Effects of compressible flow phenomena on aerodynamic characteristics in Hyperloop system

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\textbf{A B S T R A C T}

In this study, numerical simulations were conducted at various pod speeds \(v_{\text{pod}} = 100–350\) m/s using an unsteady, compressible solver with the Reynolds-averaged Navier–Stokes model to analyze the aerodynamic characteristics and pressure wave behavior in the Hyperloop system. Furthermore, the aerodynamic drag and pressure wave behavior were theoretically predicted based on quasi-one-dimensional assumptions. The flow around the pod is classified into three regimes according to the pod speed based on the compressible flow phenomena. In regime 1 \((v_{\text{pod}} = 100–170\) m/s), the compression waves develop into normal shock waves even without the occurrence of choking at the throat. In regime 2 \((v_{\text{pod}} = 180–230\) m/s), choking occurs at the throat and an oblique shock wave appears within the pod tail section. In regime 3 \((v_{\text{pod}} = 240–350\) m/s), a trailing shock wave propagates at the end of the oblique shock wave. Due to fully accelerated flow in this regime, the Mach number of the flow behind the pod in a pod-fixed coordinates remains constant as 2.1, regardless of the pod speed. This constant Mach number causes the drag coefficient to decrease while the pod speed increases. Although non-isentropic conditions such as the formation of a boundary layer and flow separation cause variation between the theoretical prediction and simulation results, the predicted properties of the pressure waves and the aerodynamic drag of the pod concur with the simulation results. Because the boundary layer along the pod is thinner at a higher pod speed, the difference between the theoretical and simulation values of the leading shock pressure decreases from 9.71% to 2.83% and that of the leading shock speed decreases from 4.35% to 1.30% as the pod speed increases from 180 to 350 m/s. Additionally, the theoretically predicted drag of the pod shows good agreement with the simulation results with an error of around 6%.

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1. Introduction

With the drastic technological advancements in the recent years and the increase in the demand for economical transportation, Elon Musk has proposed the concept of the Hyperloop, which is an evacuated tube maglev train (ETMT) system [1]. The Hyperloop system was designed to transport passengers within a maglev pod that travels at transonic speed in a near-vacuum \((1/1000\) atm) tube. The aerodynamic drag caused by the high operating speed is efficiently minimized by the low tube pressure and the maglev technology [2,3].

When an object travels at a high speed, it can cause various pressure waves [4]. Furthermore, if the object moves within a tube, such compressible flow phenomena are more severe owing to choked flow. Hruschka and Klatt conducted a comprehensive study on a high-speed projectile in a tube with experimental, simulation, and theoretical considerations [5]. They observed that a compression wave (CW) and an expansion wave (EW) are generated and propagate through the tube. Additionally, when the speed of the projectile reaches a critical value, an oblique shock wave (OSW) and a trailing shock wave (TSW) appear behind the projectile. They concluded that the pressure waves change the flow field, the aerodynamic characteristics of a projectile within the tube vary from a free-flight condition, and these characteristics are amplified when the projectile travels at transonic speeds.

The reduction of the aerodynamic drag is crucial for the economic efficiency and feasibility of high-speed train systems. Consequently, research has focused on the aerodynamic characteristics of high-speed ETMTs. The aerodynamic drag was analyzed under
The analysis of the aerodynamic characteristics in the Hyperloop system depends on the understanding of the compressible flow phenomena. However, the effect of the compressible flow phenomena on the aerodynamic characteristics is yet to be determined. Thus, in this study, the flow regimes according to the pod speed and the pressure waves in each flow regime were analyzed using computational fluid dynamics. The effect of the compressible flow phenomena on the aerodynamic characteristics of the pod was also identified. Furthermore, the pressure wave properties and the aerodynamic drag of the pod were predicted with a theoretical approach based on a quasi-one-dimensional assumption.

**2. Numerical method**

**2.1. Fluid properties**

The Hyperloop system is designed with a near-vacuum tube (1/1000 atm); however, the air within the tube is considered as a continuum. The Knudsen number (Kn) is evaluated to verify the applicability of the continuum mechanics. It is calculated as 0.00013 (Kn < 0.001) with a pressure of 1/1000 atm, temperature of 300 K, and a characteristic length of 5 m, which is the diameter of the tube. When the local minimum pressure (19.19 Pa) is considered based on the simulation results at a pod speed of 350 m/s, the Knudsen number increases up to 0.00069, which is still sufficiently small to be considered a continuum.

For the viscosity of air, Sutherland’s model was adopted in this study, which assumes viscosity as a function of only temperature (T) independent of pressure [20]. The background tube pressure (1/1000 atm) lies within the acceptable range for the ideal gas assumption to be applied, under which the isentropic speed of sound is expressed as a function of temperature (= \(\sqrt{\gamma R T}\)) by assuming the specific heat ratio (\(\gamma\)) and the individual gas constant (R) to be independent of pressure [21]. The values of \(\gamma\) and R were set...
to 1.4 and 287.058 J/kg·K, respectively. The Mach number \((M)\) is defined as the ratio of the flow velocity to the local speed of sound.

### 2.2. Computational domain

In the Hyperloop system, the shape of the pod is an important parameter that affects the aerodynamic characteristics. Previous studies have suggested various pod shapes to reduce the aerodynamic drag [7,22–24]. However, in this study, an idealized hemispherical shape is applied to the nose and tail of the pod to focus on the general mechanics by excluding the effect of the shape. The geometry was modeled as a two-dimensional (2D) and axially symmetric shape, as shown in Fig. 1.

When the pod travels within the tube, the flow around the pod encounters a change in the cross-sectional area. The cross-sectional area converges around the pod nose and diverges around the pod tail. Accordingly, the gap between the tube and the pod nose was defined as the convergent section, and the gap between the tube and the pod tail was defined as divergent section, as shown in Fig. 1. In the straight section shown in Fig. 1, the cross-sectional area remains unchanged. However, due to the viscosity effect, a boundary layer forms along the pod and tube wall, and the thickness of this boundary layer increases as the flow moves downstream. Thus, the cross-sectional area of the flow also converges through the straight section similar to the Fanno flow. Because the boundary layer is thickest at the end of the straight section, the throat where the cross-sectional area of the flow is the least is also around the end of the straight section, as shown in Fig. 1.

The length and diameter of the pod are set to 43 and 3 m, respectively. The BR is set to 0.36, and the tube diameter is calculated as 5 m for the given BR [1]. Strong pressure waves are formed, which propagate within the tube as the pod travels at a high speed. If these pressure waves reach the computational boundaries, artificial waves can be generated and reflected even under non-reflective boundary conditions. Thus, the total tube length is set to 1200 m, which is sufficient to prevent the reflection of waves during the simulation.

### 2.3. Boundary conditions

Fig. 2 schematically shows the boundary conditions. To simulate the pod motion, a moving zone is generated, and the pod is positioned at the center of the moving zone. During the simulation, the moving zone moves from the right to the left at a constant speed, which is the pod speed. The moving zone speed is set to 100, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 300, or 350 m/s. Owing to the drastic change from 150 to 250 m/s in the compressible flow behavior around the pod, the corresponding speed range is closely divided. The Reynolds number \((Re = \rho v d_{h}/\mu)\) was calculated from the background density and viscosity, pod speed, and hydraulic diameter of the gap between the tube and pod. The Reynolds number ranges from 13 000 to 45 500 according to the pod speed, which indicates turbulent flow. However, the Reynolds number is relatively low, considering the high speed of the pod and the large size due to the minimal tube pressure. A static pressure of 1/1000 atm is applied for the outlet-pressure condition. Both the pod and tube wall are set to the no-slip condition; however, the tube wall is stationary, and the pod wall moves with the moving zone. The pressure, temperature, and velocity of the initial flow field are set to 1/1000 atm, 300 K, and zero, respectively.

### 2.4. Computational grid

The overset method was applied to the computational grid, as shown in Fig. 3. The overset method has been widely adopted to simulate a moving train system [3,25,26]. Because the meshes for a stationary zone (background mesh) and a moving zone (component mesh) exist independently in the overset method, the motion of the mesh can be considered without the remeshing process, resulting in a cost-effective and time-saving simulation preventing the regeneration of the mesh.

The overset mesh consists of the component mesh, which contains the object of analysis, and the background mesh for the surrounding zone. In this study, the component mesh covers the moving zone which is large enough to contain the fluid domain where a significant variation of the flow is expected around the pod; the background mesh was generated for the entire tube. The component mesh was overlaid on the background mesh as shown in Fig. 3(c), which indicates that the component mesh and background mesh coexist around the pod. The component mesh was used for numerical computation at the point where the component mesh and background mesh overlap. The cell data was interpolated at the interface where the component mesh and the background mesh connected to transfer cell data between the component mesh and background mesh [27,28].

The hexahedral mesh was generated for both the background and component mesh. The size of the background mesh far from
the wall was set to 0.054 m, while the mesh size near the wall was set to 0.001 m considering the dimensionless first cell height ($y^+$). The size of the component mesh was set to 0.017 m in the region far from the wall and 0.0005 m in the near wall region, which is finer than the background mesh, to accurately predict the flow variation around the pod. The background mesh consists of 800,000 nodes and the component mesh consists of 485,546 nodes, while the overall number of nodes is 1,285,546. The results of the grid independence test and the value of $y^+$ are presented in Section 4.1.

2.5. Mathematical model

The mass, momentum, and energy conservation equations, which are the governing equations, are solved by using the finite volume method. A suitable turbulence model is necessary to predict the turbulence effect because the Reynolds number lies within the turbulence range. Direct numerical simulation and large eddy simulation can accurately represent the mechanics of the complex flow motion; however, the computational cost is significant [29–33]. The Reynolds-averaged Navier-Stokes (RANS) models, such as $k − \varepsilon$, $k − \omega$, and transition shear-stress transport (SST) models, have been widely adopted to balance the computational cost and performance of numerical simulation. Among RANS models, the SST $k − \omega$ model is a hybrid model that is a combination of the $k − \varepsilon$ and $k − \omega$ models [34]. It provides accurate and reliable results in terms of flow separation and shock waves at transonic speed [35]. Thus, the SST $k − \omega$ model, which has been widely used to analyze transonic to hypersonic flow, is adopted in this study [36–38]. Further details have been provided in the Supplementary Material (Supplementary Method A).

2.6. Numerical details

The simulations were conducted using a commercial software (ANSYS Fluent 18.1) with a 2D-axisymmetric, unsteady, compressible solver. The 2D-axisymmetric assumption enables economically efficient simulation with reasonable accuracy [3], and the unsteady simulation allows for the analysis of the pressure wave propagation. To solve the governing equations, the implicit Roe’s flux differencing is used for spatial discretization [39–41]. The least-squares cell-based method is used for the gradient term. The flow, turbulence kinetic energy, and specific dissipation rate terms were discretized with the second-order upwind scheme. The first-order implicit method is adopted for the time integration. To analyze the initial development of the pressure waves, the time step is set to 0.000025 s until the simulation time of 0.05 s (2000 time steps). The simulation was then conducted with a time step of 0.0001 s until the simulation time of 1 s (9500 time steps). The results of the time step independence test are presented in Section 4.2.

3. Theoretical consideration

In the theoretical consideration, the flow is mainly assumed to be inviscid and isentropic, except across the normal shock waves. A quasi-one-dimensional flow is also assumed because this approach is sufficient to capture the main flow features [42,43]. The idealized pod and tube shapes are assumed as shown in Fig. 1.

3.1. Coordinate systems and local quantities of flow

Three different coordinate systems—the absolute, pod-fixed, and shock-fixed coordinate systems—were considered in the theoretical analyses. In the pod-fixed coordinate system, the pod is stationary, and the flow moves relative to the pod. In the shock-fixed coordinate system, the shock wave is stationary, and the flow moves relative to the shock wave. The velocity and Mach number in the pod-fixed and shock-fixed coordinate systems are indicated with the superscripts $p$ and $s$, while those in the absolute coordinate system is indicated without a superscript.

Previous studies have reported that in the ETMT system, the CW was generated in front of the pod [14,18,19]. The speed of the posterior CW is higher than that of the precedent CW owing to the characteristics of the CW. Consequently, the CWs are accumulated at the head of the precedent CW and develop into energetic and non-linear shock waves, the front surface of which is normal to the direction of the flow [44]. Among these normal shock waves, the one in front of the pod propagates faster than the pod and leads the pod [2]. Therefore, in this study, this normal shock wave is called the leading shock wave (LSW).

Fig. 4 shows a schematic of the LSW in the Hyperloop system and the flow velocity in different coordinate systems. Point ε was defined as the local point in front of the LSW where the speed of the flow in shock-fixed coordinates is supersonic. Point γ represents the local point behind the LSW where the speed of the flow in shock-fixed coordinates is subsonic.

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Fig. 3. Overset mesh and computational grid. The size of the mesh in this figure is scaled by a factor of 5 in both the horizontal and vertical directions. The scale of horizontal length in this figure is 0.5 times the original scale, except in the magnified view in (a).
In the pod-fixed coordinates, sonic flow may exist at the throat owing to the high target speed of the pod. The sonic flow is accelerated to supersonic speed through the divergent section. According to the pressure condition, the shock wave can be generated within the divergent section, and the supersonic flow changes to the subsonic flow across the shock wave. However, if the shock wave is not generated within the divergent section, the flow can be fully accelerated. Point ⊙ represents the local point where the maximum Mach number is observed when the flow is fully accelerated through the divergent section. The local quantities of the flow at points ⊙, ◯, and ⊠ are indicated by the subscripts $a$, $b$, and $c$, respectively.

3.2. Converging and diverging nozzle relation

As explained above, the flow around the pod encounters the convergent, throat, and divergent sections. Thus, in the pod-fixed coordinates, the converging and diverging (C-D) nozzle relation is applicable to the flow around the pod. Under the choking condition, the Mach number of the flow ($M^p$) immediately before (after) the nose (tail) of the pod in the pod-fixed coordinates can be calculated as follows:

$$
\frac{A_t}{A_t - A_{pod}} = 1 + \frac{(\gamma - 1) (M^p)^2}{1 + (\gamma - 1) (M^p)^2} \left[ \frac{\gamma + 1}{\gamma + 1} \right],
$$

where $A_t$ is the cross-sectional area of the tube and $A_{pod}$ is the cross-sectional area of the pod.

When the pod speed is lower than the speed of sound, the velocity of flow into the convergent section in the pod-fixed coordinates is evidently subsonic. Although the pod speed is slightly higher than the speed of sound, the velocity of flow into the convergent section is assumed to be subsonic because the flow is within the subsonic side of the LSW. Thus, similar to the C-D nozzle, the subsonic solution of Eq. (1) was adopted as the Mach number of the flow immediately before the pod nose in the pod-fixed coordinates for the pod speed, which is high enough to cause choking at the throat. Under the isentropic and inviscid assumption, the flow quantities do not vary from the point behind the leading shock wave (Point ⊙) to the point immediately before the pod nose. Accordingly, the application of the subsonic solution of Eq. (1) can be extended to point ⊙. Additionally, the supersonic solution of Eq. (1) represents the Mach number of the flow immediately after the pod tail in the pod-fixed coordinates when the flow is fully accelerated under the isentropic process through the divergent section. Thus, $M^p_a$ and $M^p_b$ are set to the subsonic and the supersonic solution of Eq. (1) under the choked flow assumption. However, Eq. (1) cannot be applied in the case of low pod speeds without the occurrence of choking at the throat.

3.3. Prediction of leading shock wave propagation speed

The changes in the local quantities of the flow ($p$, $\rho$, $T$, and $M$) across the LSW are expressed as normal shock wave relations (Eqs. (2)–(7)) [45]:

$$
P^b = \frac{2\gamma (M^p_a)^2 - (\gamma - 1)}{\gamma + 1},$$

$$\rho^b = \frac{(\gamma + 1) (M^p_a)^2}{(\gamma - 1) (M^p_a)^2 + 2},$$

$$\frac{T^b}{T_a} = \frac{(\gamma - 1) (M^p_a)^2 + 2}{(\gamma - 1)^2 (M^p_a)^2} \left[ 2\gamma (M^p_a)^2 - (\gamma - 1) \right],$$

$$M^p_b = \sqrt{\frac{(\gamma - 1) (M^p_a)^2 + 2}{2\gamma (M^p_a)^2 - (\gamma - 1)}} (M^p_a)^2 + 2,$$

where

$$M^p_a = \frac{v^a}{\sqrt{\gamma R T_a}},$$

$$M^p_b = \frac{v^b}{\sqrt{\gamma R T_b}},$$

where $p$ is the pressure and $\rho$ is the density. Because $v_a$ is zero, as shown in Fig. 4, the velocity ($v_{LSW}$) and Mach number ($M_{LSW}$) of the LSW propagation can be expressed as follows:

$$v_{LSW} = -v^a, M_{LSW} = M^p_a.$$
\[ M_b^p = \frac{M_{LSW} \left[ (\gamma + 1) M_{pod} - 2M_{LSW} \right] + 2}{\sqrt{2\gamma(M_{LSW})^2 - (\gamma - 1)}} \]  

where
\[ M_{pod} = -\frac{V_{pod}}{\sqrt{\gamma R T_0}} \]  

Here, \( M_{pod} \) is the Mach number of the pod in the absolute coordinates. Further details have been provided in the Supplementary Material (Supplementary Method B). Consequently, \( M_{LSW} \) corresponding to \( M_{pod} \) can be calculated by numerically solving the system of equations that consists of Eqs. (1) and (10). All the geometric parameters \((A_s, A_{pod})\) and \( \gamma \) in this instance are known constants corresponding to the design aspect of the system.

### 3.3. Prediction of aerodynamic drag

The total drag of the pod \((D_T)\) in hyperloop aerodynamics is composed of the pressure drag \((D_P)\) generated by pressure difference and the friction drag \((D_F)\) caused by the viscosity of flow. The previous studies reported that the pressure drag is more dominant than the friction drag in the Hyperloop system \([2,3]\). The pressure drag can be expressed as follows:
\[ D_P = A_s \left( \overline{p}_{nose} - \overline{p}_{tail} \right) \]  

where \( A_s \) is the surface area of the pod nose or pod tail and \( \overline{p}_{nose} \) and \( \overline{p}_{tail} \) are the average values of pressure acting on the pod nose and pod tail along the axial direction, respectively. To predict the pressure acting on the pod nose \((p_{nose})\), the Prandtl–Glauert correction \([46]\) was applied to the pressure distribution along a sphere for inviscid, incompressible, and isotropic flow as follows:
\[ p_{nose} = p_b + \frac{1}{2\beta} \rho_b (V_b)^2 \left( 1 - 4\sin^2 \theta \right) \]  

where
\[ \beta = \sqrt{1 - (M_b^p)^2} \]  

\[ \theta \]  

where \( \theta \) is the angle between the axial direction and the normal vector of the pod nose surface and \( \beta \) is the Prandtl–Glauert correction factor. Consequently, the pressure acting on the pod nose along the axial direction was averaged as follows:
\[ \overline{p}_{nose} = \frac{1}{A_s} \int p_{nose} \cos \theta \, dA = \frac{p_b}{2} \left[ 1 - \frac{\gamma \left( M_b^p \right)^2}{2\sqrt{1 - (M_b^p)^2}} \right] \]  

Further details have been provided in the Supplementary Material (Supplementary Method C).

The viscous effect is more significant at the pod tail than at the pod nose, and the pressure distribution in Eq. (13) is not applicable for the pressure acting on the pod tail \((p_{tail})\). Thus, the uniform pressure distribution on the pod tail was assumed as the pressure at point \( \Box \) \((p_{tail} \approx p_c)\). To predict \( p_c \), the total pressure conservation in the pod-fixed coordinates was applied from point \( \Box \) to point \( \Box \).
\[ p_b \left[ 1 + \left( \frac{\gamma - 1}{2} \right) \left( M_b^p \right)^2 \right] = p_c \left[ 1 + \left( \frac{\gamma - 1}{2} \right) \left( M_c^p \right)^2 \right] \]  

Considering that both \( M_b^p \) and \( M_c^p \) are solutions of Eq. (1), Eq. (16) was simplified as follows:
\[ p_c = p_b \left( \frac{M_b^p}{M_c^p} \right)^{2\frac{\gamma}{\gamma + 1}} \]  

Subsequently, the pressure acting on the pod tail along the axial direction was averaged as follows:
\[ \overline{p}_{tail} = \frac{1}{A_t} \int p_{tail} \cos \theta \, dA = \frac{p_b}{2} \left( \frac{M_b^p}{M_c^p} \right)^{2\frac{\gamma}{\gamma + 1}} \]  

Next, by combining Eqs. (2), (8), (12), (15), and (18), the pressure drag is expressed as follows:
\[ D_P = \frac{A_s p_a}{2} \left[ 2\gamma (M_{LSW})^2 - (\gamma - 1) \right] \times \left[ 1 - \frac{\gamma \left( M_b^p \right)^2}{2\sqrt{1 - (M_b^p)^2}} - \frac{\left( M_b^p \right)^2}{\left( M_c^p \right)^{2\frac{\gamma}{\gamma + 1}}} \right] \]  

where \( M_{LSW}, M_b^p, \) and \( M_c^p \) can be obtained from Eqs. (1) and (10). \( A_s, p_a \), and \( \gamma \) are determined by the pod shape, the operating tube pressure, and the type of gas in the tube, respectively. Further details have been provided in the Supplementary Material (Supplementary Method D).

### 4. Verification

#### 4.1. Grid independence test

For the grid independence test, the number of nodes was set to 313,486 (coarse), 485,566 (medium), or 649,116 (fine), only for the component mesh. The background mesh was set to a scale similar to that of previous studies \([2,3]\). The simulations were conducted with the three different grids at a pod speed of 350 m/s. The LSW and OSW are the main factors that affect the aerodynamic characteristics in the Hyperloop system. Fig. 5 shows the pressure distribution in the LSW and OSW for the coarse, medium, and fine grids. The variations in the position and pressure of the LSW among three grids are 0.16% and 0.17%, respectively. Further, the variation in the pressure distribution in the OSW is negligible.
between the medium and fine grids. Accordingly, the aerodynamic drag of the pod shows a difference of only 0.1% among the three different grids. Therefore, it is concluded that the medium grid applied in this study provides sufficient accuracy.

To predict the boundary layer accurately, the mesh in the near-wall region was also verified based on the value of $y^+$ (Fig. 6) shows the distribution of $y^+$ for the medium mesh along the pod and tube wall at a pod speed of 350 m/s. The maximum $y^+$ is less than 1.5.

4.2. Time step independence test

The simulation results from three different time step conditions were compared to verify the time sensitivity of the simulation. For case A, the time step was set to 0.00003125 s until a simulation time of 0.05 s (1600 time steps), and 0.000125 s until a simulation time of 1 s (7600 time steps). For case B, the time step was set to 0.000025 s until a simulation time of 0.05 s (2000 time steps), and 0.0001 s until a simulation time of 1 s (9500 time steps). For case C, the time step was set to 0.00002 s until a simulation time of 0.05 s (2500 time steps), and 0.00008 s until a simulation time of 1 s (11875 time steps). Consequently, the variations in the position and pressure of the LSW among the three time step conditions are 0.16% and 0.86%, respectively. The variation in the pressure distribution in the OSW is also negligible as shown in Fig. 7(b). Accordingly, the aerodynamic drag of the pod shows a difference of only 0.3% among the three time step conditions. Therefore, it is concluded that the time step condition for case B, which is applied in this study, provides sufficiently accurate results.

4.3. Effect of acceleration

A constant velocity was applied to the moving zone in the simulation setup used in this study. In other words, the pod reaches the target speed instantly at the start of the simulation, and the effect of acceleration is not considered. To verify this approach, the effect of acceleration was analyzed by comparing the results obtained with setups considering a constant velocity (Case 1) and acceleration (Case 2) at a pod speed of 300 m/s. In Case 2, the pod speed increases from 0 to 300 m/s within 1 s, following the hyperbolic tangent function. The comparison was conducted with the results obtained at simulation times of 1 and 0.9 s after reaching the target speed (i.e., 1 and 0.9 s for Case 1; 2 and 1.9 s for Case 2).

Fig. 8 shows the pressure distribution along the axis at the upstream of the pod. The origin of the x-axis is set to the pod nose for each case.
Table 1

<table>
<thead>
<tr>
<th>Case</th>
<th>Pressure of leading shock wave (Pa)</th>
<th>Propagation speed of leading shock wave (m/s)</th>
<th>Aerodynamic drag (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>174.74 (1.4%)</td>
<td>444.07 (1.35%)</td>
<td>1061.23 (0.53%)</td>
</tr>
<tr>
<td>Case 2</td>
<td>172.32</td>
<td>438.13</td>
<td>1066.86</td>
</tr>
</tbody>
</table>

Fig. 9. Distribution of Mach number in the pod-fixed coordinates around the pod for each regime. The two representative cases for each regime are presented (regime 1: 100 and 150 m/s; regime 2: 180 and 210 m/s; regime 3: 250 and 350 m/s). The origin of the x-axis is set to the pod nose for each case.

5. Results and discussion

In the Hyperloop system, the compressible flow mechanics are better demonstrated in the pod-fixed coordinates. Therefore, in Sections 5.1, 5.2, and 5.3, the simulation results were analyzed in the pod-fixed coordinates (i.e., the Mach number in the pod-fixed coordinates ($M_{p}$) was used for analysis). To analyze the Mach number and pressure distribution, the simulation results were extracted along the horizontal line at the center of the gap between the pod and the tube at a simulation time of 1 s.

5.1. Flow regimes in Hyperloop aerodynamics

Because the flow around the pod encounters a change in the cross-sectional area, the flow regime is expected to be similar to that of the C-D nozzle. However, the relative speed of the flow is determined from the pod motion, in contrast with the typical C-D nozzle. In this condition, the air is compressed at the front of the pod, which causes the generation of a shock wave even without the effect of choking at the throat. Moreover, the gap between the tube and the pod is annular. Additionally, the pod wall moves, while the tube wall remains stationary. These geometrical and physical asymmetric conditions also create a difference in the flow regime between the C-D nozzle and the Hyperloop system. The flow field around the pod in the Hyperloop system is classified into three regimes according to the pod speed. The Mach number distribution of two representative cases for each regime is shown in Fig. 9.

Firstly, in regime 1, the Mach number of the flow at the entrance of the convergent section ($M_{m1}^{p}$), where the pod nose is located, is smaller than the critical Mach number ($M_{cr}$) owing to the low pod speed. The flow is accelerated through the convergent section but does not attain sonic speed at the throat. Therefore, the flow decelerates through the divergent section where the pod tail is located, and the flow is subsonic in all the regions, as shown in Fig. 9.

Secondly, when the value of $M_{m1}^{p}$ reaches that of $M_{cr}$ with the increase in the pod speed, the Mach number at the throat increases up to 1. This sonic flow is accelerated to supersonic flow through the divergent section. However, due to the generation of the OSW within the divergent section, the supersonic flow changes to subsonic flow across the OSW; consequently, the flow cannot be fully accelerated through the divergent section. Under this condition, as the pod speed increases, the OSW is pushed towards the end of the divergent section, and the flow is further accelerated, resulting in a higher Mach number of the flow at the exit of the divergent section ($M_{m1}^{p}$). This flow regime is classified as regime 2.

Lastly, as the pod speed increases further, the OSW is swept out of the divergent section. Thus, the flow is fully accelerated to the upper limit of the Mach number for the given area divergence ratio, and the Mach number of the flow behind the pod remains constant, despite the increase in the pod speed, as shown in Fig. 9. This flow regime is classified as regime 3.

5.2. Pressure waves

In the Hyperloop system, various pressure waves are generated for each regime. Fig. 10 schematically shows the pressure waves and the pressure distribution of the representative cases. A shock wave is generated under a supersonic condition in an open space. However, in the Hyperloop system, a normal shock wave propagates along the tube in all the flow regimes. As the pod moves within the tube, the air is accumulated at the upstream of the pod and dispersed at the downstream. Consequently, the CW and EW are generated at the pod nose and tail, respectively, and propagate in both the forward and the backward directions.

The posterior CW is faster than the precedent CW owing to the characteristics of the CW, and the CWs are accumulated at the head of the precedent CW, resulting in the development of the normal shock wave, which is non-linear. Therefore, as shown in Fig. 10, the forward CW and backward CW develop into the LSW and receding shock wave (RSW), respectively, for all the flow regimes including regime 1 where the flow is subsonic. In contrast, the EW is dispersed during the propagation and does not develop into the normal shock wave.

The LSW causes a rapid increase in the pressure, which decreases smoothly behind the LSW, as shown in Fig. 10(a)–(b). This pressure distribution is also observed in high-speed train tunnels [47]. As the EW propagates at the speed of sound, the forward expansion wave (FEW) passes across the pod under the absence of sonic flow at the throat. Despite the presence of sonic flow at the throat due to the high pod speed, the FEW can propagate across the pod when it passes the throat before the flow develops into sonic speed. When the FEW propagates across the pod, it maintains a relatively low pressure in the upstream high-pressure field, which is an interaction region. This interaction region becomes weaker as the pod speed increases.

The flow develops into sonic speed before the FEW passes the pod, especially at a speed of 300 and 350 m/s. In this case, the
FEW cannot propagate across the pod, and no interaction region is formed at the upstream of the pod, as shown in Fig. 10(c).

Similarly, the RSW and backward expansion wave (BEW) also generate an interaction region at the downstream of the pod. Because the RSW propagates along the same direction as that of the flow, it always passes across the pod, regardless of the pod speed. Thus, the downstream interaction region exists in all the flow regimes.

In regime 2, the OSW appears within the divergent section due to the sonic flow at the throat. Generally, in the C-D nozzle, the normal shock wave occurs within the divergent section. However, in the Hyperloop system, the annular shape of the gap between the pod and the tube, the difference in velocity between the tube and pod wall, and the viscosity effect cause the normal shock wave to incline and be reflected at the tube wall and the jet-boundary, resulting in the OSW. In regime 2, regardless of flow time, the position of the OSW is fixed at the point where the propagation speed of the OSW and the flow speed are balanced, as shown in the magnified view of Fig. 10(b). However, in regime 3, the flow is fully accelerated, and the OSW is swept downstream. Consequently, the OSW extends to downstream, and the TSW propagates away from the pod at the end of the OSW, as shown in the magnified view of Fig. 10(c).

5.3. Mach number and pressure field

The subsonic solution, 0.408, and the supersonic solution, 1.91, are obtained by solving Eq. (1) for the given BR (0.36). Here, the subsonic solution represents $M_{in}^p$ in the isentropic flow under the choking condition, which is known as the isentropic critical Mach number ($M_{cr,isen}$). and the supersonic solution represents $M_{in}^p$ in the isentropic flow under the choking condition, as explained earlier in Section 3.2. In regime 1, no sonic flow occurs at the throat. Notably, the pod-speed range from 100 to 170 m/s ($M_{pod} = 0.288–0.490, M_{in}^p = 0.254–0.343$) corresponds to regime 1, as shown in Figs. 11–13, which includes a higher Mach number of the pod than $M_{cr,isen}$ (0.408). Across the LSW, the Mach number of flow rapidly decreases as shown in Fig. 13(a), and $M_{in}^p$ ranges from 0.254 to 0.343. Thus, although the pod travels at a higher speed than $M_{cr,isen}$, the LSW reduces $M_{in}^p$ below $M_{cr,isen}$ and delays the choking. In other words, the choking occurs at a higher $M_{pod}$ than $M_{cr,isen}$.

In Fig. 13(b), the pressure of the LSW increases with the increase in the pod speed. Conversely, the BEW generates a low-pressure region at the downstream, and the pressure decreases with the increase in the pod speed. However, the variation of the BEW is not as prominent as that of the LSW. The pressure at the entrance of convergent section ($p_{con}$) increases with the increase in the pod speed, whereas the pressure at the exit of the divergent section ($p_{exit}$) decreases.

The cases with pod speed in the range of 180 to 230 m/s ($M_{pod} = 0.518–0.662, M_{in}^p = 0.347–0.361$) correspond to regime 2. As shown in Figs. 14–15, the OSW appears within the divergent section. In the case of a pod speed of 180 m/s, the OSW is
not prominent. However, as the pod speed increases, the OSW becomes stronger and is clearly visible from a pod speed of 190 m/s.

In regime 2, choking occurs at the throat. However, in Fig. 16(a), $M_{in}^p$ remains smaller than $M_{c,r,isen}$ because of the effect of the boundary layers. The boundary layers are formed along the pod and tube wall owing to the shear field near the wall. These boundary layers cause the flow to encounter a smaller throat area compared to that of the designed system. Thus, the actual critical Mach number is lower than $M_{c,r,isen}$. The boundary layer becomes thinner with the increase in the pod speed. Thus, $M_{in}^p$ approaches $M_{c,r,isen}$ at high pod speeds. In addition, sonic flow occurs at the end of the straight section because the thickness of the boundary layer increases as the flow goes downstream, as shown in Fig. 16(a).

$M_{ex}$ increases with the increase in the pod speed. As explained earlier, the position of the OSW is pushed backward at a higher pod speed, allowing for the flow to accelerate further through the divergent section. Due to the viscosity effect, the flow is separated at the pod tail as shown in Fig. 17. This flow separation delays the divergence of the area encountered by the flow. Thus, the acceleration of the flow does not stop at the end of the divergent section and continues a little further, as shown in the magnified view of Fig. 16(a).

The tendency of the pressure in regime 2 is similar to that in regime 1, apart from the pressure oscillation due to the OSW, as shown in Fig. 16(b). The pressure of the LSW increases and the pressure of the BEW decreases with the increase in the pod speed. Additionally, $p_{in}$ increases with the increase in the pod speed, while $p_{ex}$ decreases.

The pod speed ranges from 240 to 350 m/s in regime 3 ($M_{pod} = 0.691 - 1.01$, $M_{in}^p = 0.364 - 0.392$). In Figs. 18–19, the under-expanded jet was observed behind the pod. Owing to the flow separation, low pressure is formed behind the pod, resulting in a lower ambient pressure than $p_{ex}$. Thus, the over-expanded jet cannot be observed in the Hyperloop system. The shock cell structures are formed in the under-expanded jet. However, owing to the reflection at the tube wall, the formation of shock cell structures differs from that in an under-expanded jet structure in an open space, but is similar with that observed in an under-expanded confined jet [48]. Fig. 20(a) shows the Mach number distribution in regime 3. The OSW does not lie within the divergent section, and the flow is fully accelerated through the divergent section. Thus, $M_{ex}$ remains constant as the pod speed increases. If the flow is in the inviscid and isentropic conditions, $M_{ex}^c$ is 1.91, which is the supersonic solution of Eq. (1). However, the flow encounters a smaller throat area due to the effect of the boundary layer, and the Mach number of the flow increases up to 2.10. As explained in the context of regime 2, the maximum Mach number appears slightly away from the pod tail due to the flow separation at this instance.

Fig. 20(b) shows the pressure distribution in regime 3. The variation tendencies of the LSW pressure, BEW pressure, and $p_{in}$ with respect to the pod speed are identical to those of regime 1 and 2. However, $p_{ex}$ shows a different tendency with respect to the pod speed. When the pod speed increases, the total pressure of the flow at the exit of the divergent section also increases. The total pressure in the compressible flow is expressed by following equation:
K.S. Jang, T.T.G. Le, J. Kim et al. Aerospace Science and Technology 117 (2021) 106970

Fig. 12. Pressure contours in regime 1. The scale of the horizontal length in this figure is 0.4 times the original scale. The insets show magnified views of the flow around the pod.

Fig. 13. Mach number in the pod-fixed coordinates and pressure distributions in regime 1. The origin of the x-axis is set to the pod nose for each case. The position of the pod and the isentropic critical Mach number (\(M_{c,isen}\)) for BR = 0.36 are represented by the red dotted line. The red triangle indicates the background tube pressure.

\[
P_T = p \left[ 1 + \left( \frac{\gamma - 1}{2} \right) (M^P)^2 \right]^{\frac{\gamma}{\gamma-1}},
\]

where \(P_T\) is the total pressure. Based on Eq. (20), it is observed that the pressure increases to match the increase in the total pressure when the Mach number remains constant. Thus, in regime 3, \(p_{ex}\) increases with the increase in the pod speed.

5.4 Analysis of shock wave behavior

A theoretical approach was also considered to predict the properties of the pressure waves and the aerodynamic drag of the pod. Three main assumptions were applied with the present theoretical consideration. Firstly, inviscid flow is assumed. Thus, the effect of the boundary layer is neglected. Secondly, we assume that the flow is choked at the throat, as in regime 2. Thirdly, the flow is fully accelerated through the divergent section, as in regime 3. Thus, some of the values are limited to be predictable from regime 2 or regime 3.

Fig. 21 shows the values of \(p_b\) and \(p_c\) obtained from the theoretical calculation and simulations. In order to predict \(p_b\), \(M_{LSW}\) is calculated by numerically solving Eqs. (1) and (10). The value of \(p_b\) is then calculated from Eq. (2). Eq. (17) is used to predict \(p_c\). Here, the prediction of the values of \(p_b\) and \(p_c\) is possible from regime 2 and regime 3, respectively, due to the assumptions of the theoretical consideration. In Fig. 21, the predicted values of \(p_b\) and \(p_c\) concur with the simulation results. Because the boundary layer
was not considered in the prediction, the effects of the convergent and divergent sections are greater in the simulations. Thus, the predicted value of $p_b$ is slightly underestimated in regime 2. However, as the pod speed increases from 180 to 350 m/s, the thickness of the boundary layer reduces, and the difference between the theoretical prediction and simulation decreases from 9.71% to 2.83%. Conversely, the predicted value of $p_c$ is slightly overestimated due to the boundary layer effect.

Fig. 22 shows the propagation speed of the pressure waves obtained from the theoretical calculation and simulation. To confirm the applicability of the normal shock wave relations, the speeds of the LSW, TSW, and RSW are also calculated by applying Eq. (2) to each wave. When Eq. (2) is applied, we used the pressure in front of and behind each wave from the simulation results.

The propagation velocity of the TSW ($v_{TSW}$) is also calculated theoretically. In this case, the local quantities at point $\odot$ are used for the quantities in front of the TSW, and the 1/1000 atm condition is applied for the pressure behind the TSW. Subsequently, $M_c^p$ is calculated from these pressure conditions using Eq. (2). To convert $M_c^p$ into $v_c^p$, $T_c$ was obtained by applying the total temperature conservation from point $\odot$ to point $\oplus$.

$$T_b \left[ 1 + \left( \frac{\gamma - 1}{2} \right) (M_b^p)^2 \right] = T_c \left[ 1 + \left( \frac{\gamma - 1}{2} \right) (M_c^p)^2 \right],$$

(21)

where $M_b^p$ and $M_c^p$ can be obtained from Eq. (1) and $T_b$ can be obtained from Eq. (4). Lastly, $v_{TSW}$ is calculated as follows:

$$v_{TSW} = -v_c^p + v_c^b + v_{pod},$$

(22)
where

\[ v_L^\ell = M_L^\ell \sqrt{\gamma R T_c}, \]  
\[ v_L^P = M_L^P \sqrt{\gamma R T_c}. \]  

In Eq. (2), the normal shock wave relation is applicable for the LSW. The values of \( v_{LSW} \) from the theoretical calculation and the simulation are shown to coincide. Similar to the case of \( p_b \), the predicted value of \( v_{LSW} \) is underestimated in regime 2 due to the effect of the boundary layer. However, the difference decreases from 4.39% to 1.30% as the pod speed increases from 180 to 250 m/s because the thickness of the boundary layer decreases. For the RSW, the propagation speed from the simulation corresponds to that obtained from Eq. (2).

In case of the TSW, the value of \( v_{TSW} \) obtained from Eq. (2) shows a relatively large variation when compared to that in the simulation results. Because the TSW propagates at the end of the OSW, where the pressure oscillates, \( v_{TSW} \) oscillates as well. This oscillation causes a difference in the values of \( v_{TSW} \) obtained from the simulation and from Eq. (2). The local quantities at point \( \odot \), where the maximum Mach number is observed, are used in the prediction of \( v_{TSW} \). However, the TSW propagates at the end of the OSW, where the pressure is higher than point \( \odot \), as shown in the magnified view of Fig. 20(b). Thus, the predicted value of \( v_{TSW} \) tends to be overestimated when compared to that of the simulation results.
5.5. Analysis of aerodynamic drag

In the theoretical consideration, the local quantities at point © are calculated based on the fully accelerated condition through the divergent section, because of which the prediction in this section is limited to regime 3. As described in Eq. (12), \( \overline{p}_{\text{noise}} \) and \( \overline{p}_{\text{tail}} \) are the main factors affecting the aerodynamic drag of the pod. Thus, the values of \( \overline{p}_{\text{noise}} \) and \( \overline{p}_{\text{tail}} \) calculated from Eq. (15) and Eq. (18), are compared to the simulation results.

Fig. 23 shows the values of \( \overline{p}_{\text{noise}} \) and \( \overline{p}_{\text{tail}} \) obtained from the theoretical calculation and the simulation. The \( \overline{p}_{\text{noise}} \) values from the simulation are higher than those obtained from the theoretical calculation. This underestimation of \( \overline{p}_{\text{noise}} \) in the prediction is due to the boundary layer effect and inviscid pressure coefficient applied in the theoretical calculation. Although the boundary layer was neglected, the theoretical calculation underestimates the value of \( \overline{p}_{\text{tail}} \) when compared to the simulation results. Due to the flow separation, the flow is not yet fully accelerated at the end of divergent section, and the values of \( M_{\text{crit}}^e \) from the simulation are lower than the predicted values of \( M_{\text{crit}}^e \). Accordingly, the values of \( p_{\text{ex}} \) from the simulation are higher than the predicted values of \( p_{\text{ex}} \), resulting in the underestimation of \( \overline{p}_{\text{tail}} \).

Fig. 24 shows the ratio of the drag components to the total drag and the aerodynamic drag of the pod obtained from the theoretical calculation and simulations. In Fig. 24(a), \( D_P/D_T \) increases with a decrease in \( D_{F}/D_{T} \) as the pod speed increases. This indicates that the pressure drag is more dominant at a higher pod speed due to the increase in the pressure difference between the pod nose and tail. Owing to the increase in the pressure at the pod tail with the increase in the pod speed in regime 3, the increase in \( D_F/D_T \) is negligible at a higher pod speed than 240 m/s. Accordingly, the values of \( D_P/D_T \) and \( D_F/D_T \) remain almost constant at 0.89 and 0.11, respectively, in regime 3.

In Fig. 24(b), Eq. (19) was used in the theoretical calculation for the pressure drag. Subsequently, the ratio of the drags was applied to the theoretically predicted pressure drag to calculate the total and friction drag. Fig. 24(b) shows that the aerodynamic drag obtained from the theoretical calculation concurs with that obtained from the simulation results. The difference in the pressure drag between the theoretical calculation and simulation is 6.73% for a pod speed of 240 m/s and decreases to 5.85% for a pod speed of 350 m/s.

The aerodynamic drag of the pod increases with the increase in the pod speed, but the gradient of the aerodynamic drag starts to decrease in regime 3. As the pod speed increases, the value of \( D_{\text{tail}} \) increases in regime 3, while the value of \( D_{\text{tail}} \) decreases in regimes 1 and 2, as shown in Fig. 23. Consequently, the increase in the difference between \( \overline{p}_{\text{noise}} \) and \( \overline{p}_{\text{tail}} \) corresponding to the increase in the pod speed is less in regime 3 than in regimes 1 and 2, resulting in the relatively small increase in the pressure drag.

Fig. 25 shows the drag coefficient corresponding to the pod speed. The drag coefficient is calculated using the following equations:

\[
C_{DT} = \frac{D_T}{\frac{1}{2} \rho_0 (v_{pod})^2 A_{pod}},
\]

\[
C_{DP} = \frac{D_P}{\frac{1}{2} \rho_0 (v_{pod})^2 A_{pod}}.
\]
Fig. 18. Mach number in the pod-fixed coordinates in regime 3. The scale of the horizontal length in this figure is 0.4 times the original scale. The insets show magnified views of the flow around the pod.

\[ C_{DF} = \frac{D_F}{\frac{1}{2} \rho_0 (V_{pod})^2 A_{pod}}. \]  

(27)

where \( C_{DT}, C_{DP}, \) and \( C_{DF} \) are the total, pressure, and friction drag coefficients. The change in gradient of the aerodynamic drag in regime 3 is more conspicuous in the drag coefficients. Due to the decrease in the gradient of the aerodynamic drag in regime 3, the drag coefficient of the pod is maximized at the end of regime 2.

6. Conclusion

The flow regimes and behavior of the pressure waves in the Hyperloop system were analyzed with a 2D, axisymmetric, unsteady simulation and a theoretical quasi-one-dimensional approach. The flow around the pod is categorized into three regimes according to the pod speed based on compressible flow phenomena. The leading shock wave (LSW), receding shock wave (RSW), and expansion wave (EW) are generated in all the regimes including regime 1 where the flow is subsonic, owing to the effect of confined tube. The oblique shock wave (OSW) appears from regime 2, and the trailing shock wave (TSW) appears in regime 3. The pressure waves are observed to affect the flow field in the tube, and the LSW and OSW have a greater effect on the aerodynamic characteristics of the pod than the other waves.

The pod speed at which choking occurs is found to be affected by the LSW and boundary layer. The Mach number of the flow in the pod-fixed coordinates rapidly decreases across the LSW, which delays the choking. Conversely, due to the boundary layers at the tube and pod wall, the flow encounters a smaller throat area than in the designed system, resulting in the decrease of the critical Mach number. The effect of the LSW is more significant than that of the boundary layer, and the choking occurs at a pod speed higher than the isentropic critical Mach number. Additionally, the choking is observed at the end of the straight section because the boundary layer becomes thicker as flow goes downstream.

In regime 3, the drag coefficient decreases as the pod speed increases. This tendency of the drag coefficient has been reported in previous studies [2,3,5,8,14]. However, the details in this phenomenon did not investigated. Due to fully accelerated flow, the Mach number of the flow behind the pod in the pod-fixed coordinates remains constant while the pod speed increases, resulting in the increase in the pressure at the tail. This pressure tendency causes the gradient of the aerodynamic drag to slow down in regime 3, and the drag coefficient is maximized at the end of regime 2.

To predict the pressure wave behavior and the aerodynamic drag of the pod in the Hyperloop system, quasi-one-dimensional equations were applied to various relative coordinate systems. From the theoretical calculation, the properties of the LSW and the TSW were predicted, and the predictions concur with the simulation results. Furthermore, the aerodynamic drag of the pod was successfully predicted with a small variation of around 6%.

In this study, the compressible flow phenomena and their effects on the aerodynamic drag of the pod for different flow regimes have been comprehensively analyzed. The results are expected to help in the design of the Hyperloop system by providing an understanding of the compressible flow effects. Additionally, in the design stage of the optimal shape or operating conditions, predict-
Fig. 19. Pressure contours in regime 3. The scale of the horizontal length in this figure is 0.4 times the original scale. The insets show magnified views of the flow around the pod.

Fig. 20. Mach number in the pod-fixed coordinates and pressure distributions in regime 3. The origin of the x-axis is set to the pod nose for each case. The position of the pod, the isentropic critical Mach number ($M_{cr,isen}$) for BR = 0.36, and the line for Mach number equal to 1 are represented by the red dotted lines. The red triangle indicates the background tube pressure. The insets show magnified views.
Fig. 21. $p_b$ and $p_c$ according to the pod speed. The predicted values (theory) are shown only for the regimes in which prediction is possible. The black dotted line indicates the boundary of each regime.

Fig. 22. Propagation speed of the pressure waves according to the pod speed. The predicted values (theory) are shown only for the regimes in which prediction is possible. The black-dotted line indicates the boundary of each regime. The blue-dotted line indicates the speed of sound at 300 K.

Fig. 23. Average pressure acting on the pod nose and tail along the axial direction according to the pod speed. The predicted values (theory) are shown only for the regimes in which prediction is possible. The black dotted line indicates the boundary of each regime.

Fig. 24. (a) Drag ratio and (b) drag according to the pod speed. The black dotted line indicates the boundary of each regime. In (b), the predicted (theoretical) values are shown only for the regime in which prediction is possible. The theoretical total and frictional drag were calculated based on the drag ratio presented in (a).
ing the aerodynamic drag and the properties of the pressure waves without simulations and experiments can be immensely beneficial.

7. Limitations

In the simulations, the idealized pod and tube shapes were designed to focus on the general mechanics. In the future, simulations for designs with greater complexity could contribute significantly to the development of the Hyperloop system. Furthermore, in the theoretical consideration, Eqs. (13) and (19) were derived based on the idealized shape of the pod. Although Eqs. (13) and (19) cannot be applied for other shapes of the pod, these equations can be easily modified from the pressure coefficient for a specific geometry from the theoretical consideration procedure presented in this paper. Additionally, the choked flow at the throat and fully accelerated flow through the divergent section were assumed. These assumptions limit the regimes in which the pressure waves and aerodynamic drag of the pod can be predicted. However, because the Hyperloop system is designed for transonic speed, the applied assumptions are reasonable, and the theoretical prediction is applicable to the Hyperloop system. Finally, the lack of consideration of the boundary layer in the prediction demonstrates the difference between the prediction and simulation. Thus, in the future, considering the boundary layer in the theoretical calculation can improve the accuracy of the prediction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ast.2021.106970.

References


