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Effect of curvature radius and angle on aerodynamic characteristics of a sphere travelling in a branched tube system

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ABSTRACT

Compressible flow through a branched duct and the motion of a sphere through a high blockage ratio pipe are two important and engaging topics throughout the years. The results of studies on these topics are of practical relevance to many fields such as the gas pipeline technology, air transport systems in gas turbines technology, and tube transportation, etc. However, studies on the motion of a sphere in a branched duct are scarce. Studies of the motion of a sphere in a near-vacuum tube could contribute to the development of a branched Hyperloop system in the future. In this study, we investigated the effect of the tube curvature radius and angle on the aerodynamic characteristics of a sphere during its motion in a branched tube. We examined, quantified, and compared the variation of the drag, side force, and pressure waves for the cases where a sphere enters a branch considering six curvature radii (from 500 to 3000 m), three angles (10°, 15°, and 20°), three speeds (100, 200, and 300 m s⁻¹), and two initial pressures (1/1000 and 1 atm) in simulations. The results indicated that the drag and side force vary only in the intersection region (region where the straight tube and branched tube intersect); before and after the intersection region, they are similar. With an increase in the curvature radius, the rate of drag reduction ($F_D/\max(F_D)$) decreases, while the changes in the angle do not affect variation of drag and side forces. Furthermore, we compared the motion of a sphere in straight and branched directions and found out that the flow in front and behind the sphere was similar for both directions.

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Hyperloop system; branched tube; aerodynamic force; sphere; shock wave

1. Introduction

Compressible flow through a branched duct, where the flow can separate into branches or merge from branches, has been an interesting topic for decades, and it has been studied through experiments, theoretically, and through simulations. When a shock wave propagates in a uniform-cross-section tube, it slowly decays because of momentum and energy dissipation (Biamino et al., 2014; Igra et al., 1998). This decay is faster when the cross-sectional area increases or changes abruptly (Igra et al., 2001), or at a junction where the tube divides into branches (Igra et al., 1998; Igra & Igra, 2014). Biamino et al. (2014) investigated the propagation of shock waves with a Mach number of 1.47, and they concluded that the length of the branched tube strongly influenced the flow inside the tube system. For a short branch ($L/d < 5$), a strong pressure fluctuation was inevitable, and for a longer branch, a reflected shock wave by end branch well

propagate and leave a uniform pressure behind it. Apart from the length and cross-section of the pipe, the propagation of a shock wave in a pipe is also affected by the roughness of the wall (Mortazawy et al., 2020) and the shape of the flow passage (bending, angle of junction, etc.; (Abou-Haidar & Dixon, 1992; William-Louis et al., 1998).

The motion of a sphere in tubes has been a fundamental topic that has been comprehensively investigated over the years (Krishnan & Kaman, 2010; Mao et al., 2019). Their main focuses are the forces acting on spheres by the influence of the Reynolds number (which is normally a function of the fluid density, speed, and diameter of the sphere) and the blockage ratio (BR; the ratio between the sphere's cross-sectional area and the pipe/tube's cross-sectional area). Ahmed et al. (2002) found that the drag force on a sphere inside a tapered tube (with the ratio of an inlet to outlet diameter $R_1:R_2 = 10:1$) increased

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as the sphere moved toward the downstream tube (tube became narrower). The maximum drag force occurred when the sphere was entirely inside the downstream tube (i.e. a uniform tube with a diameter R_2), and the drag force at the exit was two orders of magnitude higher than at the entrance. Yin and Ong (2020) reported that at a Reynolds number of 500 (based on the sphere's diameter), the behaviour of the wake flow varied with increasing sphere's diameter (or d/D — sphere's diameter/pipe's diameter increases). Specifically, vortex shedding stabilized for $0.4D \leq d \leq 0.7D$ and chaotic wake vortices were observed for $d \geq 0.8D$ due to interaction with the pipe wall boundary layer. These studies have revealed that, unlike the aerodynamic characteristics of a sphere in an open space, the forces acting on a sphere and the flow fields inside a tube/pipe are strongly influenced by the interaction of the flow with the tube/pipe walls.

The results of these two investigations are of practical importance and intriguing. A wide range of applications can be identified, such as natural gas pipes, air transport systems in gas turbines, and tube transportation, etc. Studies of the motion of a sphere in a near-vacuum tube can help provide a foundation for the study of a branched Hyperloop system in the future. A Hyperloop system is a concept where transonic (or even supersonic) pods/capsules travel through a sealed low-pressure tube. Pods are not physically connected, and hence, an individual pod can be assigned any destination. In this circumstance, the tube with branches that allow pods to separate is necessary.

In recent years, there has been a noticeable growth in research on Hyperloop. In 2022, Niu et al. (2022) performed a comparative study of three different nose shapes of a Hyperloop pod, namely conical, ellipsoidal, and spherical. They quantified the aerodynamic drag, pressure, and temperature and considered three stages of speed: acceleration, cruise, and deceleration. The authors found that during the acceleration stage, the aerodynamic drag, pressure coefficient, and temperature ratio gradually increased due to the added mass effect, with the ellipsoid nose experiencing the highest drag. Moreover, the shape of the nose and tail had a stronger effect on friction drag than pressure drag. Additionally, the study found that the aerodynamic drag of the pod differed between the acceleration and deceleration stages despite the same speed due to the aerodynamic added mass effect. This group of researchers also conducted a contrastive study of aerodynamic heating and characteristics between a Hyperloop pod with a radial gap and that with an axial channel, where the effect of added mass during acceleration and deceleration was studied (Zhou, Ding, et al., 2021). They also investigated the effect of acceleration and deceleration (Jiqiang et al., 2020); and the effect of

the BR on aerothermal (Sui et al., 2020). In March 2022, Kim, Jang, Le, Lee, and Ryu (2022) provided a numerical analysis and theoretical prediction of the drag and pressure wave propagation inside a cracked sub-vacuum tube. When the tube was cracked, a highly underexpanded jet developed, and as the crack width increased, a larger oblique shock cell structure was created. When a pod was under the crack, the drag decreased and the negative lift dramatically increased, which could make the pod unbalanced because of the downward flow. In the same year, Le et al. (Le et al., 2022; Le et al., 2022b) investigated the effect of an upward/downward nose and an upward/downward tail of a Hyperloop pod on the drag, lift, and pitching moments. They found that upward nose and upward tail designs should be avoided since they produce negative lift; the downward tail with a length of 6.9 m generated the highest lift when the pod was placed in the middle of the tube. In June 2022, Bi et al. (2022) compared the aerodynamic characteristics of a Hyperloop system under two conditions, namely instantaneous startup and normal startup conditions (acceleration, cruise, and deceleration). Unlike previous studies, this study considered the reflected wave by the front tube end and its interaction with the incident waves. Apart from the studies mentioned above, from 2012 to the present, there have been many studies on the Hyperloop system (or evacuated tube train system) that have focused on the variation of the drag with the top design parameters, namely the train/pod speed (Han et al., 2022; Kang et al., 2017; Le et al., 2020; Oh et al., 2019), BR (Le et al., 2020; Oh et al., 2019; Sui, Niu, Yu, et al., 2021; Zhou et al., 2020), tube pressure (Kim et al., 2011; Le et al., 2020; Ma et al., 2013; Oh et al., 2019), tube temperature (Bao et al., 2020; Oh et al., 2019), pod length (Oh et al., 2019), and pod shape (Liu et al., 2019; Nick & Sato, 2020). The effects of these design parameters on pressure waves and aerothermal effects have also been comprehensively studied (Bizzozero et al., 2021; Hu et al., 2021; Jang et al., 2021; Le et al., 2022a; Lluesma-Rodríguez et al., 2021a, 2021b; Sui, Niu, Ricco, et al., 2021; Yu et al., 2021, 2022; Zhou, Qin, et al., 2021).

It is evident that researchers and companies all over the world are trying to explore and commercialise the Hyperloop system, which is a promising future city-to-city transportation mode. This study is a pilot and preliminary study that considered different curvature radii and angles of a branched tube, and it is expected to contribute to the development of the Hyperloop system. In this study, we examined and quantified the variation of the drag, side force, and pressure waves for a sphere entering a branch of a tube. We examined the variation of these parameters for six curvature radii (from 500 to 3000 m), three angles (10° , 15° , and 20°), three speeds (100, 200,

and 300 m s^{-1}), and two initial pressures (1/1000 and 1 atm) through simulations. The remaining sections of this paper are as follows. Section 2 presents the computational domain, computational mesh, boundary conditions, and numerical details of simulations. Section 3 presents the results and discussions, and Section 4 concludes the paper by presenting the main findings of this study.

2. Materials and methods

2.1. Governing equation and turbulence models

Simulations were performed with ANSYS Fluent by using the unsteady compressible solver and a three-dimensional model. The general forms of governing equations are as follows.

- Conservation of mass (the continuity equation):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

- Conservation of momentum (the Navier–Stokes equation):

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) \\ &= -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] \\ &+ \frac{\partial}{\partial x_j}(-\rho \{u'_i u'_j\}) \end{aligned} \quad (2)$$

- Energy equation:

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}(u_j(\rho E + P)) = \frac{\partial}{\partial x_j} \left[(k_{eff}) \frac{\partial T}{\partial x_j} \right] \\ &+ \frac{\partial}{\partial x_j} \left[u_i \mu_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] \end{aligned} \quad (3)$$

where ρ , u , P , and μ are the fluid density, velocity, pressure, and viscosity, respectively. Furthermore, E is the specific internal energy, and k_{eff} and μ_{eff} are the effective thermal conductivity and dynamic viscosity, respectively.

The RANS SST $k-\omega$ turbulent model was employed. This model combines the advantages of the standard $k-\epsilon$ and $k-\omega$ models, and it can hence enhance the predictability and accuracy of transonic shock wave analysis and has been used in many previous studies for high-speed objects (Hruschka & Klatt, 2019; Liu et al., 2019; Niu et al., 2020; Xia et al., 2020; Yang et al., 2021; Zhou & Zhang, 2020; Zhu et al., 2020).

Furthermore, the Roe flux difference splitting scheme was chosen for a convective flux type, the least-squared cell-based gradient method was employed, and the second-order upwind scheme was used for discretising the flow, turbulent kinetic energy, and specific dissipation rate. For the initialization, the pressure and temperature were set to be 101.325 Pa and 300 K, respectively.

2.2. Fluid properties

The Knudsen number was calculated to be less than 0.01, and hence, the fluid was assumed to be a continuum. Air was assumed to be compressible, viscous, and an ideal gas. The air density therefore obeyed the ideal gas law as follows: $\rho = p/\bar{R}T$, where $\bar{R} = 287.058 \text{ J kg}^{-1} \text{ K}^{-1}$ is the individual gas constant and p and T are the pressure and temperature of air, respectively. Since the viscosity is assumed to change only with temperature, the Sutherland model was used.

2.3. Computational geometry

To simplify the problem and focus on underlying physics while minimizing the number of parameters needed to define the geometry, a smooth sphere was considered. Figure 1 shows the computational geometry and boundary conditions used for the simulations. The diameters of the sphere and tube were 3 and 5 m, respectively, resulting in a BR of 0.36.

The computational domain was divided into three sections. Firstly, an initial region with $L_{initial} = 150 \text{ m}$ (which implies that with a speed of 300 m s^{-1} , the sphere would move into the branch after 0.5 s). Secondly, an intersection region with a length L_{ints} , which was directly varied by varying the curvature radius R . Thirdly, the lengths of the branched tube and the straight tube were set to be equal from the divarication point (frog tip in Figure 1). Simulations are conducted with an overset moving mesh. The overset domain had a diameter of 4.5 m and a length of 20 m, which enclosed a sphere placed at the centre of the domain.

We investigated the two main parameters that directly affected the generation of the branched tube. The first parameter was the radius of curvature R , which directly affected the length of the intersection region. As shown in Figure 2a, for an angle of 10° , with increasing R , L_{ints} proportionally increased. The second parameter was the angle between the straight tube and the straight part of the branched tube, θ . This angle was used for defining the length of curvature, which directly affected the movement of the sphere into the branched tube. As shown in Figure 2b, for an R of 1000 m, with an increase in the angle, the length of the intersection region did not

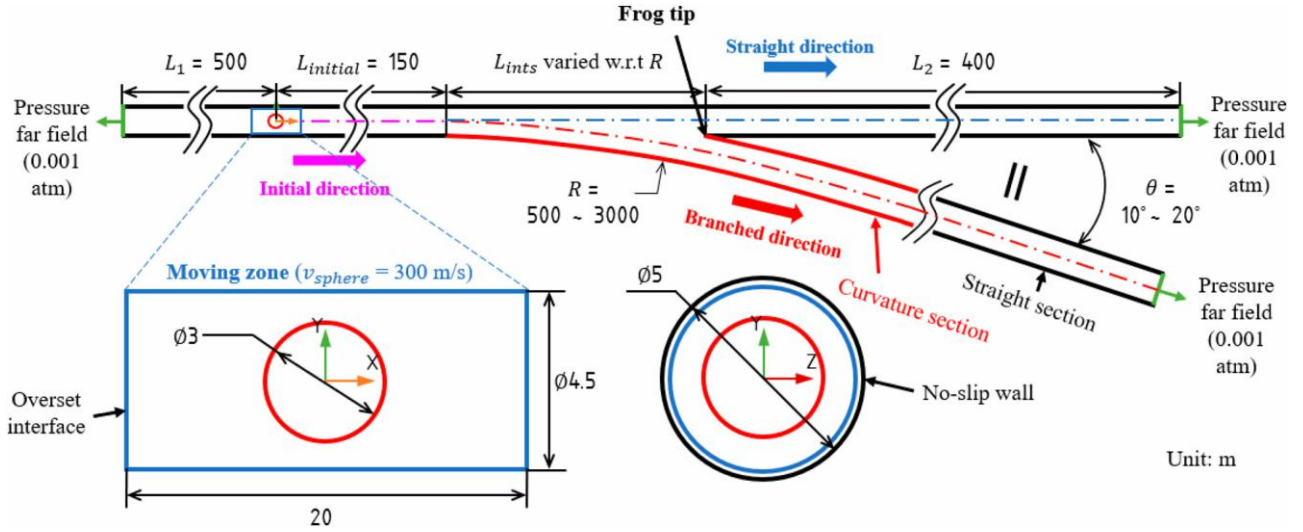


Figure 1. Geometry and boundary condition. L_{ints} is the length of the intersection section where the straight tube and branched tube intersect. L_{ints} can be directly varied by varying the radius, regardless of the angle.

change. The relationship between R and L_{ints} is as follows:

$$L_{ints} = \sqrt{(R + d_{tube})^2 - R^2} \quad (4)$$

Note that in this study, for given R , θ had to satisfy the condition

$$\theta \geq \tan^{-1}(L_{ints}/R) \quad (5)$$

From these relationships, with $\theta = 10^\circ$ and the designed parameters (L_1 and L_2), the maximum R that could be investigated in our study was 3339 m.

The length of the intersection region is expected to have more influence on the variation of the drag and side forces in the branched system. Hence, we investigated and compared six radii, namely 500, 1000, 1500, 2000, 2500, and 3000 m, for the angle of 10° (Figure 2a), and three angles, namely 10° , 20° , and 30° , for the radius of 1000 m (Figure 2b). Note that the different cases are labelled using the letters R (representing the curvature radius) and A (representing the final angle θ between the two straight sections). For example, the case with a curvature radius of 1000 and an angle of 10 is labelled R1000A10.

2.4. Boundary conditions

Figure 1 also shows the boundary conditions. The three ends of the tube were set as pressure-far-field, with a pressure of 101,325 Pa (1/1000 atm). A comparison with the pressure of 101,325 Pa (1 atm) is shown in section 3.5. All walls were set to no-slip and adiabatic conditions. The moving overset method was used to perform the movement of the sphere. The sphere was initially made to travel at a constant speed of 300 m s^{-1} for 0.5 s (corresponding to $L_{initial} = 300 \times 0.5 = 150 \text{ m}$) in order to obtain the

stationary drag and flow field around it. After 0.5 s, sphere travelled straight or in a branched direction for 0.8 s with the same speed of 300 m s^{-1} . Thus, the total simulation time was 1.3 s, and the time step was 0.001 s.

In this study, we considered extreme conditions for the motion of the sphere. Therefore, even though the speed of 300 m s^{-1} is considered too high for turning, it was used since this speed is conducive for studying pressure wave generation in a low-pressure tube (with a normal shock wave in front and behind the sphere, an oblique shock wave behind the sphere, and the presence of an expansion wave) (Bi et al., 2022; Jang et al., 2021; Le et al., 2022; Zhou, Qin, et al., 2021). Furthermore, Hyperloop tubes are made to connect like railway systems. However, the operation is considerably different. While mechanical switch systems (i.e. called railroad switches, railway junctions, turnout, etc.) are used to guide trains from one track to another, a Hyperloop switch does not need to have any moving components at the switching area; and pods are capable of going from one tube to another tube without stopping or slowing down. This can be achieved by providing each tube with a maglev guideway (track) so that the pod can pull itself leftward or rightward toward its target track at the switching area. We compared three speeds (i.e. 100, 200, and 300 m s^{-1}) and were aware that variations of forces are quite similar for all speeds. The speed of 300 m s^{-1} is used for discussing the most of results. The effect of the sphere's speed on drag and side forces is presented in section 3.4.

2.5. Computational grid

Figure 3 shows the computational mesh used in this study. Poly-hexcore of the Fluent meshing tool was used

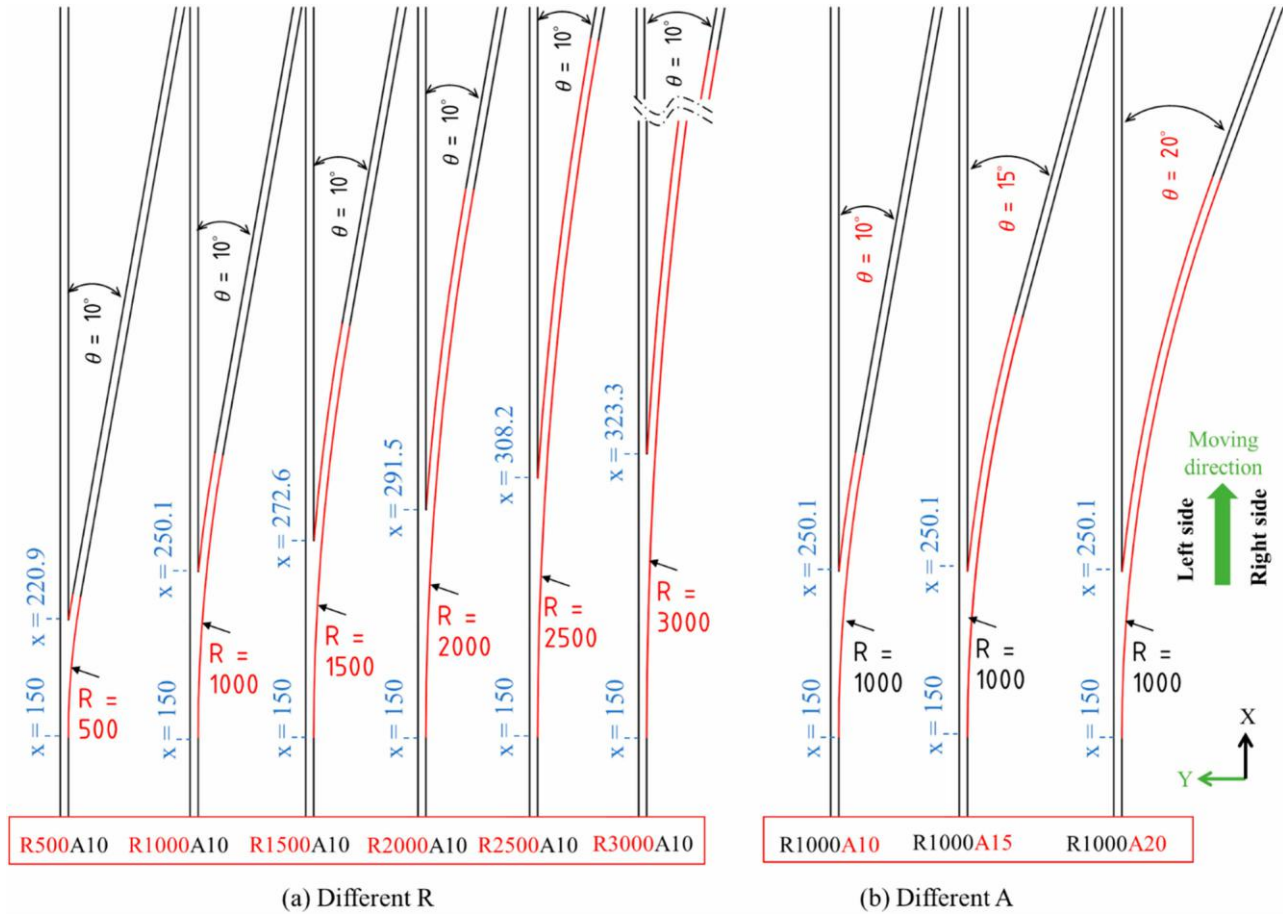


Figure 2. Geometry for (a) different curvature radii with an angle of 10° and (b) different angles for a curvature radius of 1000 (unit: m). Red colour represents the curvature walls (semicircle with radius R), and black colour indicates straight walls. The cases are labelled using the letters R (representing the curvature radius) and A (representing the final angle θ between two straight sections). For example, the case with a curvature radius of 1000 and an angle of 10° is labelled R1000A10.

for the mesh. An overset method was employed, and it required the use of separate component mesh (containing the sphere and the overset boundary) and a background mesh (tube mesh). The mesh size of the sphere mesh and tube mesh was fixed at the ratio of 1:2. In this scenario, three mesh sizes (0.17, 0.256, and 0.384 m for the tube mesh and 0.085, 0.128, and 0.192 m for the sphere mesh) were compared for the grid independence test. The mesh size of 0.256/0.128 m for the tube/sphere was chosen for the applied mesh, which resulted in the number of mesh being around 3.8 million nodes (for case R3000A10).

2.6. Verification

Validation was performed stepwise. Firstly, the mesh independence test was conducted with proving the accuracy and reliability of the mesh. Secondly, the numerical method was validated by flow through the sphere and the in-pipe projectile at various speeds, from subsonic to hypersonic; and the hypersonic flow through a wedge to prove the capacity of shock capturing.

2.6.1. Mesh independence test

The drag and side forces for the three meshes were compared. The case of R1000A10 with the sphere travelling in a straight direction was considered. The parameter details and the differences between the drag and side forces for the three meshes are presented in Table 1. The difference between the fine and medium meshes (0.1%, 0.02%, and 0.87% for the max drag, min drag, and min side force, respectively) was considerably smaller than that between the medium and coarse meshes, (0.89%, 0.26%, and 9.38% for the max drag, min drag, and min side force, respectively). Pressure contours and the pressure/Mach number distribution, shown in Figure 4, also showed that the medium mesh (which was quite similar to the fine mesh) was better than the coarse mesh. Therefore, the medium mesh was chosen.

2.6.2. Verification with flow through sphere

The experimental data for a smooth sphere (diameter: 14.28 mm) reported by Charters and Thomas (1945) were chosen for validation. The experiment covered the

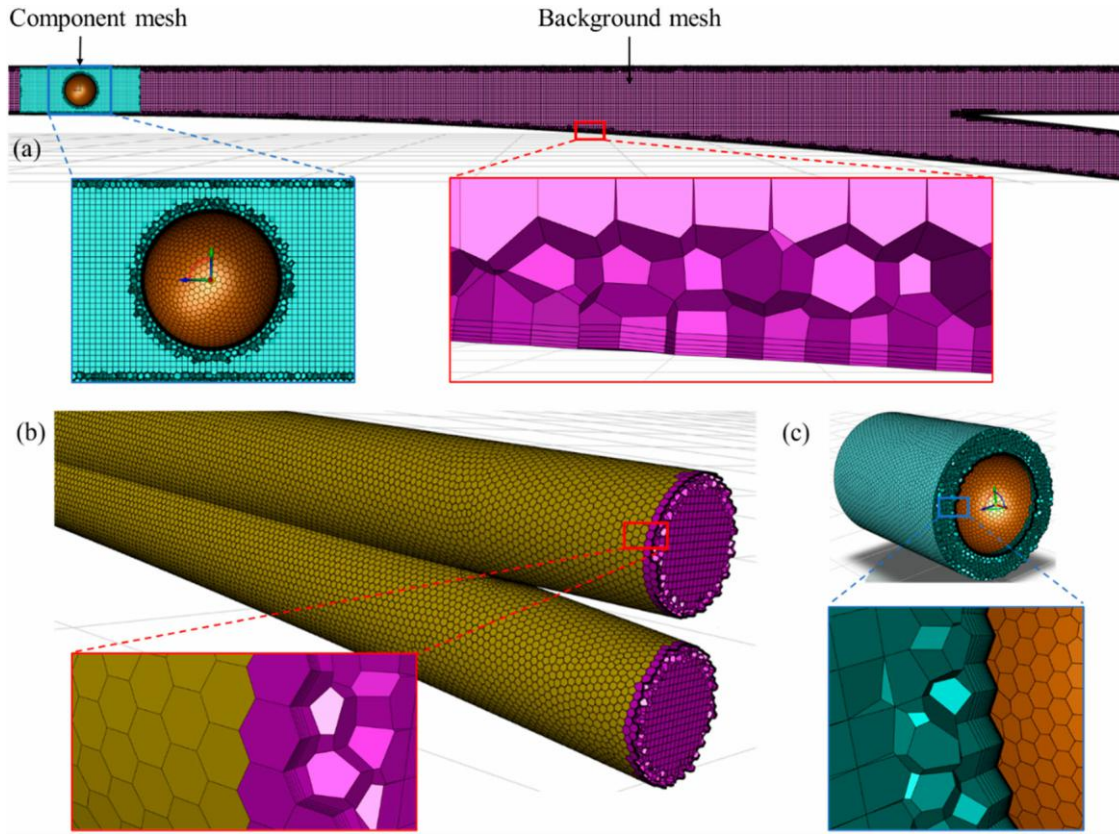


Figure 3. Computational grid for case R1000A10. The medium mesh with base mesh sizes of 0.256/0.128 for the background/component mesh is presented. (a) XY cross-sectional view at $z = 0$ m. (b) YZ cross-sectional view of the background mesh (tube mesh) at $x = 260$ m. (c) YZ cross-sectional view of the component mesh (sphere + overset mesh) at $x = 0$ m. The magnified images show the prism layers around the sphere and tube walls.

Table 1. Grid independence test for three meshes. The medium mesh was chosen as the final mesh for the simulations.

Mesh	Tube/Sphere size (m) (ratio of 2:1)	No. of cells	Average y + around tube/sphere	Max drag [N] (difference)	Min drag [N] (difference)	Min side force [N] (difference)
Coarse	0.384/0.192	1,048,817	$\sim 1.4/2.6$	856.93 (0.89%)	617.28 (0.26%)	-98.71 (9.38%)
Medium	0.256/0.128	3,700,764	$\sim 0.7/0.5$	849.24 (-0.1%)	615.70 (0.02%)	-89.45 (-0.87%)
Fine	0.17/0.085	12,402,104	$\sim 0.3/0.2$	850.08	615.56	-90.23

Mach number range of 0.29 to 3.96. The numerical details and mesh type were the same as those presented earlier. The simulation data were obtained using the moving mesh method, which considered the sphere moving within a large computational domain, as depicted in Figure 5a. The simulations were conducted for Mach numbers of 0.7, 1.0, 1.5, 2.0, and 2.5. Figure 5b shows good agreement between simulations and experimental data for both drag coefficient and drag, indicating that our numerical method was appropriate for investigating supersonic flow through the sphere.

2.6.3. Verification with in-pipe projectile

Although the validation with flow over a sphere at subsonic to supersonic Mach numbers (ranging from 0.29

to 3.96) showed the adequacy of our overset method and numerical setup to provide accurate drag results over a large range of Mach numbers (0.7 to 2.5), it has a limitation. The experiment involved a sphere placed in a free domain, not in a bounded tube. To demonstrate the capability of our method to capture the flow and drag of an object moving in compressible flow inside a tube, the experimental and simulation data from the in-pipe projectile (Hruschka & Klatt, 2019) were used. This experiment involved launching an axisymmetric projectile of $\emptyset 4.5 \times 5.6$ mm using a compressed air gun into a $\emptyset 16 \times 3000$ -mm tube. The in-pipe drag was calculated by measuring the velocity before and after the projectile went in and out of the 3000-mm tube for Mach number from 0.5 to 1.5. However, for the simulation, the

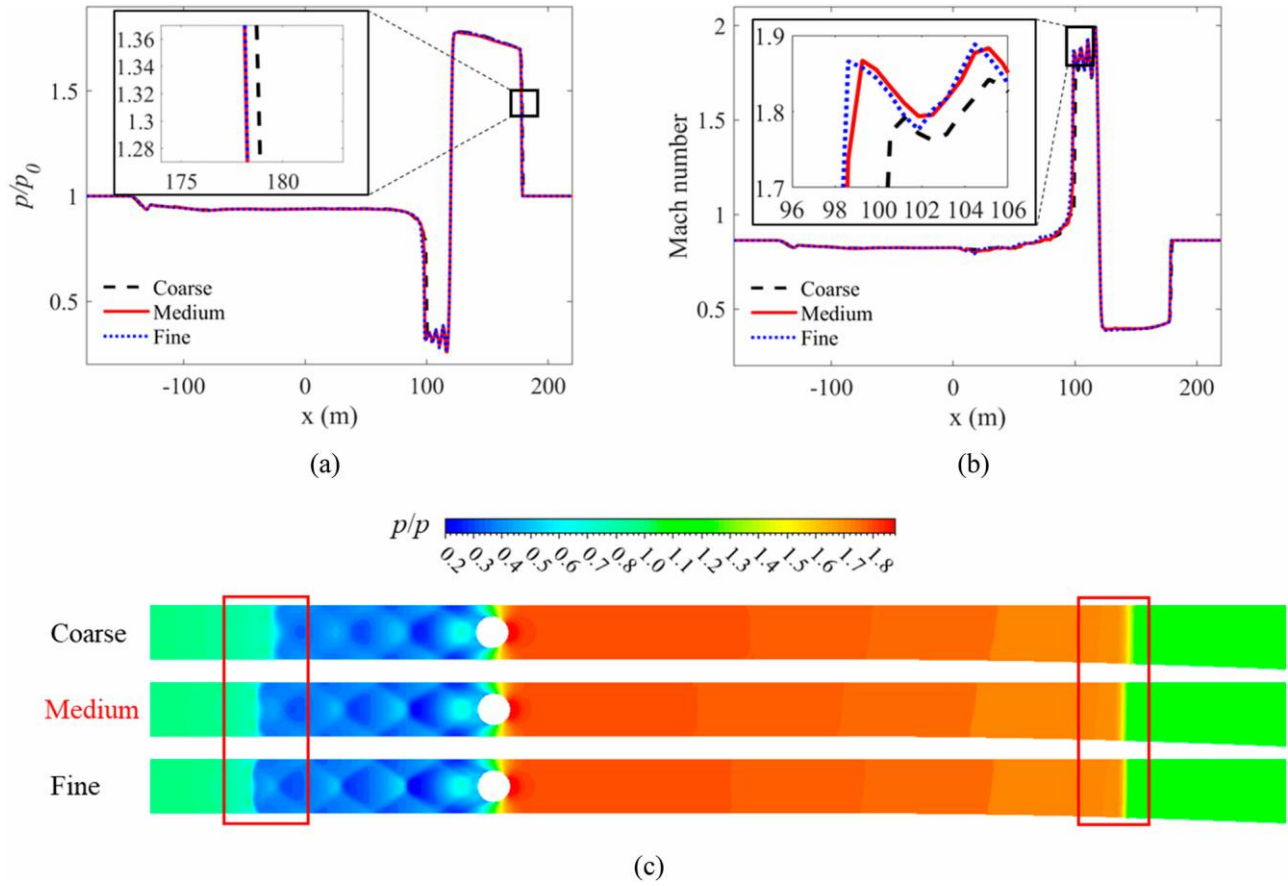


Figure 4. Mesh independence test: distribution of (a) pressure and (b) Mach number along the tube ($y = 2$ m) at $t = 0.4$ s. (c) Pressure contours around the sphere at $t = 0.4$ s.

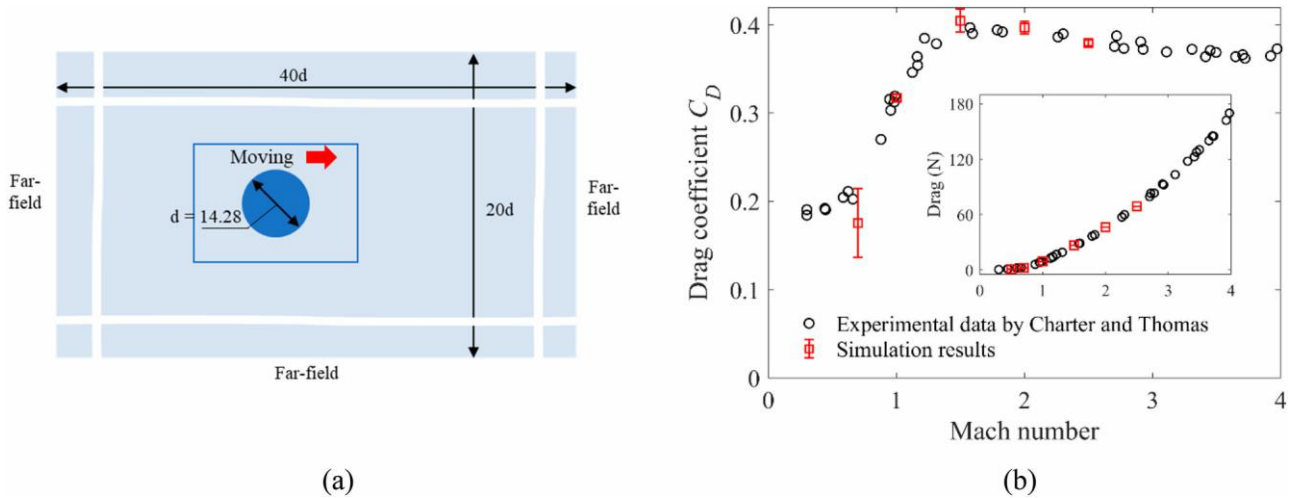


Figure 5. Sphere drag validation with the experimental data of Charters and Thomas (1945). (a) Computational domain and boundary conditions for moving overset mesh. (b) Comparison between simulation and experiments for the drag coefficient and drag. The experiments were conducted with a sphere that had a diameter of 14.28 mm and at speeds ranging from subsonic to supersonic speed.

compressed air gun was not considered, and instead, the projectile was placed 150 mm from the left end of the tube and instantly moved until the drag reached a stationary value. Figure 6a shows the dimension of the 3D projectile and the boundary conditions of the simulations.

As demonstrated in Figure 6b, our current simulation results show excellent agreement with the experimental data. Moreover, compared to the results of the 2D axisymmetric and projectile-fixed coordinate conducted by Hruschka and Klatt (2019), our 3D simulation results

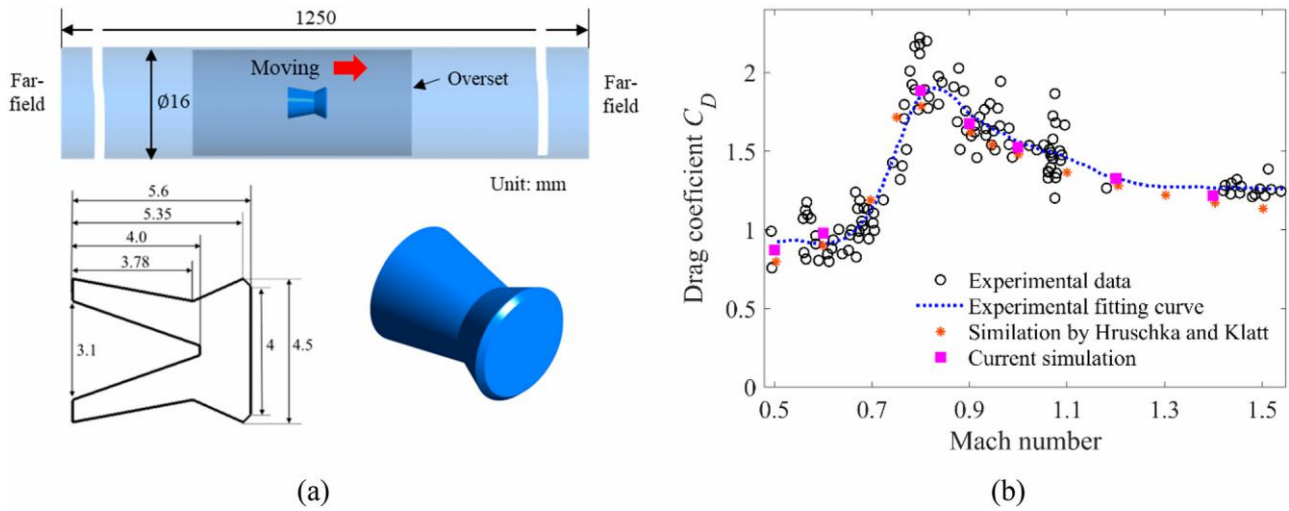


Figure 6. Validation with in-pipe projectile moving through $\text{Ø}16 \times 3000\text{-mm}$ tube by Hruschka and Klatt (2019). (a) Dimension of projectile and tube, iso-view of the projectile, and boundary condition of simulation. (b) Drag coefficient comparison between simulation and experiments.

show a better match with the experimental data and the fitting curve.

Furthermore, the verification involving hypersonic flow through a wedge (presented in our previous paper (Le et al. (2022), Section 3.1) indicated that our numerical method could capture the shock structure behind the sphere well. From the wind-tunnel-test-based verification of supersonic flow through the sphere, the in-pipe projectile, and hypersonic flow through the wedge, as well as the mesh independence test, we could infer that our numerical method provided sufficient accuracy to study the motion of a sphere in a tube.

3. Results and discussions

3.1. Comparison of sphere moving in straight direction and branched direction

The main objective of this study was to investigate the variation of the drag and side forces when the sphere passed through the intersection region. This section discusses the motion of the sphere through the tube at a constant speed of 300 m s^{-1} for the case R2000A10.

The sphere initially travelled for 0.5 s to achieve stationary drag (initial period), and it then moved into a straight or branched tube in 0.8 s. As shown in Figure 7, the drag and side force showed variations only during the intersection region, and their values before the sphere entered the intersection region were similar to their values after the sphere left the intersection region.

Figure 7a shows that for both directions of motion (straight or branched direction), the variation in the drag on the sphere was similar, and the drag reduced when the sphere passed through the intersection region. The side force showed opposite tendencies for the two directions,

as depicted in Figure 7b. In the intersection region, when the sphere moved in a branched direction, the pressure on the right side ($-y$) of the sphere was higher than that on the left side ($+y$) because of the difference in the cross-sectional area, and hence a positive side force ($+F_y$) was generated (Figure 8e–h). The opposite tendency was observed when the sphere moved in the straight direction (Figure 8a–d). Note that before (0.5 s) and after (0.97 s) the intersection region, there was no difference between the cross-sectional area on the left and right sides of the sphere, and hence, there was no side force.

It is noteworthy that the drag started to decrease before the side force did. This was because the leading shock wave (LSW) in front of the sphere reached the intersection region and generated a reflected expansion wave (REW) before the sphere entered the intersection region. The REW propagated in a direction opposite to the sphere's direction of motion, and it soon reached the sphere and reduced the pressure in front of the sphere, thereby reducing the drag (from $t = 0.4235 \text{ s}$, $x_{\text{sphere}} = 127 \text{ m}$). On the other hand, the side force resulted from the pressure difference between the left and right sides of the sphere, and the pressure difference existed only when the sphere entered the intersection region (from $t = 0.5 \text{ s}$). Note that the REW was generated because of the sudden change in the cross-sectional area between the initial tube and the intersection region, similar to what happens in the sudden expansion and contraction system studied by Kim, Le, Cho, and Ryu (2022) or during the movement of a shock wave in a branched duct (Biamino et al., 2014; Igra et al., 1998; Igra & Igra, 2014).

As the sphere continued to move, the LSW in front of it reached the end of the intersection region, and because

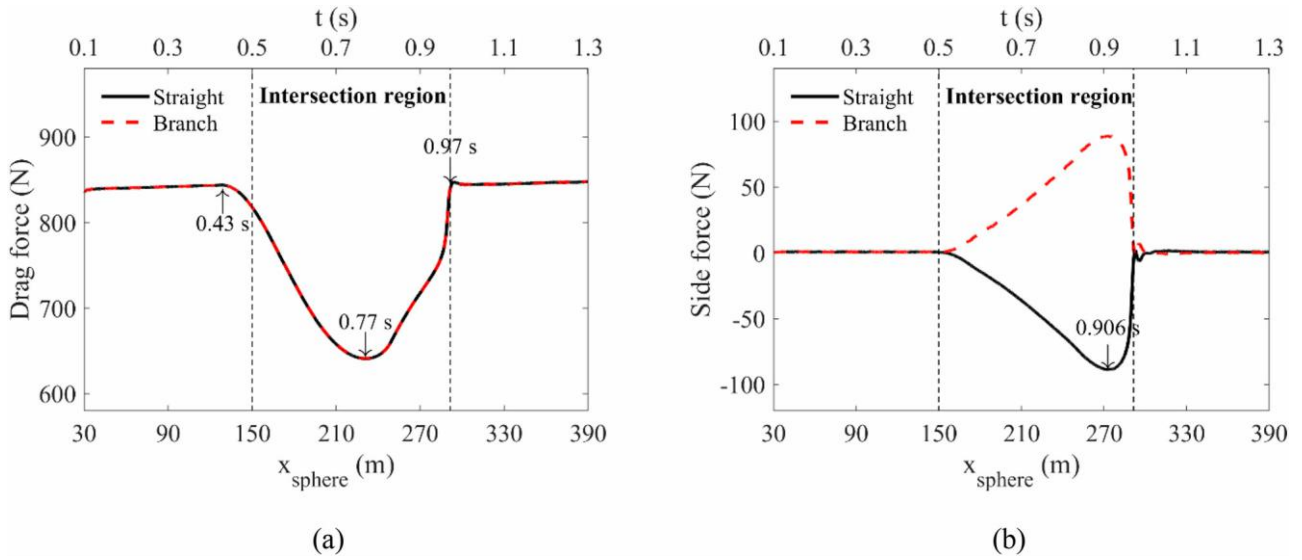


Figure 7. Comparison between spheres moving in a straight direction and in a branched direction for case R2000A10. (a) Variation of drag and (b) variation of side force. The black dashed lines show the intersection section.

of the contraction of the area, air was compressed in front of the divarication point (frog tip). This compressed air expands as the sphere moved forward. When the sphere reached the compressed air, the pressure in front of the sphere increased, which increased the drag.

After the sphere crossed the intersection region and moved straight or through the branched tube, owing to the restricted area, a new normal shockwave rapidly formed in front of the sphere. An oblique shockwave (OSW) remained behind the sphere (but with lower intensity compared with the incident OSW owing to the gradual increase in the cross-sectional area within the intersection region), and hence it quickly forms back to the same level as the original OSW (Figure 9). As the sphere continued to move, the flow field around it stabilised, and hence the drag as well as side forces had stationary values. In conclusion, irrespective of whether the sphere moved in a straight direction or a branched direction, the flow field in front of and behind the sphere was hardly affected. Note that the propagation of LSW depends on the pressure in front of it, as established by previous studies (Jang et al., 2021; Sui et al., 2021). As depicted in Figure 9c, the base condition of LSW_2 is higher than that of LSW_1 , which leads to a higher propagation speed of LSW_2 than LSW_1 . Consequently, LSW_2 will eventually catch up with LSW_1 after a sufficiently long time, and LSW_1 will no longer exist.

3.2. Effect of curvature radius

Because of the similar tendency between the motion of the sphere in a straight direction and in a branched direction, the case of the sphere in a branched direction

was chosen to investigate the effect of the curvature radius and angle on the aerodynamic characteristics of the sphere.

Figure 10 shows that for an angle of 10° , the ratio of min drag to max drag decreased as the curvature radius R increased. For an R of 500 m, the drag reduced by 31% before it started to increase back. The ratios of reduction were 27%, 25%, 24%, 23%, and 22.6% for an R of 1000, 1500, 2000, 2500, and 3000 m, respectively. However, the side force was not as strongly influenced as the drag, and it had a stable value of around 90 N. This is because as mentioned earlier, the variation of the side force resulted from the area difference between the right and left sides of the sphere. However, with an increase in R , the rate of area change was the same for all the cases. A comprehensive explanation is provided in the next paragraph.

As shown in Figure 11a, in the intersection region, the cross-sectional area gradually increased. When normalised x to L_{ints} , it shows that the rate of increase of the area was exactly equal for all R (Figure 11b). This explains why the side force variation (shown in Figure 11d) was similar for all R .

The variation of the drag was because of the pressure wave in front of and behind the sphere. For a larger R , L_{ints} was larger, delaying the generation of the compressed air around the end of the intersection as well as the interaction between LSW, REW, and the compressed air. Therefore, the minimum drag increased with R (Figure 11c).

As shown in Figure 12a, before the sphere entered the intersection region (at $t = 0.3$ s), the pressure distribution for all radii was the same (for both pressure magnitude and pressure propagation speed). However, when

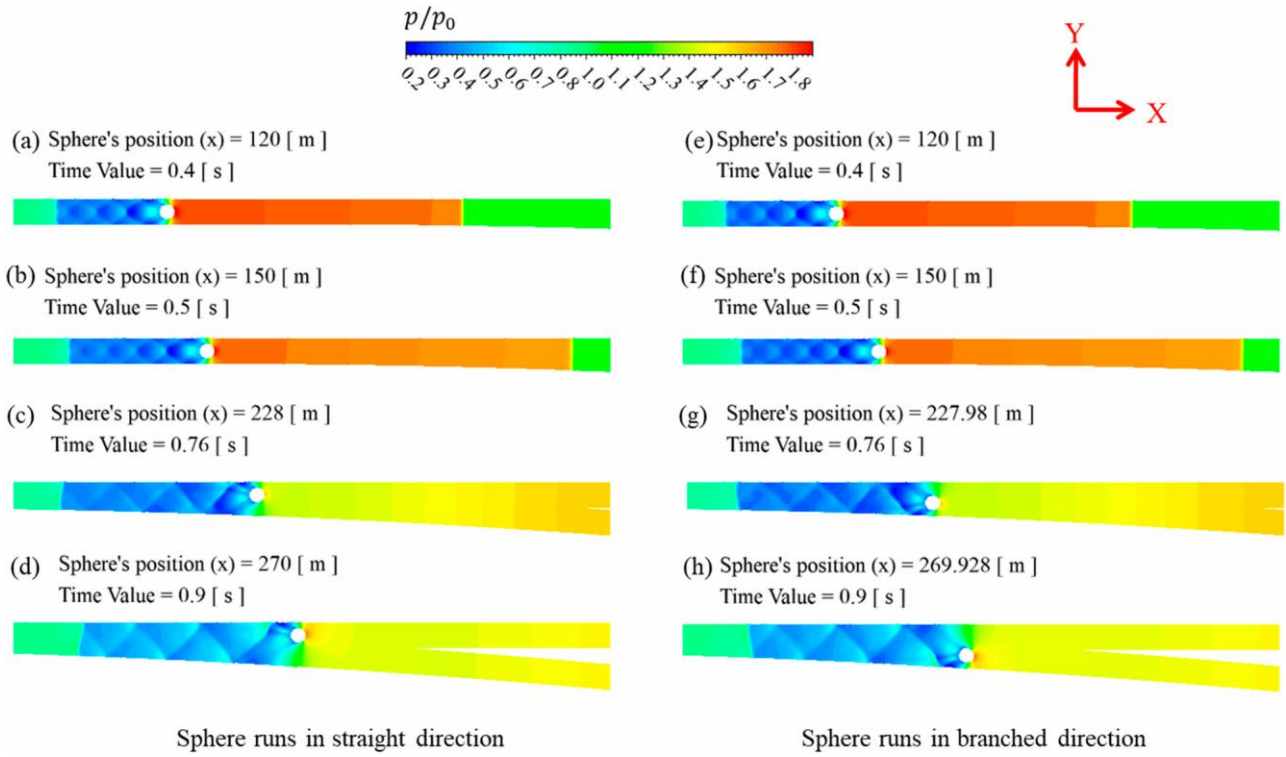


Figure 8. Pressure contour for different time simulations for case R2000A10. For the sphere moving in a straight direction, the instants shown are (a) $t = 0.4$ s, (b) $t = 0.5$ s, (c) $t = 0.76$ s (time at min drag), and (d) $t = 0.9$ s (time when the sphere was at the frog tip). For the sphere moving in a branched direction, the instants shown are (e) $t = 0.4$ s, (f) $t = 0.5$ s, (g) $t = 0.76$ s (time at min drag), and (h) $t = 0.9$ s (time when the sphere was at the frog tip). Note that before 0.5 s, the flow behaviour was the same for both cases because it was the initial period.

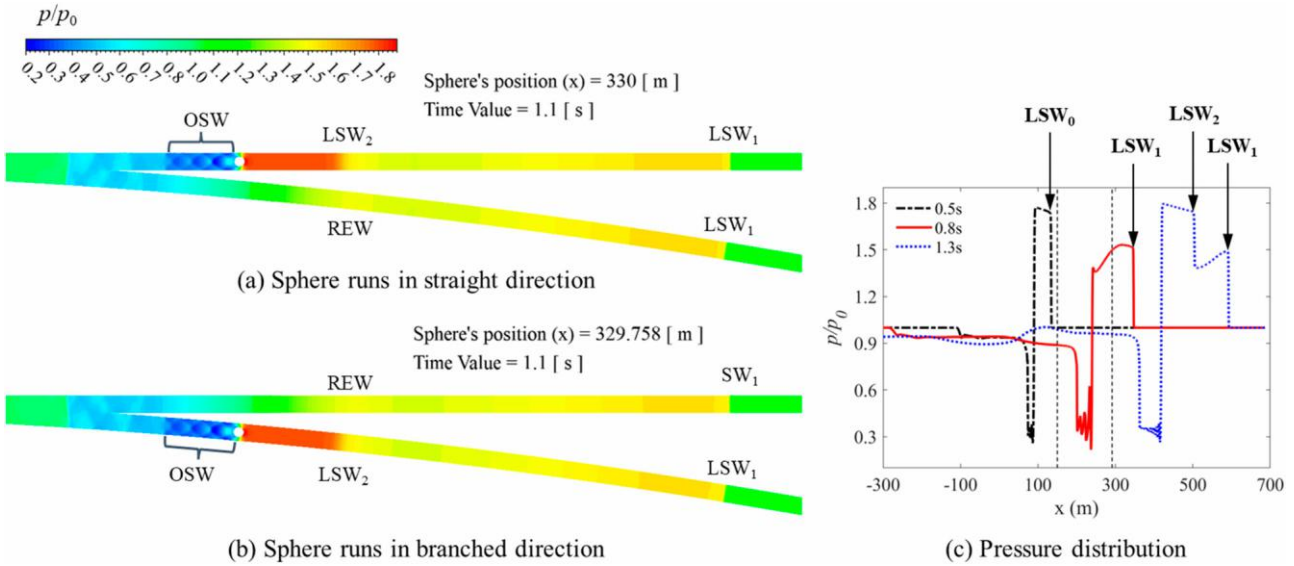


Figure 9. Pressure contours ($t = 1.1$ s) around the sphere for case R2000A10 for motion in (a) a straight direction and (b) a branched direction. (c) Pressure distribution along the tube ($z = 0$ m, $y = 2$ m) at different simulation times for case R2000A10 running in a straight direction. LSW₀ – original leading shockwave that is generated before the shockwave reaches the intersection region. LSW₁ – leading shockwave that is evenly separated from LSW₀ into 2 branches. LSW₂ – new leading shockwave which is generated in front of the sphere when it moves in a branched or straight direction.

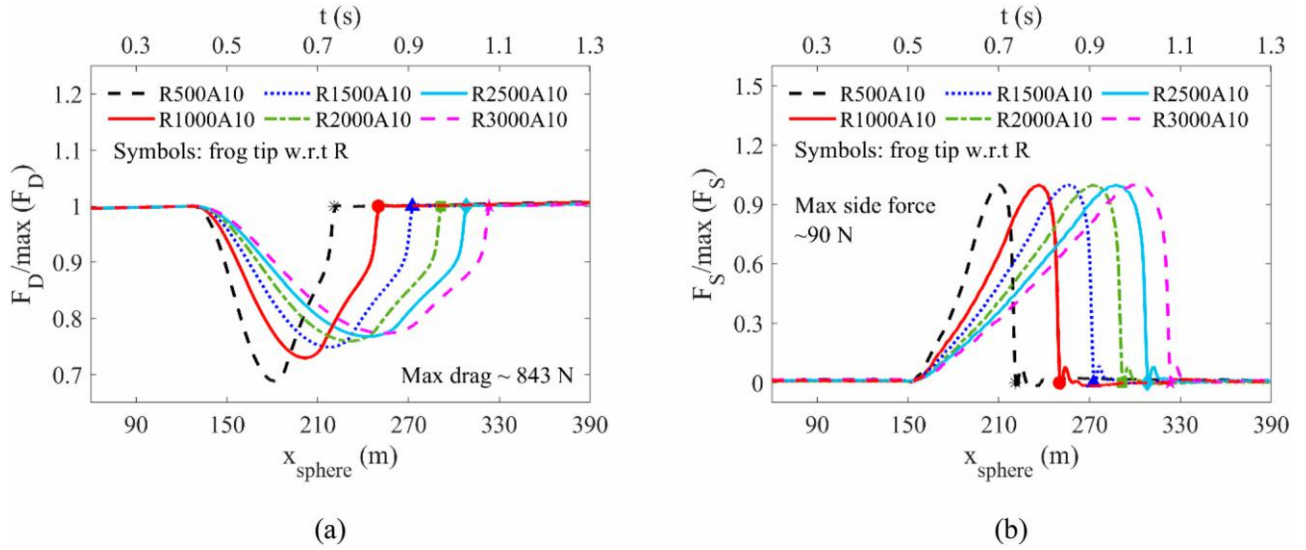


Figure 10. Effect of the curvature radius on (a) aerodynamic drag (F_D) and (b) side force (F_S) when the sphere moved in a branched direction. The curvature angle was fixed at 10° .

the sphere entered the intersection region (at $t = 0.5$ s), the pressure in front of the sphere and the magnitude of LSW decreased due to the expansion of the cross-sectional area. It is worth noting that due to the difference in the increase rate of cross-sectional area for different radii (as illustrated in Figure 11a), the pressure in front of the sphere and the magnitude of LSW decreased at varying rates (shorter radii exhibited a stronger decrease). Nevertheless, the pressure propagation speed of LSW remains the same for all cases.

If the cross-sectional area continues to increase, the pressure decreases accordingly. However, as mentioned earlier in section 3.1, when LSW reached the end of the intersection and due to the contraction of area, the air was compressed in front of the frog tip. Figure 12b ($t = 0.6$ s) shows that the pressure magnitude of LSW began to stagnate while the pressure in front of the sphere continued to drop. It should be noted that the pressure propagation speed of LSW remained quite similar for all cases, with the higher radius having a slightly higher propagation speed than the smaller radius. This can also be seen from the pressure contour shown in Figure 12c. It should be emphasized again that the pressure drop in front of the sphere was smaller for a higher R due to the more gradual increase in the cross-sectional area. Consequently, the rate of drag reduction when the sphere passed through the intersection increased when R was larger (or a longer length of the intersection region), as shown in Figure 11c.

Furthermore, the speed of the sphere remained constant and the propagation speed of LSW only slightly varied, while the length of the intersection increased for larger R . Consequently, the generation time of compressed air was delayed when LSW reached the end of

the intersection region, and in addition to the value of minimum drag, the position of the minimum drag also slightly increased for larger R .

Figure 13 shows the position of the minimum drag and maximum side force with respect to R . If the speed of the sphere were to be 300 m s^{-1} throughout its journey, the min drag would be observed around the middle of the intersection region; it would move farther with increasing R . On the other hand, the maximum value of side force occurred before the divarication point (frog tip) with a ratio of 85% of the length of the intersection region.

As illustrated in Figure 14b, the pressure in front of the sphere had already begun to rise for all R at the middle of the intersection region. This could be due to the shape of the tube, as depicted in Figure 14a, which indicates that the two branched tubes separate at this point (as depicted with the red box in Figure 14a). Hence, despite the continued increase in the tube's cross-sectional area, the sphere began to enter its own tube, which has its own cross-sectional area (a circular tube with a diameter of 5 m). However, when the pressure in front of the sphere increased, the pressure behind the sphere also increased slightly but at a slower rate. Herein, the drag exhibited the same trend as before the middle of the intersection region, i.e. it decreased, until the sphere encountered the compressed air generated when LSW reached the end of the intersection region (as previously mentioned). In conclusion, the drag only increased after the sphere passed through half of the intersection region, and the position of the minimum drag was delayed as the length of the intersection region increased (as explained in the previous paragraph).

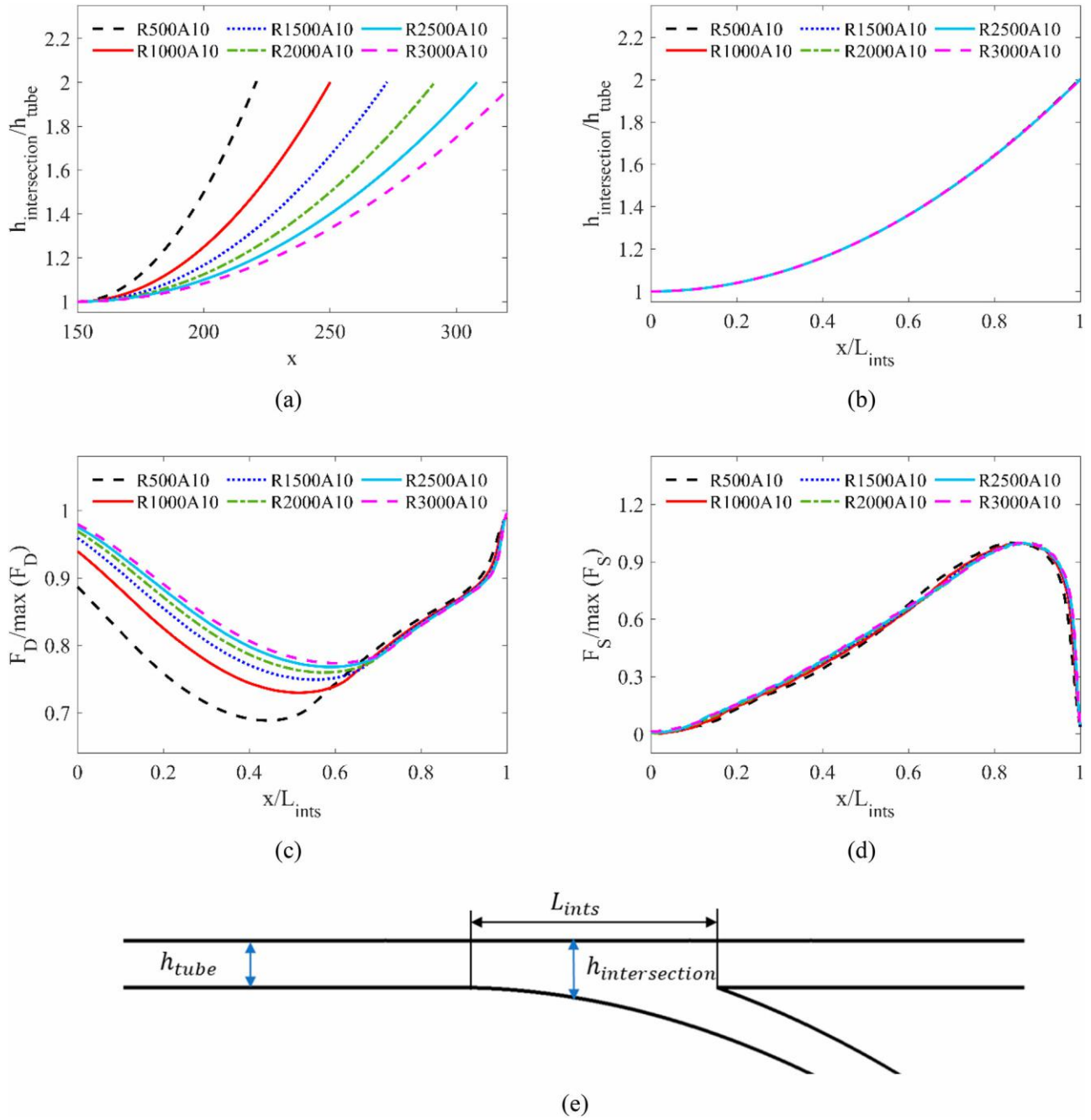


Figure 11. Effect of curvature radius. (a) Ratio of the height of intersection and the height of original tube plotted against x . (b) Ratio of the height of intersection and the height of original tube plotted against x/L_{ints} . (c) Variation of drag (F_D) within the intersection region and original tube plotted against x/L_{ints} . (d) Variation of the side force (F_S) within the intersection region and the original tube plotted against x/L_{ints} . (e) Scheme of calculated parameters; the model was scaled 0.5 by x and 2.5 by y .

3.3. Effect of angle θ

Figure 15 indicates that the variation of the drag and side force were hardly affected when θ was increased, and this was because L_{ints} did not change. Interestingly, the drag and side force started to stabilise before the sphere finished the curvature (red curves in Figure 1 or the inclined part in Figure 16) and entered the straight part of the branched tube (black lines in Figure 1 or horizontal part

in Figure 16), as shown in Figure 16. This was because of the quick formation of an OSW behind the sphere and an LSW in front of the sphere, as discussed in Section 3.1. Therefore, after passing the intersection region, the flow around the sphere quickly stabilised, and hence, stationary drag and side force were observed without finishing the curvature. This implied that a change in the angle did not affect the variation of the drag and side force because of the fixed L_{ints} . As expected, this again confirmed that

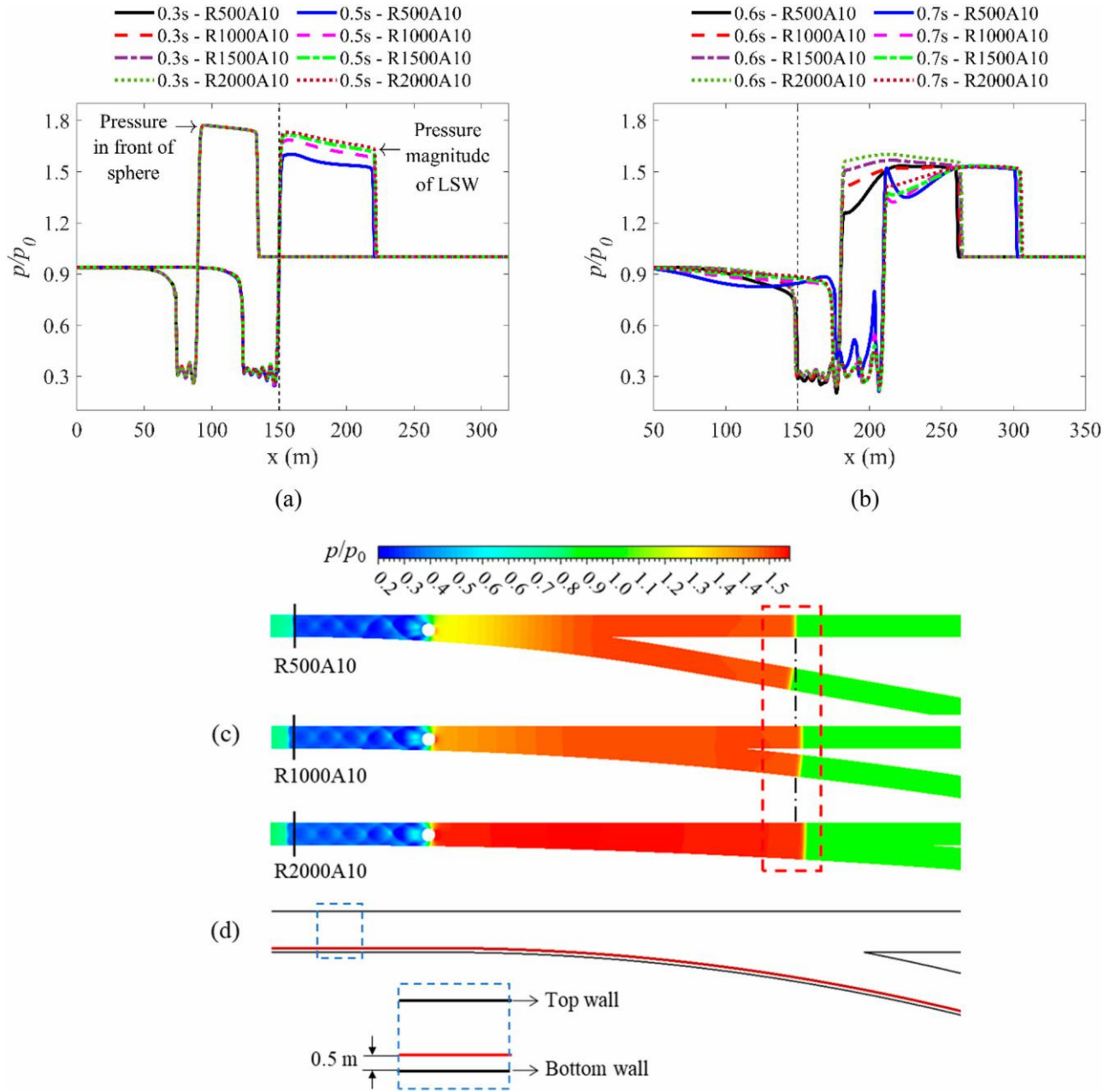


Figure 12. Pressure distribution along the tube at different simulation times for different radii. (a) 0.3 and 0.5 s, and (b) 0.6 and 0.7 s. (c) Pressure contour at $t = 0.6$ s for R500A10, R1000A10, and R2000A10. (d) The line where data is extracted (red line – 0.5 m above the bottom wall, $z = 0$ m). Vertical dashed lines in a and b refer to the start point of the intersection region. LSW – leading shockwave.

the length of the intersection region (which depends on R) is the most important factor in the branched tube system.

3.4. Effect of the sphere's speed

As mentioned, most of the simulations in this study were conducted for a speed of 300 m s^{-1} . This section compares variations of the drag and side forces for three different speeds of the sphere (100 , 200 , and 300 m s^{-1}). The case R1000A10 was considered, and hence, the length of

the intersection region was the same for all speeds. For smaller speeds, the sphere takes a longer time to travel a given distance (e.g. to travel 390 m , it takes 1.3 s with a v_{sphere} of 300 m s^{-1} , 1.95 s with a v_{sphere} of 200 m s^{-1} , and 3.9 s with a v_{sphere} of 100 m s^{-1}). Therefore, to ensure that pressure waves were not reflected from tube ends, L_1 and L_2 were increased for smaller speeds. The length of the initial period was kept the same for all speeds, and it is 150 m .

As shown in Figure 17, irrespective of the speed, the side force varied only within the intersection region. As

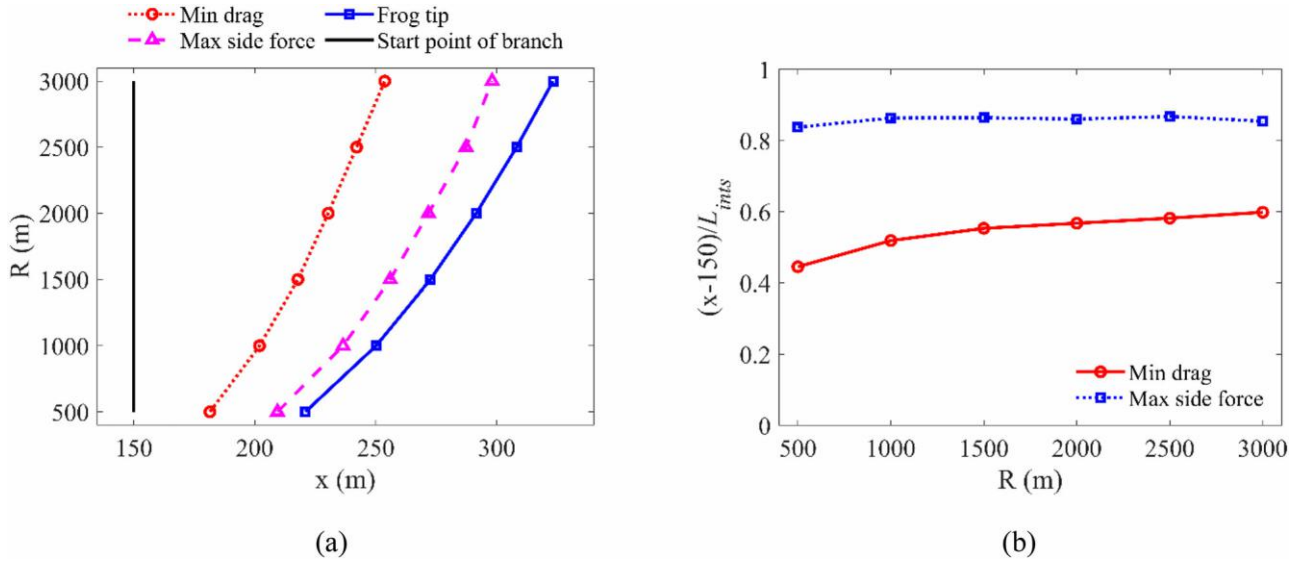


Figure 13. Effect of curvature radius. (a) Comparison of the positions of minimum drag and maximum side force with the start and end points of the intersection section (frog tip). (b) The ratio of the length of the minimum drag's position to the length of the intersection section and the ratio of the max side force's position to the length of the intersection section (L_{ints}).

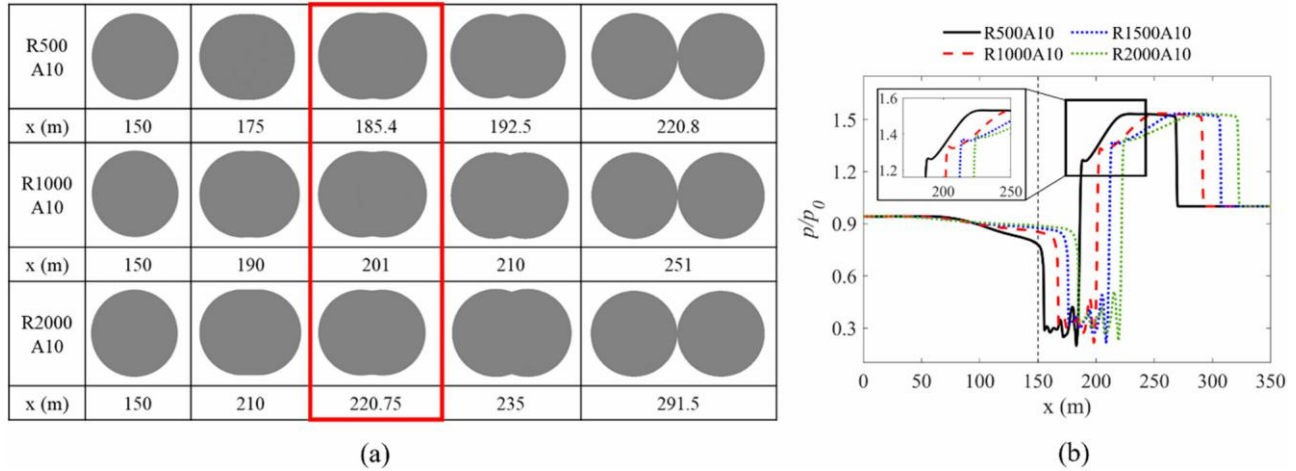


Figure 14. (a) The cross-sectional area of the tube at different x-position for cases R500A10, R1000A10, and R2000A10. The red box refers to the tube's shape in the middle of the intersection region. (b) Pressure distribution in front of the sphere. Note that, the pressure data is extracted from the red line as shown in Figure 12d (0.5 m above the bottom wall, $z = 0$ m). A vertical dashed line refers to the start point of the intersection region.

the speed increased, the maximum side force increased. In the case of the drag, similar tendencies were evident for all speeds. The drag first decreased and then increased in the intersection region, but a smaller speed corresponded to a steeper increase. The percentage of drag reduction was also different for each speed. For a speed of 100 m s^{-1} , the drag decreased by approximately 40%, and for 300 m s^{-1} , the decrease was 27%. For 200 m s^{-1} , the variation was quite different from that for the other two speeds. It appears that in this case, the drag was difficult to stabilise compared with the other cases. Jang et al. (2021) observed that in regime 2 (covering the speed range from 180 to 230 m s^{-1}), an OSW was generated within the

divergent section and it gradually propagated backward. Owing to the gradual propagation of this OSW, the flow around the sphere takes a longer time to reach the steady state.

It is also noteworthy that the minimum (drag) points for 100 m s^{-1} and 200 m s^{-1} are at later positions compared with the case of 300 m s^{-1} . To comprehensively understand the reason for this observation, average pressures at some points were extracted, as shown in Figure 18. As the drag was directly affected by the flow in front of and behind the sphere, the average pressure on cross sections of $\pm 1 \text{ m}$ in front of/behind the sphere was monitored for different positions of the sphere

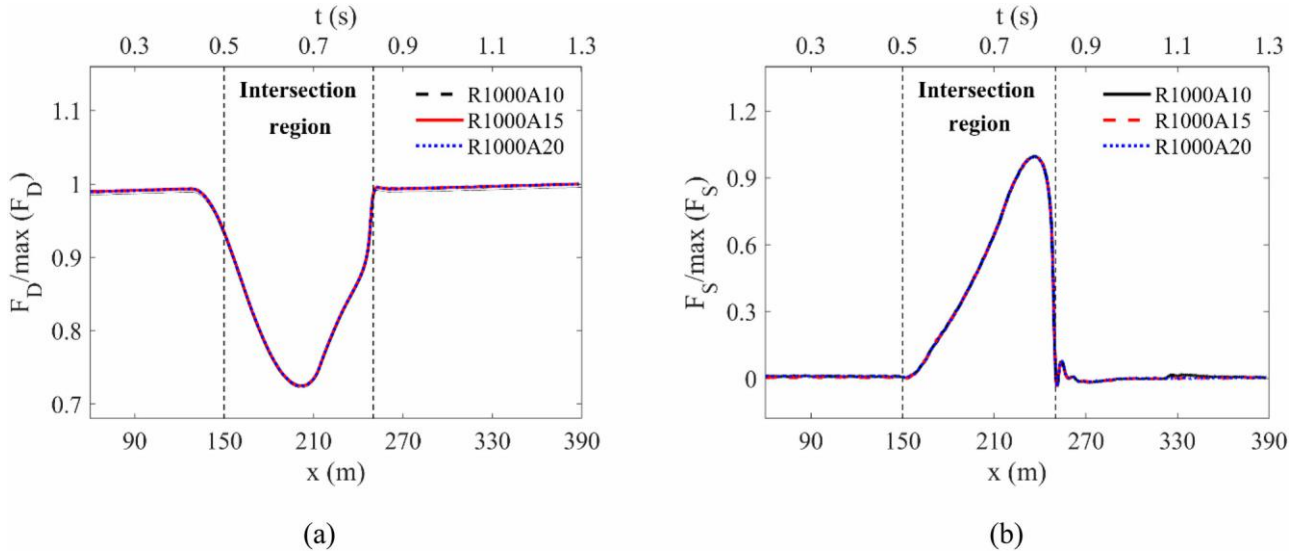


Figure 15. Effect of the angle on (a) aerodynamic drag (F_D) and (b) side force (F_S) when the sphere moved in a branched direction. The black dashed lines indicate the intersection region. The curvature radius was fixed at 1000 m.

(x_{sphere}). Furthermore, the average pressure at the cross section near the end of the intersection was monitored (i.e. $x = 248$ m).

As explained in section 3.1, for the speed of 300 m s^{-1} , when the LSW reached the intersection region, it generated REW propagating opposite to the sphere's direction of motion. This REW reduced the pressure in front of the sphere when it reached the sphere. Note that because of the shape of the sphere, when the flow affected the region in front of the sphere, it also immediately influenced the region behind the sphere. As the sphere continued to

move forward, the LSW reaches the divarication point (frog tip), and air was compressed around this region. This high-pressure region expanded with time, and it increased the pressure in front of the sphere when it reached the sphere.

Similar behaviour was observed for the speed of 100 m s^{-1} . However, there are two main differences as follows. Firstly, for the speed of 100 m s^{-1} , in front of the sphere, apart from the LSW, a forward expansion wave (FEW) was also present. This FEW was generated because of the rear expansion wave propagating forward, and it has been well explained in previous studies (Jang et al., 2021; Le et al., 2020). When the REW is formed, it merges with the FEW, and the pressure in front of the sphere remains unchanged. Thus, we observed a later drop of drag for the speed of 100 m s^{-1} (from $t = 1.52 \text{ s}$, $x_{sphere} = 152.5 \text{ m}$) compared with the speed of 300 m s^{-1} (from $t = 0.4235 \text{ s}$, $x_{sphere} = 127 \text{ m}$). Secondly, the propagation speed of the LSW is much higher than the sphere's speed (100 m s^{-1}), and hence it reached the end of the intersection region (around 0.7 s) much earlier than when the sphere reached the intersection (1.5 s). This huge time difference causes a delay in a position when the drag starts to increase (from $t = 2.33 \text{ s}$, $x_{sphere} = 233.3 \text{ m}$).

Figure 18 also indicates that when the sphere reached the intersection region (cross-sectional areas in front of and behind the sphere increased), the pressure behind the sphere decreased for the speed of 300 m s^{-1} whereas it increased for 100 m s^{-1} . This is because the pressure behind the sphere conformed to the converging-diverging nozzle theory. For the speed of 300 m s^{-1} , an OSW was present behind the sphere (flow was sub-sonic), and hence, when the area increased, the pressure

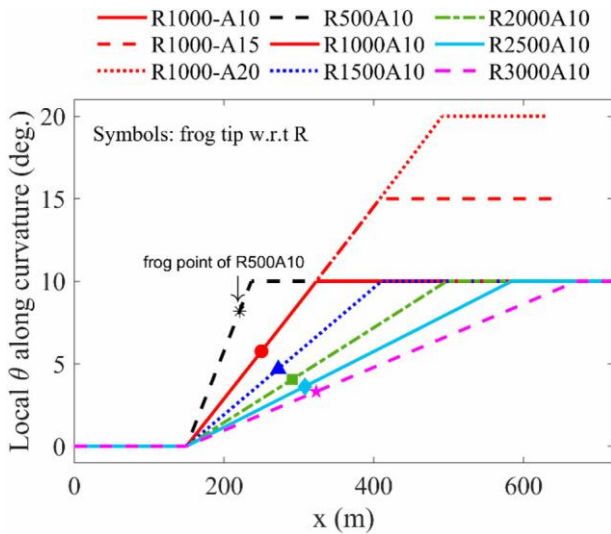


Figure 16. Increase in the local angle θ with the movement of the sphere. The symbols indicate the end of the intersection region (frog tip) and the position of min drag. The colours of the symbols correspond to the colours of the lines. For example, the radius of 500 m (black dashed line) corresponds to the black symbol.

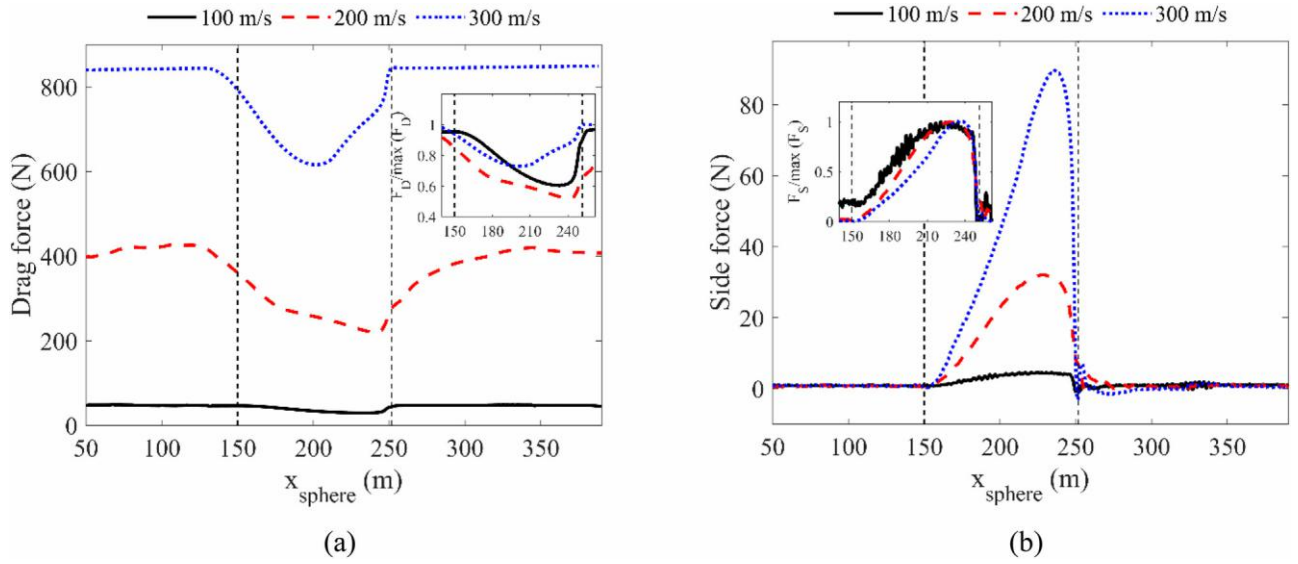


Figure 17. Comparison between spheres with different speeds for case R1000A10. (a) Variation of drag and (b) variation of side force. The black dashed lines mark the intersection region boundaries. The inset illustrates the ratio of drag/side force to maximum drag/side force within the intersection region.

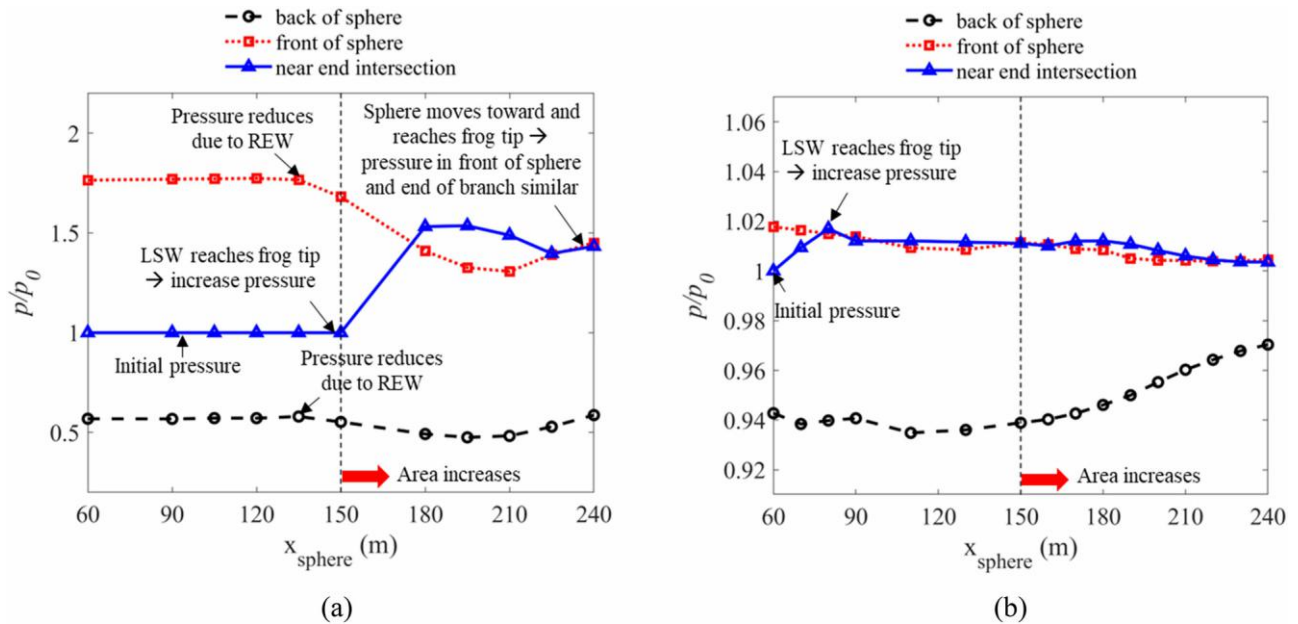


Figure 18. Average pressure on cross-sectional surface in front of/behind the sphere ($x_{\text{sphere}} \pm (r + 1)$) and near the end of branch ($x = 248$ m) for (a) 300 m s^{-1} and (b) 100 m s^{-1} . The black dashed line indicates the start of the intersection region ($x = 150$ m).

decreased. By contrast, flow was maintained subsonic behind the sphere for the speed of 100 m s^{-1} , and hence, when the area increased, the pressure increased.

On the other hand, the pressure in front of the sphere decreased for both speeds even though the flow was subsonic. Owing to the restricted area and forward movement of the sphere, the air in front of sphere was compressed. When the area increased, the compressibility decreased, resulting in a decrease in the pressure.

3.5. Effect of tube pressure

Figure 19 shows a comparison of the drag and side forces between spheres moving at a speed of 300 m s^{-1} under initial pressures of 101.325 Pa ($1/1000 \text{ atm}$) and $101,325 \text{ Pa}$ (1 atm). The case of R1000A10 was chosen for comparison purposes. Clearly, the drag and side forces increase proportionally with the pressure. However, the pressure does not affect the drag reduction

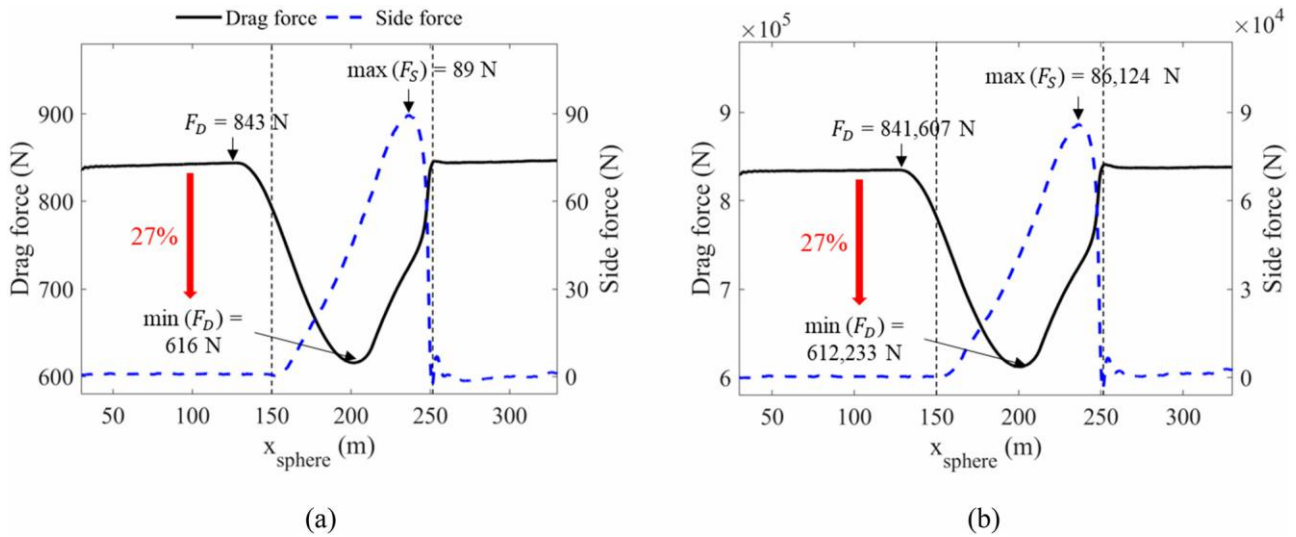


Figure 19. Variation of the drag and side force of case R1000A10 (v_{sphere} of 300 m s^{-1}) for (a) 101.325 Pa ($1/1000 \text{ atm}$) and (b) $101,325 \text{ Pa}$ (1 atm). The black dashed lines mark the intersection region boundaries.

(remains at 27% for both pressures). The side force and the pressure increased by the same factor (the forces were 1000 times higher when the pressure was increased 1000 times).

4. Conclusions

Three-dimensional simulations were conducted to evaluate the variation of the drag, side forces, and flow field characteristics of a sphere moving through a branched sub-vacuum tube. An unsteady compressible solver and the RANS SST $k-\omega$ turbulence model were employed for the numerical simulations. In this study, we assumed that the branched tube had perfect curvature (semicircle), and therefore, two main parameters—curvature radius and angle—were used to design the curvature. The investigation was performed for six curvature radii (500 to 3000 m), three angles (i.e. 10° , 15° , 20°), three speeds of the sphere (i.e. 100, 200, 300 m s^{-1}), and two initial pressures (1/1000 and 1 atm). Poly-mesh was used along with the dynamic overset mesh method to perform an unsteady simulation. From the results obtained for a speed of 300 m s^{-1} , the following conclusions were drawn.

- The drag and side forces varied within the intersection region, while before and after the intersection, their values were similar.
- With an increase in the curvature radius, the rate of drag reduction ($F_D/\max(F_D)$) decreased, while it was similar for the increase rate of side force.
- A change in the angle had a negligible effect on the variation of the drag and side forces.

- The pressure behaviour in front of and behind the sphere did not change for the motion of the sphere in a straight direction and in a branched direction.
- The tube pressure did not affect the drag reduction when the sphere passed through the intersection region.

Furthermore, considering the three speeds of the spheres, it was observed that the side force increased at the same rate regardless of the speed, while similar tendencies were observed for drag. Specifically, drag initially decreased and then increased in the intersection region, but a lower speed delayed the position of the minimum drag.

This is a pilot study of the movement of an object through a branched tube. This study could be considered as a preliminary study with the potential to contribute to the development of a divaricated Hyperloop system. We hope it will be helpful and practically contribute to the future Hyperloop.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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