Analyzing the Aerodynamic Resistance of a Transonic Vehicle With in an Air-Sealed Tube

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Abstract

Computational fluid dynamics was used to explore the aerodynamic drag characteristics of a Transonic Vehicle in an Evacuated Tube. Axisymmetric flow analysis was used to conduct a preliminary parametric assessment of the system over a wide range of values for the vehicle's speed (Machv), the evacuated pressure of the tube (Pret), and the blockage ratio (BR) between the vehicle and the tube. The BR was 0.1, 0.2, and 0.4, while the Pret was 100, 1,000, and 10,000 Pa. Based on the simulations, the aerodynamic drag of the vehicle increased with increasing BR and pressure. At Mach numbers close to the Kantrowitz limit, the drag coefficient (Cd) increased to its maximum before falling down, displaying the signature pattern of transonic flow. Subsequently, using the information provided by Hyperloop Alpha, a three-dimensional flow study was conducted by varying the Machv from 0.3 to 1.0 and adjusting the BR and Pret to 0.34 and 100 Pa, respectively. Because of the eccentricity of the vehicle inside the tube, the Cd from the three-dimensional flow simulations was calculated to be somewhat bigger than that of axisymmetric ones. Nonetheless, the Machv-based Cd pattern was consistent with axisymmetric designs.

Key words: Aerodynamic drag, Computational flow dynamics, Transonic vehicle, Evacuated tube, High-speed trains

1. Introduction

Robert H. Goddard, a pioneer in the field of rocketry, first advocated using an evacuated tube or tunnel as a means of transportation in 1909 [1]. Possible benefits include a drastic reduction in aerodynamic drag and the elimination of aero-acoustic noise pollution from trackside locations. The United States Federal Railroad Administration studied the tube-vehicle concept from 1966 to 1969.

It is the policy of [2] state governments to explore the viability of different proposals using both atmospheric and evacuated tube methods. The aerodynamic drag of a vehicle in a tube has been researched using a broad range of Mach number and Reynolds number, and fundamental aerodynamic studies have been undertaken utilizing experimental equipment. EPFL in Switzerland has been researching a proposal called "Swissmetro" [3] for an extremely high speed maglev in an evacuated tube. A commercial speed of 400 km/h is achieved with the use of two tiny diameter tunnels, each measuring about 5 m in length, and operating under a partial vacuum of 0.1 atm. Between 1994 and 1999, researchers focused on aerodynamic factors such as blockage ratio, partial vacuum, and aerodynamic drag. Early this century saw a flurry of research on this mode of transportation in the northeast Asian countries [4-6]. Despite the studies' optimistic findings and favorable feasibilities, most of them had not gone further due to the prohibitive expenses of future research and development.

An exciting new idea called the Hyperloop has been proposed in 2013.

substitute for the Los Angeles to San Francisco high-speed rail project [7] that was presented by SpaceX. The Hyperloop system differs most noticeably from its predecessor conceptions in that its top speed is about 1220 km/h, or Mach number 0.91, whereas the others are not more than 700 km/h. Hyperloop's great speed makes it an attractive transportation option, since it bridges the gap between that of high-speed trains and that of jet jets. By placing a compressor at the front of the pod, the Hyperloop design avoids the so-called Kantrowitz limit [8], an insurmountable obstacle to supersonic travel in a tube. Hyperloop's potential is bolstered by the fact that it can be scaled down to a diameter of only 2.23 meters, or less than half that of the Swissmetro.

How Vehicle Aerodynamics Impact Performance in an Evacuated Tube

is crucial because aerodynamics is the foundation of the notion that lowering air density may reduce aerodynamic drag. Parameters of the controlling system, such as the tube diameter and vacuum level, are also determined by aerodynamics. As the Hyperloop requires special attention to the compressor, aerodynamics takes on more significance.

The air pressure within the tube is 100 Pa, and the air temperature is 20 °C; nevertheless, the flow regime of Hyperloop is unusual, with Reynolds numbers of 2.8104 and with high Mach numbers over 0.91. Moreover, vehicle-induced flow disturbances are amplified between the tube wall and the train, where they might then spread throughout the system.

distances along the tube that are too great for experimental and numerical methods.

Changing both the vehicle speed and the amount of evacuation allowed for this investigation of aerodynamic drag in a transonic vehicle in an evacuated tube. It has been described how the vehicle's aerodynamic drag is affected by the Mach number and the Reynolds number.

2. Axisymmetric flow simulations of the transonicvehicle-evacuatedtubesystem

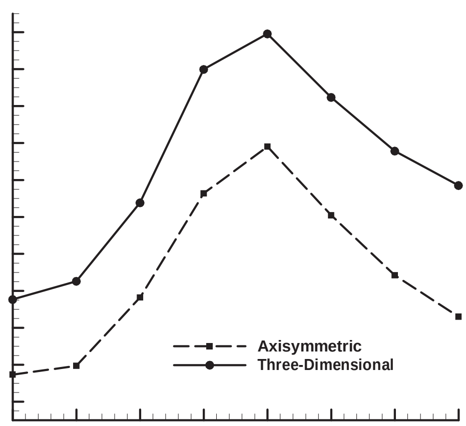
2.1 Steady state analysis of the axisymmetric flow in transonic vehicle-evacuated tube system

As a vehicle moves forward at a high rate of speed while remaining stationary, it causes compression waves to be formed in front of the vehicle and expansion waves to be generated behind the vehicle and to go in opposite directions. When determining the vehicle's dynamic stability, these wave propagations' effect on the tube's air pressure is crucial. In particular, the transonic vehicle's goal speed is extremely high, which may lead to significant coupling of wave propagation and shock, which in turn leads to substantial flow separation and damage to the vehicle's dynamic stability. So, it is necessary to execute an unsteady flow simulation in the transonic vehicle-evacuated tube system, with the complete computational domain equal to the distance over which the front and rear pressure waves travel. Nevertheless, calculating the vehicle's unsteadiness within the tube consumes a lot of computational power.

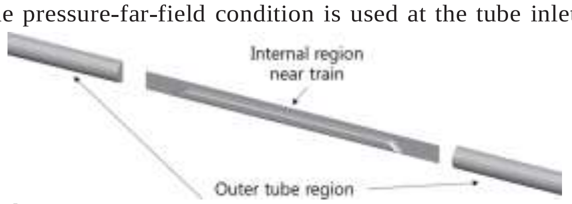
Parametric studies of design parameters for systematic design of a transonic vehicle traveling in a tube and the variation of aerodynamic coefficients like the drag coefficient (Cd) are of primary interest in this investigation, and steady-state calculations can be a good solution for the early stages of design. Hence, in an evacuated tube system, the front of the vehicle maintains a high pressure due to compression waves, while the back of the vehicle maintains a low pressure due to expansion waves. In addition, the length of the tubes in the system as a whole ensures that there will be a significant pressure differential between the front and rear of the vehicle even after the waves have reflected from the tube's exit and returned. The tube's flow may be assumed to be stable, allowing full use of the vehicle's aerodynamic features including pressure differential between the front and back of the vehicle, aerodynamic drag, and Cd. Thus, axisymmetric steady-state computations were used in this work to investigate the effect of different parameters on the drag and Cd of a transonic vehicle

In order to evaluate the actual C_D of the transonic vehicle, three dimensional flow field analysis was performed. At this time, the vehicle shape for the calculation of the three dimensional flow field was shown in Fig. 3; the reference area is the same as the axisymmetric cases about 1.4 m^2 and the total length of the vehicle is about 27 m. Here, the grid should be densely distributed around the vehicle, and the shape of the aligned grid is advantageous in the far region from the vehicle in order to maintain the flow information without dissipation. Therefore, the entire computational domain is divided into the internal region near vehicle and outer tube region as Fig. 14. At the boundary of inner and outer region, the interface boundary conditions were used which use non-conformal grid and allow the exchange of flow information. On the surface of the vehicle, triangular and square lattices were mixed as mm, and 20 layers constituted the boundary layer. After that, the tetrahedral grid was used to densely distribute the lattice around the inner vehicle. The outer region was created by extruding the lattice of the interface in the longitudinal direction of the vehicle. As a result, the total number of grids was composed of approximately 3,920,000 unstructured grids and the Y + value on the vehicle surface was set about $O(1)$.

The BR and Pre_t were determined as the specifications of the Hyperloop Alpha document; the BR was 0.36 with the Kantrowitz limit of 0.596 and the Pre_t was 100 Pa. Steady state flow analysis was performed using a density based solver by adjusting the $Mach_v$ varied from 0.3 to 1.0. Similar to the boundary conditions used in axisymmetric analyses,



the pressure-far-field condition is used at the tube inlet



and

the pressure outlet condition is at the tube outlet. And k-ω SST model was used for the calculation of turbulence. After the three dimensional flow calculations, the results were compared with those of axisymmetric ones.

The C_D and drag obtained from the analysis are shown in Table 3 and Fig. 16, respectively. The overall tendency between the results of axisymmetric and three dimensional

Fig. 14. Construction of entire computational domain

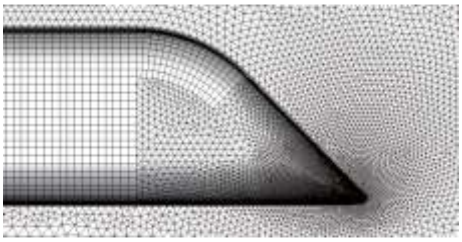


Fig. 15. Surface grid of the vehicle

Fig. 16. Comparison of CD between axisymmetric and 3D results

flow simulations are very similar. Similar to the axisymmetric cases of BR 0.4, a strong compression wave in front of the vehicle results in the decrease of $Mach_{in}$ in front of the vehicle below the Kantrowitz limit and the $Mach_v$ which Cd values started to decrease increased over the Kantrowitz limit. The quantitative difference of C_D value can be recognized between the axisymmetric and the three dimensional flow simulations. It is because the real vehicle is located eccentrically in the tube; the effective area of the flow at the bottom of the vehicle is reduced and stronger compression wave is formed in front of the vehicle than that of axisymmetric cases. However, since the tendency of the CD variation is similar to the axisymmetric one, it is possible to utilize the axisymmetric calculations with changing the main parameters in the initial design stage, and to calibrate the results by the three dimensional simulations.

Table 3. Results of axisymmetric and 3D, BR = 0.34, evacuation pressure = 100 Pa

$Mach_v$	C_d	Drag (N)	C_D	Drag (N)
0.3	2.7468	24.4	3.1526	14.19
0.4	2.7939	44.1	3.2515	26.02
0.5	3.1638	78.0	3.6762	45.97
0.6	3.7272	132.3	4.3985	79.20
0.7	3.9806	192.4	4.5389	95.91
0.8	3.6085	227.8	4.5905	112.50
0.9	3.2841	262.4	4.2464	135.92
1.0	3.0596	301.8	3.9562	160.27

4. Conclusion

In this study, the aerodynamic C_d and drag variation according to the main design parameters of the transonic vehicle-evacuated tube system such as $Mach_v$, BR and Pre_t were examined through steady state axisymmetric calculations.

First, as $Mach_v$ increased, C_d was maximized near Kantrowitz limit and decreased beyond Kantrowitz limit, which showed the typical transonic flow pattern. However, in case of large BR, the $Mach_v$ at which C_d became maximum exceeded beyond the Kantrowitz limit. It was because large BR caused the strong compression wave in front of the vehicle and the wave made $Mach_{in}$ below the Kantrowitz limit though $Mach_v$ exceeded the limit.

Second, as the BR decreased, the aerodynamic drag of the vehicle was reduced. This was because when the BR was small, the area between the vehicle and the tube was widened, the flow acceleration around the vehicle decreased and the coefficients of viscous drag also diminished. In addition, compression wave in front of the vehicle were weakened and the coefficients of pressure drag were reduced; at $Mach_v$ of 0.7 to 0.9 and Pre_t of 100 Pa, the C_d increased by about 30 - 40 % when the BR was doubled.

Third, as the Pre_t increased, the overall aerodynamic drag of the vehicle increased because of the increment of air density. However, the C_d decreased as Pre_t increased; the drag increased as 8 – 8.5 times when the Pre_t increased 10 times with large BR and low Pre_t conditions. Based on these results, three dimensional flow simulations were performed with vehicle under the conditions of BR of 0.36 and Pre_t of 100 Pa. It was confirmed that the overall tendency of the C_D variation was the same between axisymmetric and three dimensional results except the quantitative values of C_D. These results can be used as basic data for future development of transonic vehicle – evacuated tube system.

Acknowledgement

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References

[1] Goddard, R. H., "The Limit of Rapid Transit", *Scientific American*, Vol. 101, No. 21, 1909, pp. 366. DOI: 10.1038/ scientificamerican11201909-366d

[2] Trzaskoma, W. P., Tube Vehicle System (TVS) Technology Review, 1970, No. M70-4 Intrm Rpt.

[3] Bierlaire, M., Axhausen, K. and Abay, G., "The Acceptance of Modal Innovation: The Case of Swissmetro", *In Proceedings of the 1st Swiss Transportation Research Conference*, 2001.

[4] Shen, Z. Y., "On Developing High-Speed Evacuated Tube Transportation in China", *Journal of Southwest Jiaotong University*, Vol. 40, No. 2, 2005, pp. 133-137.

[5] Sato, Y., Konagai, K., Maeda, T., Saito, S., Satoh, T. and Ishida, M., "SUPERMETRO-Super-High-Speed-Train in Low Pressure Tunnel", *World Congress on Railway and*

Research, 2006.

[6] Lee, H. W., Cho, S. Y., Cho, W. Y., Lee, J. and Kwon, H. B., "Analysis of the Magnetic Effect on the Tube Infrastructure for a Super Speed Tube Train", *International Journal of Railway*, Vol. 2 No. 4, 2009, pp.170-174.

[7] Musk, E., "Hyperloop Alpha", SpaceX. Retrieved August 13 2013.

[8] Kantrowitz, A. and Donaldson, C. D., "Preliminary Investigation of Supersonic Diffusers", *National Advisory Committee on Aeronautics, Langley Memorial Aeronautical Laboratory, Langley Field, Virgini*a, 1945.

[9] Opgenoord, M. J. and Caplan, P. C.,"Onthe Aerodynamic Design of the Hyperloop Concept", *In Proceedings of the 35th AIAA Applied Aerodynamic Conference*, 2017.

[10] Van Wie, D. M., Kwok, F. T. and Walsh, R. F., "Starting Characteristics of Supersonic Inlets", AIAA paper 96-2914, 1996.

[11] ANSYS FLUENT 12.0 Theory Guide.