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Hyperloop Vehicle Aerodynamics and Shape Design-From Theoretical Investigation to Engineering Practice

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Abstract

Compared to conventional rail transit, Hyperloop trains are characterized by subsonic, transonic, and supersonic flow regimes, where abrupt transitions in the flow field induce severe fluctuations in aerodynamic loads. Although extensive research has been conducted to establish systematic flow field structures, critical aerodynamic effects—specifically shock waves and choked flow exhibit high sensitivity to vehicle geometry. These critical phenomena profoundly dictate the selection of top-level system specifications and the determination of operational safety parameters. Integrating findings from the authors' research group and the existing literature, this study provides a systematic review of flow field structures and their subsequent impacts on aerodynamic loads. Specifically, it elucidates the hysteresis effects inherent in flow field transitions during vehicle acceleration and deceleration phases. Furthermore, the paper characterizes the influence of one-dimensional, two- dimensional, and three-dimensional flows on critical aerodynamic phenomena, thereby offering essential theoretical support for the practical engineering implementation of Hyperloop systems.

Keywords: high-speed maglev, Hyperloop, aerodynamics, choked flow, shock wave, critical condition, hysteresis.

1. Introduction

The Hyperloop train system, also known as the vacuum tube maglev train or Hyperloop system, is an emerging high-speed ground transportation technology [1].By partially evacuating the air within the tube to create a low-vacuum environment and integrating magnetic levitation technology, the system enables vehicles to operate at high speeds under near-zero aerodynamic resistance, with theoretical velocities exceeding 1000 km/h. Although this innovative transportation mode traces its origins back to the pneumatic transport concepts of the late 19th century, it was the publication of the "Hyperloop Alpha" white paper by Elon Musk in 2013 that catalyzed significant global attention and a subsequent surge in research. The significance of the Hyperloop system lies in its potential to transcend the inherent limitations of conventional rail transit, offering an efficient and sustainable solution for future mobility [2-4].

Regarding the current state of research, a relatively comprehensive theoretical and experimental framework has been established in the field of evacuated tube trains. The historical lineage can be traced back to Robert Goddard’s vacuum train concept in 1904. In the mid-20th century, preliminary explorations were conducted in both the Soviet Union and the United States, yet these efforts stagnated due to technological constraints [5].Post-2013, the Hyperloop concept gained rapid momentum, with several entities such as Virgin Hyperloop and Hyperloop Transportation Technologies (HTT) initiating prototype testing. In 2020, Virgin Hyperloop successfully conducted a crewed test run on its Las Vegas track, reaching a speed of 172 km/h [6].Scholars generally contend that the technical characteristics of integrated evacuated tubes and high-speed maglev systems—including tube pressure optimization and vehicle levitation design—have become a primary focal point in contemporary high-speed railway research [7].

Figure 1: Conceptual diagram of Hyperloop System

In the field of aerodynamic research, scholars have focused extensively on subsonic, transonic, and supersonic flow regimes. The generation of shock waves and choked flow during high-speed operation in low-vacuum environments induces abrupt fluctuations in aerodynamic loads, which profoundly impact vehicle design and overall system safety. Current literature has established comprehensive flow field structures across multiple dimensions and elucidated the hysteresis effects associated with acceleration and deceleration. Research teams throughout the world have primarily investigated the influence of system parameters, such as the speed level and blockage ratio, on critical aerodynamic phenomena[8,9].Similarly, international research prioritizes aerodynamic effects as a core focus, extending these investigations to encompass aerodynamic heating and the complexities of tube-vehicle coupling[2,10].

Furthermore, the development of experimental platforms is progressing rapidly. The evacuated tube train test line in Datong, China, spanning several kilometers, has been completed to validate full-system performance. Meanwhile, scholars in Poland have proposed design schemes to integrate vacuum stations with conventional transportation hubs. Nevertheless, significant research gaps persist, particularly regarding flow field interference under multi-train formations and comprehensive economic feasibility assessments[11].

In summary, the evacuated tube train represents not only a transformative leap in transportation but also the human pursuit of ultra-high speeds and environmental sustainability. Despite existing technical bottlenecks, continuous research progress has established a robust foundation for engineering applications. Leveraging current findings, this paper provides a systematic review of the Hyperloop system aerodynamics developmental trajectory to serve as a technical reference for the field.

2. Evolution of Research Methodologies

2.1 One-dimensional research methods

One-dimensional (1D) flow analysis represents the most simplified approach for investigating the aerodynamic challenges associated with evacuated tube trains. Its core methodology involves simplifying the internal tube flow into 1D flow, thereby neglecting transverse and vertical variations to focus on the macroscopic conservation laws of mass, momentum, and energy. This approach is characterized by exceptional computational efficiency, making it highly suitable for system-level parameter sensitivity analysis, preliminary design selection, and rapid evaluation of operational conditions.

One-dimensional analytical methods play a pivotal role in addressing the unique flow choking phenomena inherent in Hyperloop systems. For instance, researchers have utilized quasi-1D computational methods to analyze the global flow field. Findings indicate that from a global system perspective, the blockage ratio is the primary determinant of aerodynamic drag; specifically, when the blockage ratio exceeds the critical threshold related with vehicle speed, the flow reaches a choked state, resulting in a dramatic increase in drag[8]. Furthermore, by establishing a system of 1D governing equations that incorporate parameters such as blockage ratio, tube friction coefficient, and heat exchange, researchers can analytically or numerically determine the distributions of pressure, density, and Mach number along the tube. This allows for the precise identification of flow choking onset and its subsequent impact on vehicle drag[12].

Other researchers have also utilized one-dimensional (1D) theoretical analysis to investigate the aerodynamic characteristics of high-speed evacuated tube trains. Grounded in 1D isentropic flow theory, this method derives drag equations while accounting for the influence of vacuum levels. The findings demonstrate a linear correlation between tube pressure and aerodynamic drag, indicating that decreasing the pressure can reduce the drag to less than 10% of that in open-air conditions. Furthermore, 1D numerical simulation models provide a robust means to calculate the discontinuities in pressure, temperature, and Mach number across shock waves, enabling the estimation of resultant wave drag and thermal loads[13-15].

2.2 Two-dimensional Research Methods

To compensate for the deficiencies of one-dimensional models in describing shock structures, expansion wave systems, and flow separation, two-dimensional (2D) numerical simulations have been widely applied. This approach simplifies the flow field into planar or axisymmetric models, typically solving the 2D Navier-Stokes equations in conjunction with the turbulence model and dynamic mesh techniques. Although this method neglects three-dimensional vortex effects, it achieves a favorable balance between computational cost and physical resolution, demonstrating high computational efficiency.

Two-dimensional simulations exhibit significant advantages in the research of shock wave evolution and flow choking mechanisms. This approach not only facilitates the clear visualization of the morphological transitions of the detached bow shock at the vehicle nose and the formation of complex shock systems at the vehicle rear but also enables effective analysis of pressure wave propagation and aerodynamic heating effects under unsteady conditions. Consequently, it serves as a vital method for elucidating the key aerodynamic phenomena of evacuated tube trains. Research findings reveal that as the vehicle accelerates, a normal shock wave is generated ahead of the nose, while expansion waves at the rear result in increased thermal loads[16].Results demonstrate that optimizing the vehicle nose geometry can reduce aerodynamic drag by 5% to 10%. When coupled with 1D theoretical models, this approach yields errors of less than 5%, rendering it suitable for preliminary aerodynamic design phases[17,18].

Two-dimensional (2D) research accurately reveals the reflections of shock waves against the tube walls and their interactions with the vehicle surface, which are the direct causes of localized pressure peaks and aerodynamic load fluctuations. Regarding the choking phenomenon, 2D simulations provide a more realistic representation of the flow contraction and expansion effects induced by the vehicle geometry, such as nose curvature and cross-sectional shape. Studies indicate that the geometric profile of the vehicle significantly influences the critical Mach number at which choking occurs. By performing parametric scans of various vehicle profiles, 2D studies enable the quantitative assessment of this sensitivity, providing direct guidance for the aerodynamic optimization of the vehicle [19,20] Due to its high computational efficiency, 2D research plays a pivotal role in elucidating the "hysteresis effect of flow field transitions." The hysteresis effect refers to the phenomenon where discrepancies persist in the flow field structures and aerodynamic loads during the acceleration and deceleration phases of an evacuated tube train, even at the same instantaneous velocity, as a result of the differing flow histories associated with the vehicle's preceding operational states[18].

2.3 Three-dimensional research methods

Three-dimensional (3D) research methodologies comprehensively employ high-fidelity Computational Fluid Dynamics (CFD) techniques. Researchers utilize the

Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with turbulence models, or more advanced Large Eddy Simulations (LES), to conduct numerical simulations of full-scale train-tube systems. These simulations enable the precise reproduction of 3D shock surfaces surrounding the vehicle, the development of 3D boundary layers on the vehicle body, complex vortex shedding in the wake, and the interactions between these flow structures and the tube walls. For instance, scholars have employed 3D compressible turbulence models to investigate the aerodynamic performance of Hyperloop capsules in low-pressure environments. This methodology is based on the 3D compressible Navier-Stokes equations, utilizing the k-ε turbulence model and the finite volume method to simulate flow fields under various blockage ratios.[21].

Regarding the investigation of flow choking and shock waves, three-dimensional (3D) simulations elucidate numerous phenomena that remain imperceptible in one- and two-dimensional analyses. For instance, as the vehicle body is not perfectly axisymmetric, the induced flow choking effects may exhibit circumferential non-uniformity, leading to asymmetric pressure distributions and the generation of lateral forces. Furthermore, the 3D curvature of the vehicle nose exerts an unsymmetric influence on the geometry and intensity of the bow shock; an optimized 3D profile can produce weaker shock waves situated further from the vehicle body, thereby mitigating wave drag. In terms of the wake flow field, 3D simulations are capable of capturing high-fidelity vortex shedding structures and localized low-pressure regions, which are critical to the aerodynamic stability of the tail car and the pressure recovery process within the tube[22,23]. For instance, scholars have developed three-dimensional (3D) models to evaluate the aerodynamic noise and drag of Hyperloop vehicles. This methodology is based on the 3D Navier-Stokes equations and the SST k-ω turbulence model, incorporating aeroacoustic simulations to analyze flow interference within the tube. Research findings demonstrate that aerodynamic noise in low-vacuum environments primarily originates from shock wave reflections, with peak levels reaching twice those of conventional high-speed rail.[24].

3. Research findings on aerodynamic effects-Flow field structures.

Extensive research indicates that choked flow in Hyperloop system exhibits commonalities: in regions far from the vehicle, the flow composition is relatively simple, displaying quasi-one-dimensional (quasi-1D) large-scale features; conversely, the near-field of the vehicle exhibits distinct 3D structures due to variable cross-section effects. However, these regions are typically confined to a range within several vehicle lengths along travelling direction. Consequently, current research pathways primarily fall into two categories: first, from a global perspective, utilizing quasi-1D reduction methods under high aspect ratio conditions—which have been widely adopted for train-tunnel flow, shock tubes, and flow choking problems—to characterize the 1D average effects of wall friction and heat transfer through established models; second, employing 3D analytical or numerical methods specifically for the local near-field to capture complex structures. The following sections will discuss the flow characteristics and aerodynamic effects of evacuated tube trains from the perspectives of both global and local flows in detail.

3.1 Global Flow Characteristics in Hyperloop Systems

In Hyperloop transportation systems, vehicle operation induces significant unsteady compressible flow. Under the combined influence of the extremely high aspect ratio of the tube and low ambient pressure, once flow disturbances are formed, they tend to propagate continuously over long-time and long-distance scales, forming a global flow structure centered on choked flow. Overall, the flow within the tube can be approximated as an axially dominant 1D unsteady flow, the evolution of which is closely related to the acceleration, constant-speed, and deceleration phases of the vehicle. The following discussion depicts the general phenomenon that one Hyperloop vehicle encounters as it accelerates from subsonic state to supersonic state.

(1) Acceleration Phase: Establishment of Choked Flow and Shock Generation

During the vehicle’s startup and acceleration process, the air ahead of the vehicle undergoes continuous compression, leading to the rapid establishment of axial velocity and pressure gradients within the tube. As the velocity approaches critical conditions, the gas mass flow rate reaches its limit due to the constraints of the effective flow area, causing the flow to transition from a non-choked to a choked state. At this stage, a series of compression waves initially forms ahead of the vehicle nose and subsequently evolves into forward-propagating moving shock waves once the choked flow conditions are satisfied.

(2) Constant-speed Phase: Quasi-steady Choked Flow Structure

When the vehicle enters the supersonic constant-speed operation phase, the flow field within the tube does not immediately reach a steady state; instead, a quasi-steady choked flow structure is formed. At this stage, the leading shock wave propagates forward at a near-constant velocity, and the flow region between the shock wave and the vehicle remains in a near-critical state, with pressure, density, and velocity exhibiting a relatively flat plateau distribution along the axial direction.

Extensive numerical studies indicate that during this phase, except for a limited area in the vehicle's near-field, the flow within the tube exhibits distinct quasi-one-dimensional characteristics. Although three-dimensional effects such as wall friction and heat exchange are non-negligible, their impact on the global flow can be reasonably characterized through one-dimensional averaged models.

(3) Deceleration Phase

During the vehicle’s deceleration phase, the capacity to compress the gas gradually weakens, causing the original choked conditions to break down. The intensity of the leading shock wave decreases alongside the reduction in vehicle velocity; in certain cases, the shock wave may degrade into compression waves or dissipate entirely. Simultaneously, the expansion waves generated at the rear of the vehicle strengthen significantly and propagate forward.

(4) Hysteresis Effect of the Flow Field

The flow for Hyperloop trains generally exhibits a clear hysteresis effect; that is, at identical vehicle velocities, the state of the flow field during the acceleration phase does not always coincide with that of the deceleration phase. Specifically, parameters such as shock wave position, pressure distribution, and the strength of choked flow exhibit significant path dependency. This hysteresis effect is primarily attributed to two factors. Firstly, the difference in initial condition: The initial condition for acceleration and deceleration process as vehicle arrives at a certain speed is different. Secondly, the energy Dissipation: Energy losses introduced by wall friction and heat exchange significantly extend the duration of the flow field recovery process.

3.2 Local Flow Characteristics

In low-vacuum environment, the nature of the near-field flow around the vehicle is highly dependent on the incoming Mach number and the blockage ratio. Based on the presence and morphology of shock waves within the flow field, the near-field flow can be categorized into three typical regimes: Subsonic Flow Regime: When the vehicle operates at low speeds, the entire external flow field remains subsonic. The airflow accelerates in the streamlined region of the vehicle nose, remains relatively stable along the middle section, and decelerates in the streamlined region of the tail. Although no shock waves are generated, the pressure gradients at the vehicle's shoulders and tail remain significant due to the blockage effect of the tube. In transonic Flow Regime: As the velocity increases, the flow begins to reach sonic speed at the shoulders of the tail car. At this stage, shock wave structures start to emerge at the tail shoulders, and the flow field Mach number subsequently fluctuates around.Ma 1. A prominent feature of this stage is the intensified oscillation of the airflow in the wake region, which may lead to greater vortex shedding instability. In the 3D confined space, the generation and propagation of shock waves exhibit complex spatial topological forms that are far richer than the phenomena described by 2D models. In supersonic flow regime, the boundary layer separation and geometric expansion on the streamlined surface of the tail car induce an initial cylindrical oblique shock wave near the nose. This shock subsequently undergoes multiple reflections and interferences within the annular space between the tube wall and the vehicle body.

These reflected shocks converge in the central region of the wake, forming a characteristic X-shaped shock structure. Furthermore, as the shock front passes through the line of intersection, it undergoes a non-linear geometric mutation—transforming from an initial convex shock into a concave shock. This 3D shock system evolves not only on the longitudinal symmetry plane but also forms complex rhombic (diamond) wave structures in the transverse space, profoundly altering the flow field distribution within the tube.

The morphology of vortex structures in the wake region is closely correlated with the presence of shock waves. In subsonic flow field (without shock waves), the wake is broader and vortex shedding is more divergent, typically characterized by a single primary vortex cluster. Conversely, in flow fields where shock waves are present, the separation bubbles near the tail car’s nose induce additional secondary vortex systems, forming a more complex dual-vortex cluster structure.

More importantly, shock waves exert significant rectification and suppression effects on wake development. By constraining the transverse expansion of the wake vortices, the shock waves effectively narrow the instantaneous wake width and make the vortex shedding process more regular and stable. This phenomenon shifts the dominant frequency of the wake toward the lower-frequency spectrum. The intricate interference and fusion between shock waves and vortex systems constitute the hallmark flow characteristic of the wake field in Hyperloop transportation.

Furthermore, the boundary layer development along the inner tube wall and the vehicle surface, as well as the flow within narrow gaps, exhibit unique three-dimensional characteristics. The boundary layer thickness on the vehicle surface increases progressively along the flow direction, with distinct transition points occurring at the junction between the streamlined sections and the constant-cross-section body. As the vacuum degree within the tube increases, both the boundary layer thickness and the width of the wake vortex systems show a slight increasing trend.

Specifically, within the narrow levitation gap between the vehicle underbody and the track, the impact of high-speed airflow induces periodic worm-like vortex structures. Meanwhile, on both sides of the streamlined surfaces of the head and tail cars, longitudinal trailing vortices are formed. These subtle near-wall flow structures interact with large-scale shock systems to collectively determine the global aerodynamic characteristics of the Hyperloop train's local flow field.

4. Research on the Optimization of Hyperloop Vehicle Shapes and Their Impact on Aerodynamic Loads.

Research on the optimization of Hyperloop vehicle shapes primarily focuses on reducing aerodynamic drag, mitigating choking effects, and improving load distribution, typically achieved through numerical simulations and parametric analyses[25]. Early studies predominantly utilized 2D models to investigate the influence of basic geometric shapes on drag. For instance, Gillani et al.[25] evaluated the aerodynamic performance of three simple geometric shapes—circular, oval, and rectangular—under various tube pressures and velocities. The results indicated that oval-shaped head and tail designs optimized the flow field, significantly reduced pressure gradients at the nose, and prevented the formation of sharp compression waves, thereby reducing total aerodynamic drag by approximately 15%-20%. Specifically, the transition from a circular to an oval profile reduced aerodynamic drag by 18%, enabling the vehicle to operate more efficiently in low-pressure environments.

Similarly, Braun et al[26] transitioned from initial 2D CFD designs to full 3D simulations to optimize Hyperloop vehicles for generating specific lift or minimizing drag. The resulting optimized shape is highly streamlined, featuring a reduced nose cone angle and a tapered tail. In this optimized configuration, the proportion of pressure drag within the total aerodynamic load decreased to 60%. However, the overall fluctuations in the load were significantly reduced. Furthermore, Opgenoord and Caplan[27] focused on delaying flow separation on the vehicle surface, ultimately deriving a waterdrop-shaped profile by managing upstream boundary layer transition.
The streamlining of the head and tail sections constitutes the core of the optimization,

aiming to delay flow separation and mitigate shock waves. By employing three-dimensional Hyperloop train models with appropriate streamlined curvatures to match parameters such as the blockage ratio, researchers have characterized the physical evolution of flow separation and shock wave formation within low-vacuum tubes. Following optimization, elliptical head and tail designs are recommended to align with these parameters; furthermore, the tube pressure must be reduced in accordance with the velocity and blockage ratio to optimize vacuum levels, thereby achieving a linear reduction in drag[28].

5. Conclusion

This paper systematically reviews the research progress on the aerodynamic characteristics of Hyperloop systems, conducting comprehensive discussions over three aspects: the evolution of research methodologies, the establishment of flow field structural hierarchies, and the optimization of vehicle shapes. The primary conclusions are as follows: First, regarding research methodologies, a comprehensive fluid mechanic research framework ranging from 1D to 3D has been established in this field. While simplified, 1D theoretical models can efficiently reflect the critical performance. 2D numerical simulations offer unique advantages in revealing shock wave evolution, choked flow mechanisms, and flow field hysteresis effects. Furthermore, 3D high-fidelity simulations compensate for the limitations of lower-dimensional models, accurately capturing complex spatial flow features resulting from engineering vehicle geometries, which serves as a critical bridge between theoretical analysis and engineering practice. Second, regarding flow field characteristics, the research reveals the flow field structure system within Hyperloop systems. The vehicle exhibits a clear hysteresis effect during acceleration and deceleration; that is, the flow field structure at a given speed depends on its prior operational state, a finding that imposes new requirements for vehicle operation and control strategies. From a near-field perspective, the flow field transitions through three typical regimes: subsonic, transonic, and supersonic, depending on the Mach number and the blockage ratio. Particularly, under supersonic conditions, the strong coupling between shock waves, boundary layers, and wake vortices collectively governs the flow structure. Shock waves not only alter pressure distribution but also exert significant rectification and suppression effects on the wake vortex system. Finally, regarding vehicle shape design, the speed level and blockage ratio is identified as the primary constraint affecting aerodynamic loads. The research indicates that simply mimicking the slender-body designs of aircraft is insufficient; the vehicle and the tube must be treated as a coupled system. By optimizing the streamlining of the head and tail and controlling the cross-sectional area distribution, the critical choking speed can be effectively delayed and shock wave intensity can be mitigated.

6. Future Perspectives

Given the diversity of maglev systems, Hyperloop train designs must break away from axisymmetric conventions to achieve customized matching with track topologies. The track configuration defines the boundary of the underbody flow field, directly determining the airflow compression characteristics and shock wave evolution within the levitation gap.

For U-type Tracks (e.g., Superconducting Maglev): The lower part of the vehicle is situated in a semi-enclosed space. High-speed operation can easily lead to the accumulation of a high-pressure air cushion beneath the car. Future optimization should focus on the matching design between the underbody contraction surfaces and the sidewalls. By constructing aerodynamic pressure-relief channels to divert high stagnation pressure, researchers can prevent sudden surges in aerodynamic lift that might trigger levitation instability.

For T-type Tracks (e.g., Electromagnetic Suspension Maglev): The wrap-around rail structure results in strong shear flow within the complex levitation gaps. Designs must focus on the optimization of conformal fairings and side skirts in the bogie region to suppress complex corner vortex shedding on the inner side of the wrapping arms. Additionally, efforts should be made to mitigate local shock waves induced by the Laval nozzle effect within the narrow gaps.

In summary, the next phase of research could establish a multi-objective optimization framework based on the strong coupling of the vehicle, track, and tube. Beyond pursuing minimum total resistance, it is essential to actively control the flow field structure within the levitation gap through refined underbody surface design. This will balance the coupled effects of aerodynamic lift and levitation guidance forces, ensuring attitude stability and thermal safety during ultra-high-speed operation.

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