Numerical study on the influence of the nose and tail shape on the aerodynamic characteristics of a Hyperloop pod

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A B S T R A C T

The Hyperloop has been proposed as a high-speed vactrain system for freight and passenger transport. Given that the Hyperloop aims to operate at subsonic to supersonic speeds, the aerodynamic environment within the tube needs to be carefully considered. The shape of a pod is also very important with regard to reduction of aerodynamic drag and lift. Therefore, this study investigates the influence of the nose and tail shape of a Hyperloop pod on its aerodynamic drag, lift, and pitching moment by comparing five pod shapes: symmetrical, downward nose–upward tail (NdTu), upward nose–upward tail (NuTu), downward nose–downward tail (NdTd), and upward nose–downward tail (NuTd). Six pod speeds from 100 to 350 m/s at 50-m/s intervals are simulated under steady-state conditions and the shear-stress transport k-ω model. The shape of the nose and tail has only a slight effect on aerodynamic drag, with minor differences in drag acting on NdTu, NuTu, NdTd, and NuTd. The symmetrical design producing a drag that is 10.7% lower than that of the other designs at a pod speed of 350 m/s. In contrast, aerodynamic lift strongly varies with a change in the shape of the nose and tail, especially for pod speeds of 250 to 350 m/s. A downward tail produces positive lift, while an upward tail experiences negative lift. The lift acting on the tail of the pod accounted for more than 90% of the total lift. Additionally, the upward nose of the pod also produce negative lift. Based on these results, pod designs with an upward nose and tail should be avoided. The results of this study thus provide useful guidelines for the design of pods for the Hyperloop.

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1. Introduction

Over a century ago, American engineer Robert Goddard proposed the concept of the vac-train, in which a train travels in a vacuum through a tube or sealed tunnel, allowing it to reach speeds in the supersonic range (i.e., Mach number > 1). Similar concepts with different designs were proposed in the years that followed, but it was when Elon Musk – co-founder of Telsa and SpaceX – published his Hyperloop Alpha white paper in 2013 [1] that the idea of the vacuum train gained global attention. Musk’s concept has been supported and subsequently improved by various researchers.

The operating principle of the Hyperloop system is based on the evacuated tube transportation (ETT) system that was proposed in a patent by Daryl Oster in 1997 [2], which features a magnetically levitated (maglev) high-speed train that can travel at the speeds up to supersonic speeds in a near-vacuum tube. The Hyperloop system has been theorized to consume less energy than aircraft or traditional high-speed trains without generating carbon dioxide or noise. Therefore, the Hyperloop system is regarded as an eco-friendly passenger transportation method that is currently undergoing trials led by companies and researchers for potential commercialization. If these trains are used for public transportation, travel speeds 3–4 times faster than those of traditional high-speed trains can be achieved while...
reducing travel times 5–6-fold. For example, a one-way trip from Los Angeles to San Francisco, which normally takes 2.5 hours, could be completed in only 35 minutes with the Hyperloop system [1,3].

In the Hyperloop Alpha document, Musk and his team proposed it as the fifth form of passenger transportation after planes, trains, cars, and boats [1]. However, as a new mode of transportation, the Hyperloop system faces many challenges before it can be put into commercial operation. Because it runs in a very low-pressure tube at very high speeds (the target speed is 1250 km/h), the aerodynamic characteristics of the system are very complex, especially the pressure waves [4–8] and aerothermal effects [9–11]. At the front of a pod, a compression wave accumulates and develops into a normal shockwave, creating a high-pressure region, while an expansion wave leads to a region of low pressure behind the pod. Due to running at subsonic (or even supersonic) speeds, the flow can accelerate to sonic speed along the bypass area (i.e., the gap between the pod and the tube walls), inducing choking. In addition, due to the restriction of the tube walls, the reflection of the shockwave behind the pod becomes more complex. This flow behavior strongly affects the aerodynamic drag, which is a crucial factor for high-speed objects. In recent years, many studies have been conducted to investigate the factors impacting aerodynamic drag in the Hyperloop system and evacuated maglev tube trains. It has been reported that aerodynamic drag increases with the square of the pod speed [8,12–15], blockage ratio (BR, the ratio between the cross-sectional area of the pod and tube; $BR = A_{pod}/A_{tube}$) [12–16], and tube pressure [12,17,18], while the effect of tube temperature and pod length is weak [12]. In addition, the drag coefficient increases and reaches a peak at a pod speed of 225 m/s for a BR of 0.36 before decreasing; for a smaller BR (0.25), the maximum drag coefficient occurs at 250 m/s [8,13].

The shape of the pod is also very important. Since Musk introduced his idea of the Hyperloop system, many companies have attempted to develop this idea. As such, many different designs of the pod have been proposed to optimize the performance of the Hyperloop system. However, the optimal shape for the Hyperloop pod has not yet been identified. Nick and Sato [19] compared the aerodynamic characteristics of two models—short and optimized—to determine the best pod shape for drag reduction. Their optimized design exhibited 24% lower pressure drag compared with the short design. In addition, Gillani et al. [5] indicated that an elliptical shape for the tail and nose of a pod can efficiently reduce aerodynamic drag, while Yang et al. [20] controlled the shape of the nose model achieving a drag reduction of 5.52%. Chen et al. [16] investigated different streamlined designs of head and tail trains; they found that the shape of the head train did not affect the aerodynamic drag, while the shape of the tail had a significant effect. Choi and Kim [21] reported that thickening the nose reduced the aerodynamic drag significantly; for a train running at 200 km/h, a streamlined nose 10 m long reduced drag by 50% compared with a blunt nose with a length of 0.5 m. They also noted that, when the nose length increased to more than 5 m, the reduction in aerodynamic drag was slight.

However, these studies only considered speeds that are lower than the average speed of the Hyperloop system [19–21], only considered the shape of the nose and tail with the same direction, or did not consider the variation in aerodynamic lift. Although the Hyperloop system is based on magnetic levitation, the variation in lift should not be neglected, with higher lift able to support the levitation process. To the best of our knowledge, no previous studies have analyzed the effects of pod design on lift. Therefore, the results of this study will be helpful to readers who have an interest in lift variation.

2. Material and methods

2.1. Numerical analysis

Commercial CFD software ANSYS Fluent with a density-based solver is used to solve the governing continuity, Navier–Stokes, and energy equations, which describe the conservation of mass, momentum, and energy, respectively:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0
\]  

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\rho u_i u_j') \]  

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

\]

\[i, j, k = 1, 2, 3\]

where $\rho$, $u$, $P$, $T$, and $\mu$ are the fluid density, velocity, pressure, temperature, and viscosity, respectively. $E$ is the specific internal energy, and $k_{\text{eff}}$ and $\mu_{\text{eff}}$ are the effective thermal conductivity and dynamic viscosity, respectively.

In this study, the air is assumed to be compressible, viscous, and an ideal gas. The air density thus obeys the ideal gas law as follows:

\[
\rho = \frac{p}{RT}
\]

where $R = 287.058$ J/kg·K is the individual gas constant, and $p$ and $T$ are the pressure and temperature of air, respectively.

Given that viscosity only changes with temperature, the Sutherland model is applied, and the simulations are performed under steady-state conditions. In general, when the pod moves through the tube, compression and expansion waves are generated in front of and behind the pod, respectively. The calculation of these waves is dependent on time. Therefore, it requires an unsteady calculation. However, in this paper, wave propagation is excluded to focus on the variation in aerodynamic forces. In addition, the flow around the pod is considered to be steady over time, so the pressure difference between the nose and tail of the pod and the aerodynamic drag can be calculated [8,13,22]. Because our study focuses only on aerodynamic drag and lift, a steady-state simulation is applicable, as illustrated by previous studies that have also employed steady-state simulations [5,12,13,17,19,22,23].

In this study, the flow is fully turbulent because the Reynolds number is much higher than 2000. The Reynolds number is defined as $Re = (\rho v d_0)/\mu$, where $\rho$, $v$, and $\mu$ are the air density, pod speed, and air viscosity, respectively. $d_0$ is the hydraulic diameter, which is determined by $d_{\text{tube}} - d_{\text{pod}} = 2$ m. In this study, the Reynolds number for pod speeds of 100 to 350 m/s is
\[
[\min (Re) : \max (Re)] = \left[ \frac{\rho \min (v) d_h}{\mu}, \frac{\rho \max (v) d_h}{\mu} \right] = [12, 752; 44, 632]
\] (5)

Because the flow is fully turbulent, a suitable turbulent model should be employed. Direct numerical simulation and large eddy simulation can effectively analyze complex turbulent structures, but these are computationally expensive [24–27]. The Reynolds-averaged Navier-Stokes (RANS) equations have a lower computational cost while still providing effective numerical analysis [28–30]. Niu et al. [31] compared various turbulent models used for simulating tube-train system (RANS SST k-ω, DDES Realizable k-ε, DDES SST k-ω, and DDES Spalart-Allmaras) and found that there was little difference (i.e., < 1%) between these models. Similarly, Kim et al. [17] found a difference of less than 2% between RANS SST k-ω, k-ε, and Spalart-Allmaras. A wind turbine test with different turbulent models was conducted by Muiruri et al. [32], and they concluded that SST k-ω was the most suitable model for the analysis of wind turbines and their pressure distribution. Thus, the RANS SST k-ω turbulent model is employed in this study. This model combines the advantages of the standard k-ε and k-ω models, which can enhance the predictability and accuracy of transonic shockwave analysis, and has been used in many previous studies for high-speed objects [11,33–37]. The SST k-ω model is structured as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = P_K - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right]
\] (6)

\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu} P_K - \beta^* \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + 2 \rho (1 - F_1) \frac{1}{\sigma_{\omega,2}} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}
\] (7)

where

\[
P_K = \tau_{ij} \frac{\partial u_i}{\partial x_j},
\] (8)

\[
\tau_{ij} = 2 \mu_t S_{ij} - \frac{2}{3} \rho \delta_{ij}
\] (9)

with \(\tau_{ij}\) denoting the Reynolds stress (\(\text{kgm}^{-1}\text{s}^{-2}\)), \(S_{ij}\) the mean deformation rate component (\(\text{s}^{-1}\)), and \(\delta_{ij}\) the Kronecker delta function.

\[
F_1 = \tanh \left\{ \min \left[ \max \left( \frac{\sqrt{K}}{\beta^* \omega y}, \frac{500 \mu}{\gamma \sigma_{\omega,2} k} \right), \frac{4 \rho \sigma_{\omega,2} k}{CD_{\omega,2} \gamma^2} \right] \right\},
\] (10)

\[
CD_{\omega,2} = \max \left( \frac{2 \rho}{\sigma_{\omega,2}}, \frac{1}{\omega} \frac{\partial \omega}{\partial x_j} \frac{\partial k}{\partial x_j} \cdot 10^{-10} \right).
\] (11)

\[
\sigma_k = \frac{1}{F_1/\sigma_k,1 + \frac{1}{\sigma_{\omega,2}}},
\] (12)

\[
\sigma_\omega = \frac{1}{F_1/\sigma_{\omega,1} + \frac{1}{\sigma_{\omega,2}}}
\] (13)

\(\sigma_k\) and \(\sigma_\omega\) are the turbulent Prandtl numbers for \(k\) and \(\omega\), respectively. \(\mu_t\) (\(\text{kg/ms}\)) is the turbulence viscosity, which is calculated as follows:

\[
\frac{1}{\rho} \frac{\partial \mu_t}{\partial x_j} = \frac{a_1 k}{\max (a_1 \omega, SF_2)},
\] (14)

\[
F_2 = \tanh \left( \max \left( \frac{2 \sqrt{K}}{\beta^* \omega y}, \frac{500 \mu}{\gamma^2 \omega \rho} \right)^2 \right).
\] (15)

In Eq. (14), the term \(S = (2S_{ij} S_{ij})^{1/2}\) is an invariant measure of the strain rate, and \(a_1\) is a constant equal to 0.31. The other constant values in the above equations are as follows:

\[
\beta^* = 0.09,
\]

\[
\sigma_{k,1} = 1.176, \quad \sigma_{k,2} = 1.0,
\]

\[
\sigma_{\omega,1} = 2.0, \quad \sigma_{\omega,2} = 1.168.
\]

In terms of the other simulation setup, the Roe’s flux difference splitting scheme is chosen to a convective flux type, the least-squared cell-based gradient method is employed, and the flow, turbulent kinetic energy, and specific dissipation rate are discretized using the second-order upwind scheme. For initialization, the pressure and temperature are set at 101.325 Pa and 300 K, respectively. The x-velocity is adjusted to have the same value as the inlet velocity.
Fig. 1. Geometry used for the simulations: (a) Side views of the five cases. The reference design is symmetrical in both the height and width directions (i.e., in the y- and z-directions). The other cases investigate the effect of the nose and tail design on the aerodynamic characteristics. Nₜ/Tₜ and Nₙ/Tₙ refer to the position of the nose and tail of the pod: N = nose, T = tail, d = downward, and u = upward. (b) Iso view of the nose and tail for different pod shapes. (c) Iso view of the geometry of NₜTₜ. This model is based on the model of the Hyperloop available on the Hyperloop Transportation Technologies website (https://www.hyperlooptt.com/).

Fig. 2. Computational domain for NₜTₜ: (a) side view, (b) top view, and (c) rear view. The pod is placed in the middle of the tube. The other cases have the same design parameters except for the shape of the nose and tail.

2.2. Computational domain

In this study, we investigate the effect of different pod shapes on the aerodynamic characteristics of the Hyperloop system. Fig. 1a presents the five cases investigated in this study. The reference design has a symmetrical nose and tail. NₜNₙ has a downward nose and an upward tail, while NₙTₙ has an upward nose and an upward tail. In contrast, NₜTₙ has a downward nose and a downward tail, while NₙTₙ has an upward nose and a downward tail. Fig. 1b presents a 3D view of the symmetrical, upward, and downward noses and tails. NₜTₙ, shown in Fig. 1c, is based on the design produced by Hyperloop Transportation Technologies (https://www.hyperlooptt.com/). The other cases are based on variations of this model. In this study, we assume that the pod surface is smooth, so components of a typical pod, such as the brakes, windows, and doors, are excluded from consideration in the model. The use of a compressor is also not considered in this study.

Fig. 2 presents the computational geometry of the pod and tube used for the simulations. The pod is placed in the middle of the tube. The pod length is fixed at \( L_{\text{pod}} = 43 \) m, with a nose length of 10.4 m and a tail length of 6.9 m. The height \( h_{\text{pod}} \) and width \( w_{\text{pod}} \) of
the pod are both set at 3 m. Because the BR is fixed at 0.36 in this study, the diameter of the tube is 5 m. The total tube length is 258 m. The distance from the nose of the pod to the inlet is $2L_{pod} = 86$ m (or $28.67h_{pod}$), while the distance from the tail to the outlet is $3L_{pod} = 129$ m ($43h_{pod}$). These distances are considered suitable for the purposes of this study. Nick et al. [19] used $1.13L_{pod}$ and $2.47L_{pod}$ as the upstream and downstream distances, respectively, while smaller upstream and downstream distances also were used in Zhang et al. [38] ($1.27L_{pod}$ and $2.35L_{pod}$ for upstream and downstream, respectively). Gillani et al. [5] used upstream and downstream distances of $2L_{pod}$, while Li et al. [39] used $1.62L_{pod}$ and $3.72L_{pod}$. These distances are shorter or similar to our parameters.

2.3. Computational mesh

ANSYS ICEM with hexahedral mesh is used for the 3D model (Fig. 3). Ogrid mesh is employed along the tube and pod wall to ensure that the mesh is fine enough to maintain a $y^+$ that is below 1. This also provides meshing along the curve that can adapt to the curved shape of the pod. The first cell heights from the pod and tube wall are fixed at 0.05 mm for all cases.

A grid independence test is conducted using the reference case (Table 1). Coarse (5,216,048 nodes), medium (7,870,336 nodes), and fine (10,620,585 nodes) meshes are compared in terms of aerodynamic drag. The difference in drag between the coarse and medium meshes is 2.09%, while the difference between the medium and fine meshes is 0.77%. Fig. 4 presents the pressure distribution along the tube at $y = 2$ m, showing that the difference between the medium and fine meshes is slight. Hence, the medium mesh is used in the model for all of the cases. The averaged $y^+$ value obtained for the pod and tube walls is 0.41 and 0.24, respectively.

2.4. Boundary conditions

Fig. 5 presents the boundary conditions used for the simulations. For the inlet, a pressure far-field boundary condition with a Mach number designed for pod speeds of 100 to 350 m/s at 50-m/s intervals and a pressure of 101.325 Pa (1/1000 atm) is applied. Under an isentropic assumption, the speed of sound is calculated as $c = \sqrt{\gamma RT}$, where $\gamma = 1.4$ is the ratio of specific heat, $R = 287.058$ [J/kg·K] is the individual gas constant, and $T$ is the flow temperature. The resulting Mach numbers are 0.2881, 0.4321, 0.5762, 0.7203, 0.8643, and

| Grid independence test for three different meshes. Medium mesh is chosen as the final mesh. |

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Number of nodes</th>
<th>Drag (N)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>5,216,048</td>
<td>992.87</td>
<td>2.09</td>
</tr>
<tr>
<td>Medium</td>
<td>7,870,336</td>
<td>972.08</td>
<td>0.77</td>
</tr>
<tr>
<td>Fine</td>
<td>10,620,585</td>
<td>964.53</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Computational mesh for the reference case. (a) Side view showing the mesh on the pod surface and the symmetric plane. (b) Rear view showing the mesh on the sectional plane in the middle of the pod, indicated by the red line in figure (a). The mesh in this figure is scaled down 5 times compared with the original. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)
1.008 for speeds of 100, 150, 200, 250, 300, and 350 m/s, respectively. For the outlet, a pressure outlet set at 101.325 Pa is adopted. The reference frame moves with the pod; hence, the wall is set to move at the same speed as the inlet flow. Due to the symmetrical width (z-direction), only half of the model is simulated to reduce computational costs and time.

2.5. Evaluation factors

For most objects examined in relation to the motion of a fluid, drag is considered the most crucial fluid force. The reduction of aerodynamic drag is vital for high-speed trains, especially for pod-tube systems where space limitations can increase drag. In addition, although the pod moves using proprietary magnetic levitation and propulsion, the aerodynamic lift caused by the pod shape contributes significantly to the lifting of the pod. Hence, the main objective of this paper is to investigate the effect of various pod shapes on aerodynamic drag and lift. The change in drag and lift is proportional to the square of the speed, as shown in Eqs. (16)–(17):

$$F_D = \frac{1}{2} C_D \rho v^2 A$$

(16)

$$F_L = \frac{1}{2} C_L \rho v^2 A$$

(17)

where $F_D$, $C_D$, $F_L$, and $C_L$ are the drag force, drag coefficient, lift force, and lift coefficient, respectively. $\rho$ is the air density, $v$ is the pod speed, and $A$ is the cross-sectional surface.

Fluid forces also generate moments that cause the body to rotate. The moment about the drag direction is known as the rolling moment, the moment about the lift direction is the yawing moment, and the moment about the side force is the pitching moment. For bodies that are symmetrical about the lift–drag plane, such as cars, airplanes, ships and the proposed Hyperloop system, the side force and the yawing and rolling moments are zero when the angle of attack of the flow is zero. Thus, drag, lift, and the pitching moment are the forces of interest in our model. The following equations are used to determine the force and moment vectors:

$$F = \int_{\text{surface}} \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \, dA = \begin{bmatrix} F_D \\ F_L \\ 0 \end{bmatrix}$$

(18)

$$M = \int_{\text{surface}} \begin{bmatrix} yf_x - zf_y \\ zf_x - zf_z \\ xf_y - yf_x \end{bmatrix} \, dA = \begin{bmatrix} 0 \\ 0 \\ M_z \end{bmatrix}$$

(19)
Fig. 6. Mach number distribution for the reference design with respect to the pod speed. Pod speeds of 100 and 150 m/s fall within Regime 1, in which the local Mach number for the flow (M) is below the actual critical Mach number (M_{cr, ac} = 0.52) and there is no shockwave. A pod speed of 200 m/s falls under Regime 2, in which M is higher than M_{cr, ac} but the flow does not fully accelerate: a shockwave occurs within the divergent section, but the effect of the shockwave is minor. Pod speeds of 250 to 350 m/s fall under Regime 3, in which the flow fully accelerates within the divergent section, and an oblique shockwave is distinguishable behind the pod. The Mach number is obtained from the line along the tube, with y = 2 m and z = 0 m.

3. Results & discussion

3.1. Flow in the Hyperloop system

The Hyperloop system exhibits three flow regimes with different flow behaviors [7]. In the present study, the variation in drag and lift, and thus the pitching moment, is investigated in accordance with these three regimes. It is worth noting that, similar to a converging–diverging nozzle, the flow around a Hyperloop pod also exhibits convergent (at the nose of the pod) and divergent (at the tail of the pod) regions. Under choking conditions, the Mach number for the flow in front of and behind the nose and tail, respectively, of the pod can be calculated using the following equation:

\[
\frac{A_{\text{tube}}}{A_{\text{pod}}} = \frac{1}{M} \left\{ \frac{1 + [(\gamma - 1)/2]M^2}{1 + [(\gamma - 1)/2]} \right\}^{\frac{\gamma + 1}{\gamma - 1}}
\]  

where \(A_{\text{tube}}\) and \(A_{\text{pod}}\) are the cross-sections of the tube and pod, respectively, and \(M\) is the Mach number of the flow.

Eq. (20) is also widely used to calculate the critical Mach number (M_{cr}) under an isentropic assumption. When the BR is 0.36, M_{cr} = 0.41. However, previous studies [7,12] have reported that the actual M_{cr} occurs at a pod speed of 180 m/s (M_{cr, ac} = 0.52) for a BR of 0.36, which is higher than the M_{cr} calculated using a one-dimensional isentropic assumption. In addition, the term M in Eq. (20) can have two solutions – one in the subsonic and one in the supersonic range. The subsonic solution is obtained from the M of the flow immediately before the pod nose, which is also known as M_{cr}, while the supersonic solution is the M of the flow immediately behind the pod tail. In this situation, three regimes are observed depending on the speed of the pod. In Regime 1 (100 m/s to 170 m/s), in which the pod speed is lower than M_{cr, ac} and the flow is subsonic, there is no shockwave behind the pod. In Regime 2 (180 m/s to 230 m/s), the pod speed reaches M_{cr, ac} but the flow does not fully accelerate (i.e., the local Mach number for flow M does not reach the supersonic solution presented in Eq. (3)) and the shockwave occurs within the divergent section. In Regime 3 (240 m/s to 350 m/s), the flow fully accelerates (i.e., M reaches the supersonic solution shown in Eq. (20)), and the presence of a shockwave can be clearly observed. More details are available in [7].

Although this regime classification is based on 2D axisymmetric conditions and a semicircular pod shape, it remains valid for use in our study. Classifying the three regimes provides a clearer understanding of the effect of the pod shape on the aerodynamic characteristics of the Hyperloop system, especially the variation in the lift force, as discussed in Section 3.3. However, because more complicated shapes are employed in this study, the flow in this study is a little different.

Fig. 6 presents the Mach number distribution along the tube with respect to the pod speed for the reference design. In our study, six pod speeds are used for the simulations. Thus, Regime 1 covers the pod speeds of 100 and 150 m/s, Regime 2 covers 200 m/s, and Regime 3 covers 250, 300, and 350 m/s. At a pod speed of 250 m/s, although the flow is fully accelerated within the divergent section, the local Mach number of the flow does not reach the supersonic solution for M in Eq. (20). This may be because of the shape of the tail or a limitation of steady-state simulations.

3.2. Effect on aerodynamic drag

Fig. 7 presents the effect of pod speed and nose/tail shape on aerodynamic drag. Drag increases significantly with an increase in the pod speed, while pod shape has little effect on drag. These results are in good agreement with previous research [16]. The symmetrical design has the lowest drag at all pod speeds, though this difference is only clearly observed at pod speeds higher than M_{cr, ac} or when choking occurs. At a pod speed of 350 m/s, the difference between the reference case and N_{ref} (which is the highest drag) is 10.7%.
Aerodynamic drag consists of friction and pressure drag as follows:

\[ F_D = F_{DF} + F_{DP} \]  

where \( F_{DF} \) is friction drag, which is directly due to wall shear stress acting on the body, while \( F_{DP} \) is pressure drag.

Many previous studies have shown that pressure drag is a major factor in the Hyperloop system, while the contribution of friction drag is very low. Le et al. [8], Oh et al. [12], and Kang et al. [13] have all reported that friction drag is responsible for less than 10% of overall aerodynamic drag. Pressure drag can be calculated using \( F_{DP} = \Delta P A \), where \( \Delta P \) is the pressure difference between the nose and the tail of the pod, and \( A \) is the maximum cross-sectional area, which is constant for the five cases in the present study. Therefore, the variation in drag is mostly affected by \( \Delta P \). As shown in Fig. 8, there is no major difference in \( \Delta P \), which is why there is no significant difference in drag between the cases.

3.3. Effect on aerodynamic lift

The pressure difference between the top and bottom surfaces of an object generates lift. In the Hyperloop system, aerodynamic lift is necessary to lift the pod in conjunction with the levitation of the magnetic field. Unlike drag, the shape of the nose and tail strongly affect the lift, especially in Regime 3. Fig. 9a presents the variation in lift due to changes in the pod speed. Because the reference case is symmetric along both the \( x-y \) and \( x-z \) planes (i.e., the width and height directions), there is no lift due to the lack of a difference in pressure between the upper and lower surfaces of the pod. The variation in the pitching moment is also presented in Fig. 9b. As mentioned above, our Hyperloop model is symmetric in the \( x-y \) plane; therefore, only the pitching moment is observed in this study.
As discussed in Section 3.2, the differences in drag between the five cases are low. Thus, the variation in the moment is similar to the variation in the lift. The next two paragraphs will explain the variation of lift according to three regimes.

3.3.1. Aerodynamic lift for Regimes 1 and 2 (pod speeds of 100 to 200 m/s)

For Regimes 1 and 2, lift is negligible. In these two regimes, an upward pod tail leads to positive lift, while a downward tail leads to negative lift. This is due to the change in the area between the pod and the tube, with the separation of the flow occurring at the end of the tail, reducing the velocity (Fig. 10a) and increasing the pressure in the separation area. With an upward tail, the lower surface of the pod has a larger change in area compared with the upper surface. This results in a higher pressure on the lower surface, thus lifting the pod. In contrast, with a downward tail, the opposite behavior is observed, with negative lift generated. However, the lift in these two regimes is very low when compared with Regime 3.

3.3.2. Aerodynamic lift for Regime 3 (pod speeds of 250 to 350 m/s)

For Regime 3 (i.e., pod speeds of 250, 300, and 350 m/s), a trend opposite to that for Regimes 1 and 2 is observed. An upward tail produces negative drag, whereas a downward tail leads to positive drag. This is because of the fully accelerated flow within the divergent section, which pushes the oblique shockwave to behind the pod, increasing the pressure difference between the upper and lower pod surfaces. The two types of tail design also lead to differences in the pattern of the oblique shockwave, as shown in Fig. 10b.

To clarify these observations, Fig. 11 presents the average pressure on the upper and lower surfaces of the nose and tail of the pod for $N_dT_d$ and $N_dT_d$ with respect to the pod speed. There is no difference in the nose pressure, whereas the tail pressure exhibits a noticeable difference in Regime 3. Thus, as expected, the variation in the lift is strongly dependent on the shape of the tail. Note that $N_dT_d$ and $N_dT_d$ demonstrate opposite trends, as shown in Figs. 11 and 12.

For $N_dT_d$, which has a downward tail, the pressure on the upper surface of the rear of the pod is lower than on the lower surface, resulting in positive lift acting on the pod. This is related to local area changes when choking occurs. As explained in Section 3.1, in Regime 3, the flow fully accelerates within the divergent section. With a downward tail, due to the smaller change in the area below the pod, the flow gradually accelerates between the pod and the tube wall (see Figs. 10b and 12b). In contrast, the local area increases quickly above the pod, causing the local velocity of the flow to also increase quickly, which results in lower pressures.

Note that, at the rear of the tail, the difference between the divergent section and the entire area of the tube is larger for the lower surface; thus, the highest Mach number occurs at the lower surface of the rear end of the pod. However, due to its location, its impact on lift is negligible.

3.3.3. Aerodynamic lift acting on the front and rear halves of the pod

As described in the previous section, lift varies according to the shape of the tail of the pod. As a comparison, Fig. 13 presents the variation in lift acting on the front and rear halves of the pod (the front and rear halves are illustrated in Fig. 1). The front of the pod
experiences much lower lift compared with the tail. For example, for $N_uT_u$ at a pod speed of 350 m/s, front lift accounts for only 4.6% of the total lift while, for $N_uT_d$, although the front lift is negative and the rear lift is positive, the ratio for the size of the two is approximately 9%, which means that the lift acting on the front half of the pod is much weaker than that on the rear half. This explains why the variation in lift is strongly affected by the shape of the tail.

It is interesting to note that, unlike the lift acting on the rear half of the pod (the variation in which is distinguishable in all three regimes), for the front half of the pod, regardless of the regime, an upward nose produces positive lift while a downward nose leads to negative lift. As the result, using both a downward tail and a downward nose (i.e., $N_dT_d$, in this study) creates positive lift, which could be beneficial for the Hyperloop system.

3.3.4. Lift-to-drag ratio

In Regime 3, despite the fully accelerated flow and oblique shockwave leading to significant variation in aerodynamic lift, this lift is very low due to the low-pressure conditions inside the tube. Fig. 14 displays the ratio of lift to drag. For a downward tail, this ratio increases with an increase in pod speed, but starts to level off when a pod speed of 250 m/s is reached (i.e., in Regime 3). For instance, the lift-to-drag ratio for $N_uT_d$ is 17.5% and 18.1% for pod speeds of 250 m/s and 350 m/s, respectively. In contrast, an upward tail for the pod decreases the ratio of lift to drag as the pod speed increases, becoming negative in Regime 3, which is of no benefit to the Hyperloop system. At a pod speed of 350 m/s, the lift-to-drag ratio is approximately −26.7% for $N_uT_u$. As a result, to achieve a more efficient Hyperloop system, the use of an upward tail should be avoided.

4. Conclusions

This study investigates the influence of the nose and tail shape of a Hyperloop pod on aerodynamic drag, lift, and pitching moment. Five different pod shapes are simulated under steady-state conditions and the SST k-ω turbulence model. Six pod speeds from 100 to 350 m/s at 50-m/s intervals are classified into three regimes: Regime 1 for pod speeds lower than the actual critical Mach number (i.e. 100 and 150 m/s), Regime 2 for pod speeds higher than the actual critical Mach number but where the flow does not fully accelerate within
the divergent section (i.e., 200 m/s), and Regime 3 for pod speeds of 250 to 350 m/s, where fully accelerated flow occurs and a strong oblique shockwave is observed.

The results of the present study can be summarized as follows:

1. Aerodynamic drag is not strongly affected by the shape of the nose or tail of the pod. The reference case has a drag that is 10.7% lower than the other cases in Regime 3. The drag acting on the other cases, i.e., $N_u$ and $N_d$, is similar.

2. Aerodynamic lift is strongly affected by the shape of the tail. For Regimes 1 and 2, an upward tail leads to positive lift, while a downward tail generates negative lift. The opposite trend is observed in Regime 3, where a downward tail produces positive lift and an upward tail generates negative lift.

3. In this study, due to the small difference in drag, the variation in the pitch moment is influenced by variation in the lift.

4. The total lift is mostly the result of the lift acting on the tail of the pod, with the lift acting on the nose of the pod accounting for less than 10% of the total lift. It is interesting to note that, unlike the lift acting on the rear half of the pod, which clearly varies between the three regimes, an upward nose produces positive lift and a downward nose produces negative lift for the front half of the pod regardless of the regime.

5. The lift-to-drag ratio increases with an increase in the pod speed and with a downward tail, whereas it decreases with an upward tail.

As a result, to harness the beneficial effects of lifting in a Hyperloop system, the use of an upward nose and tail for the pod should be avoided.

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Conceptualization, methodology, and investigation: T.T.G.L. and J.R.; writing – original draft preparation: T.T.G.L.; formal analysis, data curation, and visualization: T.T.G.L., K.S.J., and J.K.; writing – review and editing, supervision, project administration, and funding acquisition: K.S.L. and J.R. All authors have read and agreed to the published version of the manuscript.

**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.
Fig. 12. Mach number distribution behind the pod for (a) $N_u T_u$ and (b) $N_d T_d$, and the pressure distribution behind the pod for (c) $N_u T_u$ and (d) $N_d T_d$, at a pod speed of 350 m/s. Line 1 represents the black line ($y = 2$ m), Line 2 represents the red-dashed line ($y = 0$ m), and Line 3 represents the blue-dotted line ($y = -2$ m) in the contours. The contours show the side view of the Mach number and the pressure behind the pod. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Fig. 13. Lift acting on the (a) front and (b) rear halves of the pod. The front and rear halves are illustrated in Fig. 1.
Fig. 14. Lift-to-drag ratio ($F_L/F_D$) with respect to the pod speed. The ratio decreases with an upward tail and increases with a downward tail.

References


