Theoretical and numerical analysis of pressure waves and aerodynamic characteristics in Hyperloop system under cracked-tube conditions

Jihoon Kim, Kyeong Sik Jang, Thi Thanh Giang Le, Kwan-Sup Lee, Jaiyoung Ryu

A R T I C L E   I N F O

Article history:
Received 23 August 2021
Received in revised form 13 December 2021
Accepted 25 February 2022
Available online 3 March 2022
Communicated by Cheng Wang

Keywords:
Hyperloop system
Compressible flow
Aerodynamics
Shock wave
Underexpanded jet

A B S T R A C T

The Hyperloop system is a new transportation mode in which a maglev capsule travels in a confined sub-vacuum tube at transonic speed. If the sub-vacuum tube is cracked, supersonic flow is induced by the pressure difference with the atmosphere. This flow affects the traveling pod, and the Hyperloop system becomes unstable. In this study, we focused on pressure waves generated by a crack and a pod, and investigated the aerodynamic characteristics. The pressure magnitude and propagation speed of the normal shock wave and the drag were considered in a theoretical approach. In addition, numerical simulations for various crack widths and pod speeds were performed. A highly underexpanded jet develops owing to the crack, which results in a distinct Mach disk. As the crack width increases, a larger oblique shock cell structure is created. The leading shock wave generated in front of the Mach disk propagates as a normal shock wave. The propagation speed and pressure of the normal shock wave increase with increasing crack width. Moreover, the normal shock wave propagates in front of the nose, and the expansion wave propagates behind the tail owing to the pod movement. The drag increases rapidly as the normal shock wave caused by the crack reaches the pod. As the pod moves under the crack, the drag decreases and the negative lift steeply increases owing to the downward flow. The pressure of the normal shock wave and the aerodynamic drag were predicted with the theoretical approach; the predictions agree well with the simulation results.

© 2022 Published by Elsevier Masson SAS.

1. Introduction

Technological innovations in transportation have led to savings in time and energy. Among these technological advances, the concept of an evacuated tube transport (ETT) system was proposed by Oster [1]. The ETT system has numerous advantages over conventional railways, e.g., its high speed, low noise, and low operating cost [2,3]. In 2013, Elon musk introduced a tube-train system (i.e., “the Hyperloop system”) based on the ETT system [4]. The basic idea of the Hyperloop system is the transport of a maglev pressurized capsule (i.e., a pod) at a target speed of 1250 km/h in a sub-vacuum tube.

Shock waves of compressible flow phenomena and aerodynamic drag are critical issues when an object moves at supersonic speed. In open space, shock wave and aerodynamic characteristics have been studied in the presence of a counter-flow jet in blunt bodies for drag reduction [5,6]. Hermes et al. [7] studied the unsteady shock wave phenomena of transonic flow of an airfoil.

When the object moves at high speed in a confined tube, choking, compression wave, expansion wave, and oblique shock wave are generated, which propagate through the tube. These waves change the flow field around the object and affect the aerodynamic drag. Hruschka and Klatt [8] studied the aerodynamic characteristics of a projectile in a pipe with experiments, simulations, and theoretical considerations. They theoretically predicted the magnitude of shock waves and the drag on the projectile in the pipe and compared the predictions with the simulation and experimental results. Zhou et al. [9] studied the generation and development of pressure waves in a high-speed evacuated tube maglev train. They observed the formation of a bow shock wave and a normal shock wave in the head and an expansion wave in the tail owing to the train movement. Le et al. [10] performed unsteady-state simulations for a large parametric space. They discovered that compression waves propagate as normal shock waves, thereby obeying the normal shock relations. Jang et al. [11] studied com-
pressible flow phenomena in the Hyperloop system with theory and simulations. They concluded that the characteristics of shock waves and aerodynamic drag at a specific transonic speed of the pod, tube pressure, temperature, and blockage ratio (i.e., the ratio of the cross-sectional area of the pod to the cross-sectional area of the tube) can be predicted with a theoretical approach. Moreover, an optimized design for aerodynamic drag was analyzed according to different pod shapes in a confined tube [12–16]. Other researchers have analyzed the flow phenomena and aerodynamic characteristics with respect to the pod speed and the effects of the blockage ratio on the aerodynamics [17–21]. Accordingly, the drag is greater at a higher pod speed and blockage ratio. The aerodynamic drag proportionally increases with the tube pressure, while the drag slightly increases with the tube temperature [22–24]. Niu et al. [25] studied the aerodynamic drag and effect on the flow fields and heat transfer when the pod is accelerating.

When the tube surface cracks, a high-speed flow immediately enters the tube owing to the extreme pressure difference between the atmosphere (1 atm) and tube (1/1000 atm); this flow is expected to affect the aerodynamic characteristics in the Hyperloop system. Subsequently, the flow expands in the tube and forms a jet with shock waves. The general phenomena of the jet and shock waves have been analyzed theoretically [26] and with numerical simulations [27,28]. As the fluid flows through the jet nozzle and becomes choked, the sonic flow accelerates and becomes a supersonic flow with decreasing pressure. If the exit pressure exceeds the ambient pressure, an underexpanded jet is formed. Franquet et al. [29] presented schematics of moderately and highly underexpanded jets; Fig. 1 illustrates the latter. When the ambient-to-total pressure ratio is 7 or higher, a highly underexpanded jet is developed; many researchers have studied highly underexpanded jets [30–34]. Once the underexpanded jet has developed, the Mach number increases, and the static pressure, temperature, and density decrease. The compression waves are generated and combined into one wave, which is called “intercepting oblique shock” or “barrel shock”, as shown in Fig. 1. The intercepting oblique shock is reflected at a specific point and forms a reflected oblique shock and Mach disk. Radulescu et al. [35] performed numerical simulations of unsteady highly underexpanded jets and analyzed the shock wave formation in the initial transient phase. They observed the generation of a leading shock wave that propagated in front of the Mach disk.

The aims of this study were to investigate pressure waves due to the crack and pod movement, and the aerodynamic characteristics of the Hyperloop system under cracked-tube conditions with computational fluid dynamics (CFD). Moreover, theoretical analysis was performed with the normal shock relations and compressible Bernoulli equation for isentropic flow. The remainder of the paper is organized as follows: In Section 2, the theoretical approach based on gas dynamics is presented. In Section 3, the numerical method is explained. Section 4 presents the results and discussion of the pressure waves and aerodynamic characteristics. Finally, the conclusions of the study are presented in Section 5.
2. Theoretical approach

In the theoretical part of this work, the shock wave and aerodynamic drag due to the crack and pod movement were considered by assuming a quasi-one-dimensional flow. This assumption is reasonable for the main flow fields [36–38]. Moreover, absolute, shock-relative, and pod-relative coordinate systems were considered in the theoretical approach. In the absolute coordinate system, both the shock wave and pod move with respect to the observer. In the shock-relative coordinate system, the moving normal shock wave is considered a stationary normal shock wave with respect to the observer. The pod-relative coordinate system assumes that the pod is stationary and that the surrounding flow moves at the pod speed.

2.1. Shock wave dynamics

In previous studies of the tunnel–train system, the generation of a normal shock wave has been analyzed when the train moves at subsonic speed in the tunnel [39,40]. In the Hyperloop system, a normal shock wave is created when the pod travels at subsonic speed in the tube because the air is compressed in front of the pod, which generates compression waves. Fig. 2 presents the propagating compression waves in the open space and confined space at t = 3 s [41–43]. The compression waves emitted at t = 0, 1, and 2 s propagate with the distance of 3c, 2c, and c from the wave source, respectively. Here, c is the speed of sound which is defined as $\sqrt{\gamma RT}$ under isentropic flow and ideal gas conditions. When the object moves at subsonic speed in the open space, the compression wave propagates in all directions with respect to time. Thus, the compression waves rapidly dissipate owing to the energy loss as the wave propagates. On the contrary, when the object moves at subsonic speed in the confined space, the compression wave is restricted by the tube wall. In other words, the compression wave propagates along the axial direction of the confined area in the tube. These physics result in a slight energy loss of the compression wave such that it does not dissipate in the confined space. When the compression wave propagates in the confined space (as shown in Fig. 2(b) and (c)), a shock wave is generated owing to this characteristic [43]. The pressure distribution of the compression wave has a gradual profile. In the pressure profile for c, the local quantities such as the pressure, density, and temperature are different. The higher temperature occurs at the higher pressure such that the local speed of sound is highest at the local maximum temperature. Owing to these characteristics, the pressure profiles of the compression waves emitted at $t = 0$ and $1 \, \text{s}$ are gradually steepened, and a shock wave is developed with a rapidly change in the characteristics across the wave. The generation of the shock wave in the confined space at subsonic speed was observed in the study of a moving projectile [8] and the Hyperloop system [11,44]. Thus, our theoretical approach assumes that a shock wave is generated in the tube, although the pod moves at subsonic speed.

Fig. 3 shows the propagation of the waves as the pod approaches the crack and the local points for the theoretical calculations. The leading shock wave generated owing to the crack is expected to propagate as a normal shock wave in the confined tube. The pod movement creates a high-pressure field at the nose and a low-pressure field at the tail. The high- and low-pressure waves propagate as compression and expansion waves, respectively. Furthermore, the waves generated by the crack and pod movement are expected to affect the aerodynamics after their interaction. The normal shock wave relations for theoretically determining the characteristics of a shock wave are as follows [41]:

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

$$\rho_b = \frac{M_a^2}{\gamma - 1} + 2,$$

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

$$v_b = \sqrt{\frac{\gamma - 1}{2\gamma} M_a^2 + \frac{2\gamma M_a^2 - (\gamma - 1)}{\gamma - 1} \sqrt{\gamma RT_b}},$$

with
The area in normal wave

\[ M_a = \frac{v_a}{\sqrt{\gamma RT_a}}. \]

Here, the subscript \( a \) indicates the local quantities in front of the normal shock wave, and \( b \) indicates the local quantities behind the normal shock wave in the shock-relative coordinate system. \( M_a \) is the Mach number and \( v_a \) is the velocity in front of the normal shock wave in the shock-relative coordinate system.

Fig. 3(a) shows the normal shock waves generated by the crack (\( S_C \)) and pod (\( S_P \)) in unstirred waves; \( M_{a,C} \) is the Mach number in front of the \( S_C \) in the shock-relative coordinate system. The local quantities in \( \circ \) are the operating conditions, which are not subjected to the shock waves. Therefore, the local quantities in Eqs. (1)–(5) in \( \circ \) are functions of \( v_{a,C} \) that can be calculated with an additional condition. In this study, the additional condition includes the assumption that the mass flow rate at the crack is symmetrically distributed in the tube to focus on the fundamental physics of a perpendicular crack in the tube. The mass flow rate for compressible flow is expressed as follows:

\[ \dot{m} = \frac{P_t}{RT} \sqrt{\frac{\gamma}{R}} M \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{1}{2(\gamma - 1)}}, \]

where \( P_t \) is the total pressure, \( T_t \) the total temperature, \( \gamma = c_p/c_v \) the specific heat ratio, and \( R \) the individual gas constant. The flow was assumed to be choked (\( M=1 \)) in the cross-sectional area of the crack \( (A_C) \). Hence, the compressible mass flow rate at the crack \( (\dot{m}_C) \) is expressed as follows:

\[ \dot{m}_C = A_C \frac{P_t}{RT} \sqrt{\frac{\gamma}{R}} \left( \frac{\gamma + 1}{2} \right)^{-\frac{1}{2(\gamma - 1)}}. \]

The total pressure and total temperature were set to 1 atm and 300 K, respectively. The mass flow rate behind the \( S_C \) \( (\dot{m}_2 = \rho_2 v_2 A_t) \) was set to half \( \dot{m}_C \) based on the assumption. This can be expressed based on Eqs. (2), (4), (5), and (7):

\[ \frac{\dot{m}_C}{2} = \frac{\rho_2 v_2 A_t}{\gamma - 1} \frac{M_{a,C}^2}{(\gamma - 1) M_{a,C}^2 + 2} \times \left[ \frac{(\gamma - 1) M_{a,C}^2 + 2}{2\gamma M_{a,C}^2 - (\gamma - 1)} \right] \times \frac{\sqrt{\gamma R T_3}}{(\gamma - 1)(\gamma + 1)^2 M_{a,C}^2}. \]
conserved. Therefore, the mass flow rate passing the pod can be calculated from the total pressure and total temperature behind the normal shock wave. Based on the Eq. (6), the compressible mass flow rate passing between the pod and tube (\(\dot{m}_p\)) is expressed as follows:

\[
\dot{m}_p = A_s \frac{P_{t,3}}{\sqrt{T_{t,3}}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{\gamma - 1}} \rho_{t,3},
\]

with

\[
p_{t,3} = p_3 \left[1 + \left(\frac{\gamma - 1}{2}\right) M_{t,3}^2\right]^{\frac{\gamma}{\gamma - 1}},
\]

\[
T_{t,3} = T_3 \left[1 + \left(\frac{\gamma - 1}{2}\right) M_{t,3}^2\right],
\]

\[
M_{t,3} = \frac{\rho_{t,3}}{\sqrt{RT_{t,3}}},
\]

where \(p_{t,3}\) is the total pressure and \(T_{t,3}\) the total temperature behind the shock wave \(S_P\); \(M_{t,3}\) is the Mach number behind the \(S_P\) in the shock-relative coordinate system considering the pod speed. The mass flow rate behind the \(S_P\) \(\dot{m}_p = \rho_{t,3} V_{A_t}\) is set equal to the mass flow rate passing the pod \(\dot{m}_p\). This can be expressed based on Eqs. (2) and (9)-(14):

\[
\dot{m}_p = \rho_{t,3} V_{A_t} = \frac{\rho_1(\gamma + 1) M_{d,p}^2}{(\gamma - 1) M_{d,p}^2 + 2} \left(\frac{(\gamma - 1) M_{d,p}^2 + 2}{2\gamma M_{d,p}^2 - (\gamma - 1)}\right) \frac{\sqrt{RT_3}}{\gamma} \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{\gamma - 1}} \rho_{t,3}.
\]

Therefore, the local quantities of \(\Box\) can be calculated with Eqs. (1)-(3) and (10)-(15).

The \(S_c\) and \(S_P\) pass each other after the waves interact. Fig. 3(b) shows the propagating normal shock wave \(S_{C_i}\) from \(S_c\) and the propagating normal shock wave \(S_{P_i}\) from \(S_P\). After the waves interact, the flow quantities in front of the \(S_{C_i}\) and \(S_{P_i}\) are identical to those behind the \(S_P\) and \(S_c\), respectively. The flow quantities behind the \(S_{C_i}\) and \(S_{P_i}\) are assumed to experience identical conditions. Based on this assumption, the normal shock relations in the shock-relative coordinate system are expressed as follows:

\[
p_4 = p_2 \frac{2\gamma M_{d,p}^2 -(\gamma - 1)}{\gamma + 1} = p_3 \frac{2\gamma M_{d,ci}^2 -(\gamma - 1)}{\gamma + 1},
\]

\[
\rho_4 = \rho_2 \frac{(\gamma + 1) M_{d,pi}^2}{(\gamma - 1) M_{d,ci}^2 + 2},
\]

\[
T_4 = T_2 \left[\frac{(\gamma - 1) M_{d,pi}^2 + 2}{2\gamma M_{d,pi}^2 -(\gamma - 1)}\right] = \frac{(\gamma + 1)^2 M_{d,ci}^2 + 2}{(\gamma + 1)^2 M_{d,ci}^2 - (\gamma - 1)},
\]

\[
\frac{v_4}{v_2} = \frac{\sqrt{\frac{(\gamma - 1) M_{d,pi}^2 + 2}{2\gamma M_{d,pi}^2 -(\gamma - 1)} \sqrt{RT_4}} + v_2}{\sqrt{\frac{(\gamma - 1) M_{d,ci}^2 + 2}{2\gamma M_{d,ci}^2 - (\gamma - 1)} \sqrt{RT_4}}} - v_3,
\]

with

\[
M_{d,pi} = \frac{v_{d,pi}}{\sqrt{\gamma RT_1}}.
\]

\[
M_{a,ci} = \frac{v_{a,ci}}{\sqrt{\gamma RT_2}}.
\]

where \(M_{a,pi}\) and \(M_{a,ci}\) are the Mach numbers, and \(v_{a,pi}\) and \(v_{a,ci}\) are the velocities in front of the shock wave in the shock-relative coordinate system. The local quantities of \(\Box\) are expressed as in Eqs. (16)-(21), which are functions of \(v_{a,pi}\) and \(v_{a,ci}\). The normal shock wave speeds \(v_{a,pi}\) and \(v_{a,ci}\) can be obtained by combining two relations in Eqs. (16)-(19); subsequently, all local quantities of \(\Box\) can be calculated.

When the propagating normal shock wave reaches the solid surface, a reflected normal shock wave with rapidly increasing pressure is generated and propagates through the system. In the theoretical approach, it is assumed that the distance between the pod and crack is sufficiently long such that a normal shock wave is created. Fig. 3(c) shows the propagation of the \(S_{pi}\) and normal shock wave \(S_{Ci}\) from the \(S_C\) after reflection at the pod. The \(S_{Ci}\) passing between the pod and tube interacts with the expansion wave behind the pod. However, the conditions behind the pod are not considered because this study focuses on the shock wave in front of the pod due to the crack. The reflected normal shock wave based on Prandtl’s relation [43] is as follows:

\[
\frac{p_r}{p_i} = \left[\frac{(3\gamma - 1)p_i - (\gamma - 1)p_f}{(\gamma + 1)p_f + (\gamma - 1)p_i}\right],
\]

where \(p_r\) is the pressure of the reflected normal shock wave, \(p_i\) the pressure of the incident normal shock wave, and \(p_f\) the pressure in front of the incident normal shock wave before \(p_i\) is reflected at the solid surface. As the incident normal shock wave propagates, the pressure of the flow across the shock wave remains constant. The pressure of the reflected normal shock wave is a function of the pressure values behind and in front of the incident normal shock wave:

\[
p_5 = p_4 \frac{\sqrt{(3\gamma - 1)p_4 - (\gamma - 1)p_2}}{(\gamma + 1)p_4 + (\gamma - 1)p_2}.
\]

Because \(p_3\) and \(p_4\) are known from the \(S_P\) and \(S_{Ci}\), \(p_5\) can be calculated. When the pressure ratio across the reflected normal shock wave is calculated, \(v_{S,Ci}\) can be determined and all quantities of \(\Box\) can be predicted with Eqs. (1)-(5) and (23).

As \(S_{Pi}\) propagates, the shock cell structure induced by the crack may be pushed in the propagation direction of \(S_{Pi}\). In the turbulent jet flow, the normal velocity of the stream gradually increases from the jet boundary to the center owing to the effect of the turbulent shear layer [45]. The normal shock wave is expected to be reflected at the jet boundary. Fig. 3(d) shows the propagation of \(S_{Ci}\) after the reflection at the jet. The propagating reflected normal shock wave \(S_{Ci}\) is reflected again at the jet boundary. The wave that is reflected at the jet boundary and develops into a normal shock wave is \(S_{Ci}\). Its pressure magnitude can be calculated with Eq. (22).

### 2.2. Aerodynamic drag

The theoretical prediction of the aerodynamic drag under cracked-tube conditions is particularly important for stability because the drag is expected to increase rapidly owing to the normal shock wave due to the crack. The total drag \(D_T\) is the sum of the pressure drag \(D_p\) and friction drag \(D_f\). The pressure drag is primarily affected by the pressure distribution on the surface of a moving object. The friction drag is a horizontal force with respect to the surface due to the shear stress. The pressure drag is more significant than the friction drag in the Hyperloop system. For this reason, our study focused on the prediction of the pressure drag. It can be expressed as follows:

\[
M_{a,pi} = \frac{v_{a,pi}}{\sqrt{\gamma RT_1}}.
\]
\[ D_p = A_p \cdot (p_{\text{no}} - p_{\text{tail}})\cos \theta, \quad \left( -\frac{\pi}{2} < \theta < \frac{\pi}{2} \right), \]  
(24) 

where \( A_p \) is the surface area of the nose and tail, \( p_{\text{no}} \) the average pressure at the nose, \( p_{\text{tail}} \) the average pressure at the tail, and \( \theta \) the angle from the end of the pod to a certain point. Because the drag force acts in the horizontal direction of the flow, the pressure according to \( \theta \) acting on the surface was considered.

To predict the pressure drag, the pressure distribution of the pod nose and tail must be calculated. To predict the pressure acting on the nose, the velocity distribution on the surface was considered by using Bernoulli’s equation of compressible flow. The Bernoulli equation for ideal gas and isentropic flow is as follows:

\[ \left( \frac{\gamma}{\gamma - 1} \right) \frac{p_u}{\rho_u} + \frac{v_u^2}{2} + g_z = \left( \frac{\gamma}{\gamma - 1} \right) \frac{p_d}{\rho_d} + \frac{v_d^2}{2} + g_{zd} \]
(25)

where the subscripts \( u \) and \( d \) indicate the upstream and downstream flow, respectively. In the flow around a stationary circular object, the velocity on the surface \( v_\theta \) is a function of the upstream velocity \( \left( 42 \right) \). By substituting the isentropic relation \( \rho_d/\rho_u = (\gamma/\rho_0)^{\gamma/\gamma - 1} \) and velocity \( v_\gamma = v_\theta = -v_\theta \sin \theta \) into Eq. (25), the surface pressure distribution can be determined:

\[ p_s = \left[ \frac{\gamma - 1}{\gamma} \right] \frac{p_u}{\rho_u} + \frac{\gamma - 1}{\gamma} \rho_u \frac{v_u}{2} \left( 1 - \frac{\gamma}{\gamma + 1} \sin^2 \theta \right) \left( \frac{v_u}{\gamma + 1} \right)^{\gamma/\gamma - 1}, \]
(26)

where \( p_s \) is the pressure distribution of the pod surface. The pressure distribution can be theoretically calculated with Eq. (26). The above equation cannot be applied to the pressure distribution at the pod tail owing to flow separation in the Hyperloop system. Therefore, the averaged pressure at the pod tail was considered identical to the exit pressure in the divergent cross-sectional area. In a converging-diverging nozzle, the Mach number inside the nozzle of the flow is determined by the specific-to-critical area ratio. Thus, the Mach number of the flow passing the pod under choking conditions can be calculated with a function of the tube cross-sectional area \( A_t \) and the smallest cross-sectional area \( A^* \) with the nozzle relation:

\[ \frac{A_t}{A^*} = \left( \frac{\gamma + 1}{2} \right)^{\gamma + 1} \left( 1 + \frac{\gamma - 1}{2} \frac{M^2}{\gamma + 1} \right)^{\gamma/\gamma - 1}. \]
(27)

In Eq. (27), the Mach numbers of the subsonic and supersonic flows are calculated. The subsonic solution is the critical Mach number \( M_{\text{crit}} \), and the supersonic solution is the exit Mach number \( M_{\text{exit}} \). The flow with \( M_{\text{exit}} \) in the convergent cross-sectional area becomes the flow with \( M_{\text{exit}} \) in the divergent cross-sectional area with choking in \( A^* \). Because the total pressure of the flow passing the pod is identical, the static pressure of the flow with \( M_{\text{exit}} \) can be calculated as follows:

\[ p_{\text{exit}, 3} = p_{\text{exit}, 3} \left[ 1 + \left( \frac{\gamma - 1}{2} \right) M_{\text{exit}}^2 \right]^{\gamma/\gamma - 1}, \]
(28)

\[ p_{\text{exit}, 5} = p_{\text{exit}, 5} \left[ 1 + \left( \frac{\gamma - 1}{2} \right) M_{\text{exit}}^2 \right]^{\gamma/\gamma - 1}, \]
(29)

where \( p_{\text{exit}, 3} \) and \( p_{\text{exit}, 5} \) are the exit pressures in the unstirred waves and after reflection at the pod, respectively; \( p_{\text{exit}, 3} \) and \( p_{\text{exit}, 5} \) are the total pressures behind the normal shock wave of the SP and SCj, respectively. After the pressure of the pod nose and tail has been determined, the drag can be predicted with Eq. (24).

After reflection at the jet, \( S_{Cj} \) reaches the pod after \( S_{Cj} \) is reflected at the jet structure induced by the crack. The pressure at the pod nose was assumed to be \( p_{nc} \). The pressure at the pod tail can be obtained with Eqs. (28) and (29), and the drag can be calculated with Eq. (24).

### 3. Numerical method

#### 3.1. Numerical simulations and assumptions

In this study, a two-dimensional planar model was applied for all simulations under cracked-tube conditions. Although the crack shape affects the flow field under real-world conditions, the shape cannot be specified. Nevertheless, the effects of the crack can be analyzed based on the simplified crack shape because the mass flow rate is important in the tube.

The existence of a compressible and viscous fluid was assumed in the numerical simulations. The air was an ideal gas, and the fluid viscosity was applied in Sutherland’s viscous model, which is a function of temperature \( [46] \). Moreover, the tube and pod wall were considered smooth surfaces. The Mach number is defined as the ratio of the flow velocity \( v \) to the local speed of sound \( c \). All simulations were conducted with a commercial CFD solver (ANSYS Fluent). More specifically, unsteady-state simulations were performed to analyze the development of the pressure waves due to the crack and pod over time. To obtain the accurate solution, the time step \( (\Delta t) \) was set to 0.00001 s because the initial pressure difference between the atmosphere and tube was significant. At 0.01 s of the simulation, the time step was set to 0.00005 s until the end of the simulation. The Reynolds-averaged Navier–Stokes equation was solved by applying the compressible and implicit solver with a second-order upwind scheme for the flow, turbulent kinetic energy, and specific dissipation rate. To capture strong shock waves, Roe’s flux difference splitting scheme was applied.

#### 3.2. Computational model and boundary conditions

Fig. 4 presents the geometry and boundary conditions of the simulations. In this study, two models were established to analyze thoroughly the flow fields due to the crack and investigate the effects on the pod. Fig. 4(a) shows the geometry of the cracked tube without pod. The atmospheric domain and crack were located in the middle of the tube. The height and length of the atmospheric domain were 1 and 2 m, respectively. The crack widths (i.e., the main parameter) were 1.5, 5, and 10 mm, and the crack height based on the tube thickness was set to 0.1 m. The tube height was assumed to be 5 m, and the tube length was set to 500 m for the three crack widths. Fig. 4(b) shows the geometry of the cracked tube with moving pod, moving zone, and direction of the moving pod. When the pod accelerates, the magnitude of the shock wave gradually increases. However, once the pod moves at the target speed, the posterior compression wave propagates faster than the precedent shock wave, thereby entailing that the magnitude of the shock wave becomes stationary. Thus, the pod started to move instantly in all simulations. To simulate the pod movement, the speed of the moving zone was constant with respect to that of the pod. The pod nose and tail had idealized semi-circular shapes to analyze the compressible flow phenomena and aerodynamic characteristics in detail. Moreover, the blockage ratio was set to 0.6 based on the pod and tube heights, and the pod length was 43 m. The total lengths of the tube with moving pod were 1093, 1193, and 1293 m for the pod speeds of 150, 250, and 350 m/s because a long tube prevents the reflection of pressure waves, which affects the simulation results. The total lengths of the tubes were considered such that the moving pod could reach the crack after 1 s. Fig. 4(c) presents the boundary condition. The atmospheric boundary was a far-field pressure boundary with atmospheric pressure (1 atm). The tube and pod wall were stationary and a moving wall
with no-slip conditions, respectively. The initial pressure levels of the tube and atmospheric domain were set to 1013.25 Pa (1/1000 atm) and 1013.25 Pa (1 atm), respectively. Finally, the initial velocity and temperature were set to zero and 300 K for the tube and atmospheric domain, respectively.

3.3. Computational grid

In this study, the overset mesh method used for the fine grid in the specific domain was used as the dynamic mesh [47,48]. The overset mesh comprises a background and a moving zone, which overlap. The overset mesh method reduces the simulation time because the moving zone slides in the background without regenerating the cells. In addition, the result is accurate because the grid cells around the moving object are not changed. Fig. 5 presents the quadrilateral meshes of the background and moving zones. For the background grid in Fig. 5(a), a fine mesh was generated around the crack where the high speed and complex flow were expected. Because a large velocity gradient was expected near the tube wall, a fine mesh was generated in this region. Fig. 5(b) shows the moving zone grid of the cracked tube with moving pod. To analyze the aerodynamic characteristics accurately, the dimensionless first cell height (wall y+) did not exceed 1 because a shear stress field was expected near the pod.

3.4. Governing equations

The governing equations for compressible flow consist of the conservation of mass, momentum, and energy equations. In a turbulent flow, the velocity in the Navier–Stokes equation is decomposed into the mean part and fluctuating part. To predict the evolution of the turbulent flow, the RANS equations that govern the mean flow containing the mean velocity are solved. In the field of CFD, various RANS models have been studied to predict turbulent flow motion. In this study, the k –ω shear stress transport (SST) turbulence model [49] was applied, which has been widely used for transonic to hypersonic flows [50,51]. The k –ω SST model accurately predicts the shock location and phenomena in the separation region at transonic speed [52]. Jang et al. [53] studied the supersonic jet flow with experiments and RANS simulations; the RANS model sufficiently captures the discontinuous shock wave and drastic velocity variations.

4. Results and discussion

4.1. Verification

The atmospheric domain size, background grid, and moving zone grid were verified. As mentioned in Section 3.1, the mass flow rate is an important factor in a cracked-tube. The domain size was verified to determine the mass flow rate. In addition, the characteristics of the large atmospheric domain (50 × 50 m) and applied atmospheric domain (2 × 1 m) with a 10 mm wide crack were compared. The resulting mass flow rates and pressures according to the atmospheric domain size are listed in Table 1. The relative errors of the mass flow rates and pressures between the large and applied domains are 0.08% and 0.13%, respectively; thus, the differences are slight.

A grid independence test was performed for each background and moving zone. When a highly underexpanded jet is created owing to the crack, the leading shock wave propagates through the tube. It is expected to reach the pod and affect the aerodynamic drag; thus, this wave must be independent of the grid. The mass flow rates and pressures behind the leading shock wave according to the number of nodes are compared in Table 2. Accordingly, Mesh-2 (with 817,000 nodes) with relative errors of the mass flow rate and pressure of less than 1% was applied for the background grid. Moreover, the grid independence test for the moving zone was performed for pod speed of 350 m/s. Fig. 6 compares the drag with respect to the mesh number. The force per unit length (N/m) represents the physics well because the two-dimensional planar model was applied in all simulations. Finally, Mesh-2 (with 817,000 nodes), which exhibits a relative error of 0.04% for the drag with respect to that of the fine mesh, was applied to the moving zone grid.

4.2. Aerodynamic effect of crack without pod

4.2.1. Highly underexpanded jet

The initial stage of the highly underexpanded jet is presented in Fig. 7. The development of the oblique shock cell structure can be considered sonic in the crack. Once the highly underexpanded jet develops around the crack, the pressure rapidly decreases owing to an infinite number of expansion waves. As the jet boundary is created, the size of the shock cell structure increases with the crack width. The Mach disk shows a discontinuous change from a
Fig. 5. Computational grids of (a) background and (b) moving zones. Background grid consists of atmospheric and tube domains and presents 10 times reduced mesh scale in (a). Red and blue rectangles in background grid present magnified real-scale mesh of crack. Moving zone grid presents 10 times reduced mesh scale in (b). Red and blue rectangles in moving zone present magnification of 10 times reduced mesh scale.

Table 1
Verification of atmospheric domain size. Table 1 lists the mass flow rate and pressure for 10 mm wide crack.

<table>
<thead>
<tr>
<th>Case</th>
<th>Length and height (m)</th>
<th>Mass flow rate (kg/s)</th>
<th>Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large domain</td>
<td>50, 50</td>
<td>9.995</td>
<td>45690</td>
</tr>
<tr>
<td>Applied domain</td>
<td>2, 1</td>
<td>9.987 (0.08%)</td>
<td>45630 (0.13%)</td>
</tr>
</tbody>
</table>

Table 2
Grid independence test for a background mesh zone. A grid independence test was conducted with 605300 (Mesh-1), 817000 (Mesh-2), and 995000 (Mesh-3) nodes for a 10 mm wide crack. The mass flow rates and pressures behind the leading shock wave due to the crack were compared.

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of nodes</th>
<th>Mass flow rate (kg/s)</th>
<th>Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh-1</td>
<td>468,400</td>
<td>4.737 (1.35%)</td>
<td>130.82 (1.16%)</td>
</tr>
<tr>
<td>Mesh-2 (Applied)</td>
<td>689,700</td>
<td>4.802 (0.72%)</td>
<td>129.32 (0.27%)</td>
</tr>
<tr>
<td>Mesh-3</td>
<td>838,900</td>
<td>4.837</td>
<td>128.97</td>
</tr>
</tbody>
</table>
low-to a high-pressure disk at all crack widths. In addition, the pressure of the flow across the Mach disk increases with the crack width. The leading shock wave with high-pressure propagates in front of the Mach disk.

Fig. 8 shows the normalized pressure ($p/p_{tube}$) and Mach number profiles along the y-axis from the tube bottom wall to the crack. In Fig. 8(a), the distance from the crack and Mach disk increases with the crack width. The pressure of the leading shock wave increases with the crack width because the mass flow rate increases. In Fig. 8(b), the flow reaches supersonic speed behind the Mach disk because the velocity rapidly increases owing to flow expansion in the tube area and the flow across the Mach disk that reaches subsonic speed.

4.2.2. Flow characteristics with respect to crack width

Fig. 9 shows the pressure contours at 0.1 s with respect to the crack widths. In the initial stage of the undereexpanded jet (shown in Fig. 7), the Mach disk moves to the tube bottom wall behind the leading shock wave. The leading shock wave is reflected by the tube bottom wall and interacts with the Mach disk. Thus, the location of the Mach disk becomes stationary. The oblique shock structure increases with the crack width owing to the distance between the crack and Mach disk after wave interaction. The pressure at the bottom tube wall increases because the leading shock wave becomes reflected. In addition, the leading shock wave generated by the highly undereexpanded jet propagates symmetrically in the tube (such as a normal shock wave) owing to the confined space in the tube.

Fig. 10 shows the normalized pressure profiles along the centerline of the tube at 0.1 and 0.5 s with respect to the crack width. The pressure magnitude and propagation speed of the normal shock wave vary with the crack width. In Fig. 10(a), the normal shock wave propagates with a discontinuous change in its pressure magnitude. Moreover, the pressure of the normal shock wave increases with the crack width owing to the mass flow rate. The undereexpanded jet results in complex flow fields with an inhomogeneous pressure distributions around the crack. In Fig. 10(b), the locations of the normal shock waves are different because the speed of the normal shock wave is determined by the pressure ratio in front of and behind the shock wave. In addition, the propagation speed of the normal shock wave increases with the crack width. More specifically, the pressure of the normal shock wave varies with respect to the crack width. When 1, 5, and 10 mm wide cracks occur in the tube, the normal shock wave propagates with pressures of 125.7, 140.1, and 167.5 Pa, respectively. Moreover, a flow with high velocity is induced by the crack such that the total pressure affecting the pod is significant. The pressure profiles with respect to the crack widths oscillate because the Mach disk and leading shock wave interact in the tube. This oscillating pressure is expected to affect directly the aerodynamic drag when the wave reaches the pod; consequently, the system becomes unstable.

4.3. Effect of crack on moving pod

4.3.1. Propagating shock wave

In this section, the propagation and interaction characteristics of the different shock waves are discussed. Fig. 11 shows the pressure and Mach number distributions around the pod according to the different shock waves with respect to the crack width at a pod speed of 350 m/s. In general, the physics of subsonic and supersonic flows are significantly different. However, as mentioned in Section 2, the normal shock wave ($S_{p}$) is created by a combination of a series of compression waves, even if the pod moves at supersonic speed. In addition, the flow velocity across the normal shock wave ($S_{p}$) rapidly decreases. Therefore, the incoming flow is evidently subsonic in the pod-relative coordinate system, although the pod moves at supersonic speed. In other words, the compressible flow phenomena such as the normal shock wave and chocking point are similar from subsonic to supersonic pod speeds in the Hyperloop system. The chocking point with respect to the pod speed was observed between the tube and pod in previous study [8,11]. Therefore, the numerical results at pod speed of 350 m/s were mainly discussed as the compressible flow phenomena under cracked-tube conditions in this study. More specifically, Fig. 11(a) shows the un-stirred waves before the $S_{C}$ and $S_{p}$ interact. Thus, the region between the $S_{C}$ and $S_{p}$ is described by the operating conditions ($p = 1/1000$ atm, $M = 0$). As the $S_{C}$ and $S_{p}$ propagate, a high-pressure flow field with a high Mach number is created behind the shock waves. The $S_{C}$ propagates faster with a higher pressure for a larger crack width than for a smaller crack width. Behind the pod, an oblique shock wave is generated owing to the effect of divergence in the cross-sectional area. As the oblique shock wave is reflected at the pod and tube wall, shock cell structures are repeatedly formed. Fig. 11(b) shows the normal shock waves after wave interaction. Owing to the effect of the $S_{C}$ and $S_{p}$, the pressure magnitude significantly increases in the interaction region, which is the area between the $S_{C}$ and $S_{p}$. The pressure in the interaction region is higher for a larger crack width owing to the stronger generated $S_{C}$. Because the propagation speed of the shock waves depends on the pressure difference across the shock wave (as shown in Eq. (1)), the formation of the high-pressure field affects the propagation speeds of the $S_{C}$ and $S_{p}$. The pressure of the $S_{p}$ depends on the pod speed, regardless of the crack width. Thus, the magnitude of the pressure field between the $S_{C}$ and pod is almost similar at a constant pod speed. Accordingly, the propagation speed of the $S_{C}$ increases with the crack width. Although a higher pressure field is formed in the interaction region for a larger crack width, the propagation speed of the $S_{p}$ decreases as the crack width increases because the pressure between the crack and $S_{p}$ increases. Fig. 11(c) shows the normal shock waves after the $S_{C}$ is reflected at the pod. The $S_{C}$ is generated and propagates to the crack. Because the pressure magnitude of the $S_{C}$ depends on that of the $S_{C}$ (as shown in Eq. (23)), the higher pressure of the $S_{C}$ increases the pressure of the $S_{C}$. Thus, the pressure magnitude of the $S_{C}$ increases with the crack width. Fig. 11(d) shows the normal shock wave after the $S_{C}$ is reflected at the jet. The jet structure is pushed in the direction of the $S_{p}$. The $S_{C}$, which is followed by the $S_{p}$, is reflected at the jet boundary and propagates to the pod. The region between the crack and $S_{p}$ becomes a high-pressure field; this pressure increases with the crack width. Fig. 11(e) shows the direct effect of the crack width when the center of the pod is below the crack. The jet flow acts on the top surface of the pod, thereby resulting in an unbalanced pressure distribution. The pressure of the top surface of the pod increases with the crack width because the mass flow rate increases. The dif-
different mass flow rate behind the pod results in the generation of asymmetrical shock cell structures, which destabilize the system.

4.3.2. Pressure field

Fig. 12 shows the pressure profiles along the tube according to the waves for different crack widths at the pod speed of 350 m/s. As explained above, the flow becomes choked at the tail between the tube and pod from subsonic to supersonic pod speeds. Accordingly, the compressible phenomena are similar at each pod speed considered in this study. Therefore, the pressure distribution at the pod speed of 350 m/s was discussed as a representative result. Because the magnitude and propagation speed of shock waves depend on the pod speed, those of the shock waves were quantified; they are discussed in Section 4.4.1. Fig. 12(a) shows the pressure magnitudes of the SC and SP. As shown in Fig. 10, the pressure profile of the SC oscillates and propagates through the tube. The pressure decreases at the nose and tail owing to the convergence–divergence effect with the physics of the subsonic and supersonic flows in the cross-sectional area. At the tail, an oblique shock wave with oscillating pressure is generated. In Fig. 12(b), the pressure behind the SCi and SPi increases in the interaction region of the waves. Although the pressure in the interaction region of the waves oscillates, those of SCi and SPi are almost identical. The propagation speeds of SCi and SPi are different because the pres-
sure values in front of the shock waves differ. Fig. 12(c) shows the pressure profile after the $S_{CI}$ is reflected at the pod. As the $S_{CI}$ reaches the pod, a reflected wave and wave passing between the pod and tube are generated. The wave that passes between the pod and tube increases the pressure from nose to tail. The magnitude of this pressure field increases with the crack width because the pressure magnitude of the $S_{CI}$ increases. Fig. 12(d) shows the pressure profile after the $S_{CP}$ is reflected at the jet. The pressure of the $S_{CI}$ is higher than that of the $S_{CP}$, and $S_{CI}$ propagates to the pod. Furthermore, the pressure magnitude of the $S_{CI}$ increases with the crack width because the pressure magnitude of the $S_{CP}$ increases.

Fig. 13 shows the normalized pressure ($p_{pod}/p_{tube}$) distributions along the pod surface for a crack width of 10 mm and pod speed of 350 m/s before and after the $S_{CI}$ ($t_1 = 0.45$ s) and $S_{CI}$ ($t_2 = 0.85$ s) reflect off the pod. In Fig. 13(a), the pressure distribution spans from the nose to the tail before the $S_{CI}$ becomes reflected. As the $S_{CI}$ reaches the pod, the pressure of the nose increases and the $S_{CI}$ propagates between the pod and tube. In Fig. 13(b), the pressure increases after the $S_{CI}$ reaches the pod, and the $S_{CI}$ propagates at a high pressure level. Thus, the aerodynamic drag becomes affected when the $S_{CI}$ and $S_{CI}$ reflect off the pod.

4.3.3. Aerodynamic drag and lift

Fig. 14 shows the drag variations for crack widths of 1, 5, and 10 mm at speeds of 150, 250, and 350 m/s. The presented drag variations originate from the moment after the flow around the pod becomes stable at $t = 0.2$ s. The changes in the drag show similar trends. The drag increases with the pod speed before the shock waves reach the pod. Subsequently, the drag is directly affected; the influence of the $S_{CI}$ and $S_{CI}$ is indicated by arrows in Fig. 14(c). When the $S_{CI}$ reaches the pod, the drag drastically increases, thereby creating fluctuating waveforms because the pressure magnitude of the $S_{CI}$ oscillates. This oscillation directly affects the pod, which is expected to vibrate. After the $S_{CI}$ reaches the pod, the drag rapidly increases owing to the increasing pressure at the nose, as shown in Fig. 13(b). In the jet on the pod, the flow due to the crack vertically affects the pod wall and the drag drastically decreases because the pressure at the nose decreases.

When the pod moves under the crack, the flow due to the crack affects perpendicularly the top surface of the pod. A negative lift acts on the pod owing to the high pressure at its top surface and low pressure at its bottom surface (as shown in Fig. 11(e)). Fig. 15 shows the negative lift with respect to the crack width and pod speed when the pod center is below the crack. As the crack width increases at a constant pod speed, the magnitude of the negative lift increases because the mass flow rate and pressure increase.

4.4. Theoretical analysis

4.4.1. Shock wave prediction

The theoretical analysis was performed to predict the pressure values and propagation speeds of the normal shock waves and aerodynamic drag. This section presents the calculated results for a 0.6 blockage ratio based on the theoretical approach in Section 2.

Fig. 16 presents the propagation speeds ($v_{S,P}$) and normalized pressures ($p_{S,P}/p_{tube}$) for the $S_{CI}$ from the simulation and theoretical results. To combine the simulation and theoretical results (red curves), the values of $p_1$, $T_1$, and $p_2$ for $v_{S,P}$ and the values of $p_1$, $T_1$, and $v_{S,C}$ for $v_{S,P}$ were substituted into Eqs. (1)–(8). The $v_{S,C}$ and $p_{S,C}$ values agree well for 5 and 10 mm wide cracks. In the case of the 1 mm wide crack, the simulation results are higher than the predicted ones owing to the smaller shock cell structure, which results in complex interactions between the Mach disk and leading shock wave.

Fig. 17 shows the propagation speed ($v_{S,P}$) and normalized pressure ($p_{S,P}/p_{tube}$) of the $S_{P}$ according to the pod speed. The flow becomes choked in the smallest cross-sectional area at pod speeds from 150 to 350 m/s. Therefore, the mass flow rate behind the $S_{P}$ ($m_{S,P}$) and that passing between the pod and tube ($m_{S,P}$) agree well; thus, the predicted normal shock wave speed and pressure agree well with the simulation results. As the pod speed increases, more mass accumulates owing to the choked flow, which increases the $p_{S,P}$ and $v_{S,P}$.

Fig. 18 shows the predicted pressure distribution and normalized pressure after the waves interact ($p_{S,C,P}/p_{tube}$), after reflection at the pod ($p_{S,C,P}/p_{tube}$), and after reflection at the jet ($p_{S,C,P}/p_{tube}$) according to the crack width and pod speed. The pressure values of the $S_{CI}$ and $S_{P}$ are different owing to the oscillation of the pressure profile due to the crack. However, the pressure difference is slight, as shown in Fig. 12(b); thus, the pressure magnitude is represented by $p_{S,C}$. After the shock wave interaction, the effects of the crack width and pod speed must be considered simultaneously. Therefore, the predicted pressure distribution is obtained from the theoretical calculations with respect to the pod speed and crack width, as shown in Fig. 18(a). When a crack occurs and the pod speed and crack width are known, all pressures can be predicted from the theory. Fig. 18(b) presents the pressures from the simulation and theory with respect to the crack width at specific pod speed of 150, 250, and 350 m/s. As the crack width and pod speed increase, $p_{S,C}$ increases after the interaction of the $S_{C}$ and $S_{P}$. The simulated $p_{S,C}$ value for the 1 mm wide crack is higher than the predicted value owing to $p_{S,C}$. After the reflection at the pod, $p_{S,C}$ increases with the crack width and pod speed. The simulated $p_{S,C}$ value is higher than the predicted one after the reflection at the pod owing to $p_{S,C}$ for the 1 mm wide crack. Moreover, the $p_{S,C}$
Fig. 11. Pressure and Mach number contours at $v_{pod} = 350$ m/s. Left side presents pressure contours, and right side presents Mach number contours for 1, 5, and 10 mm wide crack (from top to bottom), respectively. Fig. 10 (a) presents unstirred waves at $t = 0.3$ s, (b) after wave interaction at $t = 0.4$ s, (c) after reflection at pod at $t = 0.6$ s, (d) after reflection at jet at $t = 0.8$ s, and (e) of jet on pod at $t = 1$ s.
Fig. 12. Normalized pressure profiles of waves passing between the pod and tube for \(v_{pod} = 350 \text{ m/s}\) along the tube. Each wave location for \(W_{crack} = 10 \text{ mm}\) is indicated by an inverted triangle. Red solid lines represent the pod nose and tail.

Fig. 13. Normalized pressure (\(p_{pod}/p_{tube}\)) distributions along pod surface for \(W_{crack} = 10 \text{ mm}\) and \(v_{pod} = 350 \text{ m/s}\) before and after (a) \(S_{Ci}\) (at \(t_1 = 0.45 \text{ s}\)) and (b) \(S_{Cj}\) (at \(t_2 = 0.85 \text{ s}\)) reach the pod.

Fig. 14. Drag variation with respect to \(W_{crack}\) for \(v_{pod}\) of (a) 150 m/s, (b) 250 m/s, and (c) 350 m/s. At (c) \(v_{pod} = 350 \text{ m/s}\), drag increases owing to \(S_{Ci}\) and \(S_{Cj}\) (indicated by arrows).
predicted pressure at the tail is underestimated because the actual exit Mach number is lower than $M_{exit}$. For this reason, the drag at 150 m/s is overestimated with respect to the simulation result. At pod speeds of 250 and 350 m/s, the flow fully accelerates in the divergent cross-sectional area. However, the actual area through which the flow passes behind the pod tail decreases during flow separation. The predicted pressure drag is overestimated because the calculated $M_{exit}$ is lower than the actual exit Mach number.

Fig. 20 shows the predicted drag for all pod speeds and crack widths and the total drag, pressure drag, and predicted pressure drag after the $S_{CJ}$ and $S_{CI}$ reach the pod with respect to the crack width and specific pod speed of 150, 250, and 350 m/s. The drag after the reflection at the pod must consider the effects of the crack width and pod speed owing to the pressure of the normal shock wave after wave interaction, as shown in Fig. 18. The drag can be predicted with the pod speed and crack width from the theoretical approach, as shown in Fig. 20(a). In Fig. 20(b), the total drag and pressure drag increase with the crack width and pod speed of 150, 250, and 350 m/s after reflection at the pod. The predicted pressure drag at a pod speed of 150 m/s is in close agreement with the simulated drag because the drag in the un-stirred waves is underestimated and $p_{S,CI}$ is overestimated. The predicted pressure drag agrees well at 250 and 350 m/s when the flow fully accelerates at the pod tail. Fig. 20(b) presents the drag after the $S_{CJ}$ reaches the pod according to the pod speed and crack width. When the normal shock wave reflected at the jet reaches the pod, the total drag and pressure drag increase. In addition, the predicted pressure and drag values in the reflection due to the jet agree well at all pod speeds.

5. Conclusions

In this study, unsteady-state simulations were performed to analyze the pressure waves and aerodynamic characteristics in the Hyperloop system under cracked-tube conditions. The analysis was conducted by studying the system without a pod and with a moving pod. In the cracked tube without a pod, the flow characteristics in the confined tube were analyzed. In the cracked tube with a moving pod, the normal shock wave and aerodynamic characteristics were investigated with a theoretical approach and simulations. The primary findings are as follows:

(1) Our theoretical approach successfully predicts the pressures and propagation speeds of the normal shock waves due to the crack and pod and the aerodynamic drag under cracked-tube conditions. The normal shock wave and aerodynamic drag were predicted with the compressible mass flow rate, Bernoulli equation, normal shock relations, and nozzle relation.

(2) When the tube cracks, an instantaneous flow is induced by the difference between the atmospheric and tube pressures; this leads to the development of a highly underexpanded jet and leading shock wave. As the crack width increases, the size of the oblique shock cell structure containing the Mach disk increases.

(3) The leading shock wave propagates as a normal shock wave through the confined tube and increases the aerodynamic drag and fluctuations, which makes the system unstable.

(4) The normal shock waves caused by the crack and pod have different pressure values and propagation speeds after their interaction and reflection; the simulated and predicted values agree well.

(5) The aerodynamic drag increases rapidly as the normal shock wave caused by the crack reaches the pod; in addition, the predicted and simulated pressure drag agree well. A negative lift is induced as the flow due to the crack hits the pod perpendicularly; the lift strengthens with increasing crack width.

This study focused on theoretical calculations and numerical simulations to investigate shock waves and aerodynamic character-
istics to ensure stability under cracked-tube conditions. Although an ideal geometry was investigated in this study, understanding the characteristics of the Hyperloop system under cracked-tube conditions is essential for ensuring safety in emergencies. Therefore, in this study, the characteristics of the pressure waves were predicted and analyzed. The results can be used to design a Hyperloop system with suitable safety features.

The applicability of the presented results is limited owing to the assumptions and complexity. In the theoretical approach, $S_{PI}$ only considers changes in the jet structure, and the normal shock relation is calculated based on the pressure behind the $S_{PI}$ and $S_{CP}$. However, the simulation results differ from the theoretical results because the pressure field around the jet structure is expected to change owing to the $S_{PI}$. Furthermore, the three-dimensional effect was not considered because the simulation was performed with a two-dimensional planar model. Three-dimensional model simulations and a complex crack shape based on fracture mechanics should be used to analyze more realistic conditions.

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.

Acknowledgements

This research study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MEST) (No. 2019R1A2C1087763), by the “Core Technology Development of Subsonic Capsule Train” of the Korea Railroad Research
Institute under Grant PK2101A1-2, Korea, and by the Chung-Ang University Graduate Research Scholarship in 2020.

References


