The Janus sphere under consideration possesses hemispheres that are both sticky and slick. The XZ plane divides these two hemispheres. The Janus sphere can be oriented in two different ways:

1. Case 1: The free-slip hemisphere faces the channel's centreline in this arrangement.

2. Case 2: The no-slip hemisphere faces the channel's centreline in this arrangement.

3 Computational Methodology

The research addresses the steady, laminar, incompressible, and isothermal a Newtonian fluid's flow. The following mass and momentum conservation equations can be used to describe this type of flow: At the inlet of the channel, a uniform velocity that equals the average fluid velocity and has a fixed direction that is normal to the intake boundary in the simulation. The distance between the channel intake and the sphere, on the other hand, is kept sufficiently large to ensure that the flow in the channel develops fully as it reaches the sphere. A uniform pressure of 0 Pa is defined at the output boundary. A no-slip boundary criterion applies to the channel walls. Furthermore, the sticky and slippery hemispheres have distinct border conditions: no-slip on the sticky hemisphere and free-slip on the slippery hemisphere. Integrating the pressure and viscous stresses on the sphere's surface yields the total force acting on it. In this investigation, the finite volume-based computational fluid dynamics (CFD) software program ANSYS FLUENT 19.2 was used to solve the governing equations. A second-order upwind technique was used to discretize the convective term in the momentum equation. A pressure-based coupled system was used for the pressure-velocity coupling. A collocated approach was used in ANSYS FLUENT 19.2, which means that both velocity and pressure variables are stored in cell centres. For pressure discretization, a standard approach was used, which involves interpolating values from cell centres to obtain face fluxes.

4 Grid Independence

The simulations are run on a structured hexahedral grid. As seen in Fig. 2(c), the mesh is refined near the Janus sphere and closer to the wall. The initial cell height in the vicinity of the sphere is a/80 for all Y/H scenarios that were examined. The orthogonal mesh quality for the instance, a/H 14 0.20 and Y/H 14 0.38, is 0.8. The angle between the cell canters 'connection vector and the inner face of the control volume's normal vector is known as the orthogonality factor. The Jacobian ratio is defined as a given element's divergence from the ideally formed element. The smallest Jacobian ratio is 0.802.

5 Results and Discussion

The drag force operating on the Janus sphere was calculated using computational fluid dynamics simulations of a continuous, three-dimensional flow. The Janus sphere was placed at various points along the channel, namely between 0 and 0.38 times the channel height (0 Y/H 0.38). The particle-to-channel size ratio employed was a/H = 0.20, and simulations ranged from 0.1 to 50. The flow parameters evaluated in the study are listed in Table 1. Water with a density of 998.2 kg/m3 and a dynamic viscosity of 0.001 kg/m s was employed in the simulations. It is worth noting that the flow stayed constant throughout all cases investigated in this study. Unsteady simulations with a particle Reynolds number of ReP = 50 corroborated this.

5.1 Pressure and Velocity Field

The contours of the nondimensional pressure distribution, which is expressed as Cp0 = (P - Pexit) / (Ps - Pexit), for a particle Reynolds number (ReP) of 10 on a XY plane that passes through the centre of the sphere. In this case, Pexit represents the pressure at the outlet, while Ps stands for the pressure at the sphere's front stagnation point. For all values of Y/H, there is a zone of low pressure on the free-slip hemisphere in scenario 1, when the free-slip hemisphere faces the channel centreline. When Y/H is equal to 0.38, the pressure is at its lowest point. Case 2's pressure distribution, on the other hand, is dependent on the particle's position in relation to the centreline. Two pressure minima exist, one on the no-slip and one on the free-slip hemisphere, at particle positions close to the centreline (Y/H = 0.10 and 0.20). Nonetheless, there is just one pressure minimum at particle positions close to the channel wall (Y/H = 0.30 and 0.38). Plotting velocity distributions on the same plane allows one to examine and comprehend the distribution of pressure on the Janus sphere's better. For various Y/H values, considering both case 1 and case 2 at particle Reynolds number (ReP) = 10 and 50, Figures 5 to 8 display the distribution of the x-component of velocity in the region of the Janus sphere. The flow field on both sides of the channel centreline is impacted by the sphere's surface when Y/H = 0.1. Near the centreline at Y/H = 0.2, the sphere disrupts the flow field outside the channel's midplane. But for larger Y/H ratios, the Janus sphere's presence has no effect on the velocity field over the channel's midplane. This conduct is consistent with findings from an earlier investigation involving sticky spherical particles. Only positive values of the x-component of velocity are shown for low particle Reynolds numbers (ReP = 10), indicating that flow recirculation is not observed for either of the Janus sphere's approaches. The negative x-component of velocity, as shown in Figure 8, indicates the presence of a vortex on the no-slip hemisphere for case 2 at particle Reynolds number (ReP) = 50 in all positions of the Janus particle. The larger the vortex and the bigger the magnitude of negative velocity, the particle placements nearer the centreline of the channel. Nevertheless, even at the maximum Reynolds number of ReP = 50 for scenario 1, no flow separation is seen. The reason for this is that in example 1, the fluid's velocity was lower near the no-slip hemisphere. The comparison of the x-velocity profile along a line passing through z/H = 0.0 for two distinct Janus sphere orientations. "1" denotes the scenario in which the Janus sphere's free-slip hemisphere confronts the channel centreline (case 1), and "2" represents the circumstance in which the no-slip hemisphere faces the channel centreline (case 2). The velocity profile is given for a specific position of the Janus sphere in the channel (a/H = 0.20 and Y/H = 0.30 at particle Reynolds number (ReP) = 10). It appears that the velocity in the opposite half of the channel is unaffected by the sphere's presence. It is worth noting that when the free-slip hemisphere is oriented toward the channel wall, the flow flows more freely between the channel wall and the sphere. This observation implies that the orientation of the Janus sphere, specifically the option between a free-slip or no-slip hemisphere facing the channel wall, can have a considerable impact on the flow patterns and interactions in the area of the sphere.

5.2 Drag Coefficient

The force per unit projected area is the definition of the drag coefficient (CD)., normal to the streamwise direction, and is non-dimensionalized by the dynamic pressure (1/2 * * V2) for a sphere. The fluctuation of CD with respect to the particle Reynolds number (ReP) and the position parameter Y/H is given. The magnitude of the drag coefficient for a stick sphere is constantly the largest, regardless of sphere position. In both cases 1 and 2, CD falls as particle Reynolds number (ReP) rises. CD is bigger when the Janus sphere is near the channel centreline, regardless of hemisphere orientation. However, the amplitude of CD is significantly bigger in example 2, particularly when the top hemisphere possesses a no-slip condition, especially at high Reynolds numbers. Logarithmic graphs for cases 1 and 2 are also shown. The force operating on the sphere is caused by viscous and pressure drags in both the tangential and normal directions to the sphere's surface. Figure 11 depicts the contributions of viscous and pressure drags for distinct Y/H positions of the Janus particle at varied particle Reynolds number (ReP) levels. CD viscous drops as the Janus particle (Y/H) travels from the centreline toward the wall. The lowest particle Reynolds number investigated yields the greatest values of CD viscous. For the same Y/H and particle Reynolds number (ReP) values, CD viscous is lower in example 1 than in case 2. Notably, the no-slip hemisphere is the only one to experience viscous drag. Rags are shown for various Y/H positions of the Janus particle with various particle Reynolds number (ReP) levels. There is no discernible difference between examples 1 and 2 in the pressure component of the drag coefficient, and the trends are comparable to the viscous component. Nonetheless, it can be deduced that in scenario 2, the viscous force's contribution is greater than the pressure components.

5.3 Local Drag Coefficient

The drag coefficient in the situation of Stokes flow around a no-slip sphere in uniform flow is known to be inversely related to the particle Reynolds number. In the current investigation, it was found that the drag dramatically decreased as the Reynolds number rose. In order to clearly comprehend how the wall affects the drag coefficient, the drag coefficient's dependence is displayed as CD vs particle Reynolds number (ReP) The local drag coefficient's quantification is shown, with a rise in the drag coefficient at spots close to the wall (Y/H = 0.38). The velocity at the streamline that approaches the Janus sphere centre determines the local drag coefficient (CD*). The CD* particle Reynolds number (ReP) variant including Y/H and particle Reynolds number (ReP). The mean velocity in the channel is the basis for the particle Reynolds number in this case. The way CD* particle Reynolds number (ReP) behaves is as follows: The expected inverse relationship between the drag coefficient and Reynolds number is shown in the fact that CD* ReP increases as ReP increases. In contrast to the pattern seen for the overall drag coefficient (CD), CD* ReP also increases as Y/H increases. The greater velocity gradient in the vicinity of the wall is the reason of this. The influence of Y/H is negligible close to the centreline, but it becomes more noticeable at the greatest value of Y/H. The local drag coefficient rises as the particle position is moved closer to the wall for a given particle Reynolds number. The slope increases slightly from Y/H = 0.30 to 0.38, suggesting that the wall's impact on the local drag coefficient is accelerating.

5.4 Ratio of Drag to Lift Coefficient

A nonzero lift is a component of the hydrodynamic force in the direction normal to the streamwise direction, and it is produced by the non-symmetric flow field around the Janus sphere and its off-centre location. Ref. [23] Sprovides a thorough examination of the lift coefficient. Our goal in this instance is to contrast the lift and drag coefficients' respective magnitudes. In example 1 (shown in Figure 13(a), all CD/CL values are positive, suggesting that the Janus sphere continuously experiences lift directed toward the channel centreline in this configuration. For both circumstances, the ratio is significantly higher at low Reynolds numbers and diminishes as the Reynolds number increases. This implies that with higher Reynolds numbers, the lift force becomes equivalent in magnitude to the drag force. There is no discernible trend in CD/CL for Case 2 (as shown in Figure 13(b)). The change in sign is caused by a shift in the direction of lift caused by various Janus sphere placements in the channel. Case 2's CD/CL ratio shows no discernible trend. For Case 2, the fluctuation of drag and lift coefficients with sphere position in channel. While drag constantly decreases with Y/H, the lift coefficient changes sign with Janus sphere placements and particle Reynolds number. The non-monotonic trend in the drag-to-lift ratio can thus be traced to changes in the behaviour of the lift component.

5.5 Correlation for Drag Coefficient

Correlations are provided to represent the Drag Coefficient as a function of Y/H and Reynolds number of the particle (ReP) based on the acquired drag coefficients. The correlations for Case 1 and Case 2 are provided by the following equations after a linear regression analysis:

Equation 6 states that for case 1, $CD = 13.4 * (Y/H)^{0.73} * ReP^{(-0.84)}$

In instance 2, use Equation 7 to calculate CD = 22.69 * (Y/H) ^0.50 * ReP^ (-0.85).

The formula to determine the absolute average relative error (AARE) is as follows: AARE = 1/n * Σ |Predicted - CFD| / CFD * 100%

The AARE is 19.3% in instance 1 and 18.06% in case 2.

Figure 14 displays a parity plot that contrasts the CFD results with the correlation values. These relationships hold true for all particle Reynolds numbers and Janus particle positions ($0.1 \leq Y/H \leq 0.38$).

6 Conclusion

A major effect on the flow field surrounding the Janus sphere is caused by its orientation. A vortex is created when flow separates on the hemisphere with non-slip surface facing the channel at higher Reynolds numbers. For the other orientation, however, no flow separation was seen. The drag on a Janus sphere, positioned at various positions between the wall and the centre of the channel and featuring both sticky and slippery hemispheres, was calculated using 3-dimensional Computational Fluid Dynamics (CFD) simulations in this research. The study focused on Reynolds numbers greater than or equal to 50. The Janus particle's two hemispheres meet at the channel midplane. Two scenarios were examined: the first involved the slippery hemisphere facing the channel centreline, while the second involved the sticky hemisphere facing the same location. The flow field surrounding the Janus sphere was discovered to be significantly affected by its orientation. A vortex forms in instance 2 when flow separation takes place on the no-slip hemisphere at higher Reynolds numbers. But throughout the range of Reynolds numbers examined, no flow separation was seen for case 1. Between stick and slip spheres, the drag force on the Janus sphere is in between, and it is greater in case 2 than in case 1. As the particle Reynolds number increased, the drag coefficient was found to decrease, and for both scenarios, the drag coefficient's dependence on Reynolds number followed a similar trend, represented as CD ∝ ReP^ (-0.85). Moving the sphere closer to the channel wall also resulted in a drop in the drag coefficient as well as the drag contributions from pressure and viscous forces. For both situations, the drag coefficient had a different dependence on the dimensionless distance from the channel centreline: CD ʌ (Y/H) ^ (-0.73) for case 1 and CD ʌ (Y/H) ^ (-0.50) for case 2. At low Reynolds numbers, the lift coefficient was found to be minimal; but, at higher Reynolds numbers, it became like the drag. The effect of the channel wall on the drag was illustrated by a local drag coefficient, which was based on fluid velocity close to the centre of the sphere. Except for the area close to the wall, where it greatly increased, the local drag coefficient was nearly independent of Y/H. Additionally, it was noted that when the particle Reynolds number grew, so did the local drag coefficient. A local drag coefficient around the sphere's centre, based on fluid velocity, revealed that it was nearly independent of Y/H except in the vicinity of the wall, where it increased noticeably. Additionally, when the particle Reynolds number grew, so did the local drag coefficient. The hydrodynamics of Janus spheres in various positions and orientations within a channel flow are better understood thanks to this study. Drag forces for such complicated particle geometries can be predicted in a variety of engineering applications thanks to the developed correlations for drag coefficients, which are strong and valid for a range of particle positions and Reynolds numbers.