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Numerical simulation and analysis of aerodynamic drag on a subsonic train in evacuated tube transportation

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Abstract: The aerodynamic drag on a train running in an evacuated tube varies with tube air pressure, train speed and shape, as well as blockage ratio. This paper uses numerical simulations to study the effects of different factors on the aerodynamic drag of a train running at subsonic speed in an evacuated tube. Firstly, we present the assumption of a steady state, two dimensional, incompressible viscous flow with lubricity wall conditions. Subsequently, based on the Navier-Stokes equation and the k-ε turbulent models, we calculate the aerodynamic drag imposed on the column train with a 3-meter diameter running under different pressure and blockage ratio conditions in an evacuated tube transportation (ETT) system. The simulation is performed with FLUENT 6.3 software package. An analyses of the simulation results suggest that the blockage ratio for ETT should be in the range of 0.25–0.7, and the tube internal diameter in the range of 2–4 m, with the feasible vacuum pressure in the range of 1–10 000 Pa for the future subsonic ETT trains.

Key words: subsonic train; evacuated tube transportation; aerodynamic drag; blockage ratio

1. Introduction

High-speed Maglev evacuated tube transportation (ETT) is able to run at supersonic and even hypersonic speeds [1-5]. The operation speed at the initial stage should be in the subsonic range of 500–1000 km/h. The train running in the evacuated tube is subjected to aerodynamic drag, the value of which is function of tube air pressures, train speed and shape, and blockage ratios. The study of the effects of various factors that affect aerodynamic drag on the ETT train is necessary for a complete understanding of ETT aerodynamics.

ETT trains should run in a closed vacuum (rarefied gas) surrounding. This is in contrast to the dense gas surroundings in the tunnel where high-speed trains typically run. Furthermore, ETT trains run in a finite space which is different from the infinite boundary surroundings where a space shuttle flies. ETT aerodynamics is a new subject different from tunnel and aviation aerodynamics. Zhou et al. [6-7] simulated the aerodynamic drag on a ETT train and the blockage ratio of the ETT tube through a train model with half-arch front and tail, and obtained dynamic trends of the relationship among the air pressure in tube, the train speed, and the tube blockage ratio. However, they only considered speed under 200 m/s and air pressures above 1 000 Pa.

This paper explores a wider calculation range, such as the ETT train speeds ranging from 50 to 300 m/s and tube pressures from 10 to 10 000 Pa. Consequently, detailed numerical values of aerodynamic drag on the subsonic ETT train are obtained. Furthermore, this paper will search for an approach of selecting ETT tube section size from the aerodynamic consideration. Using FLUENT 6.3 software package, together with the assumptions of a steady two dimensional, incompressible viscous flow, and lubricity wall conditions, the Navier-Stokes equations coupled with k-ε turbulent models are applied in simulating the aerodynamic drag imposed on ETT trains running at different vacuum degrees and blockage rate conditions [8-9].

2. Calculation conditions

2.1. Basic consumptions

(1) The gas in ETT tube is incompressible and viscous, with a flow field space that is two dimensional and steady [10].

(2) The inside wall of tube and train body are smooth.

(3) The gas density accords with standard gas state equation $p=\rho RT$, the gas pressure p={10 132.5, 1 013.25, 101.325, 10.132 5} (Pa) and ρ={0.122 5, 0.012 25, 0.001 225, 0.000 122 5} (kg/m^3).

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(4) Flow field Reynolds number Re is defined in accordance with Refs. [11-13] as

$$Re = \frac{\rho VL}{\mu},$$

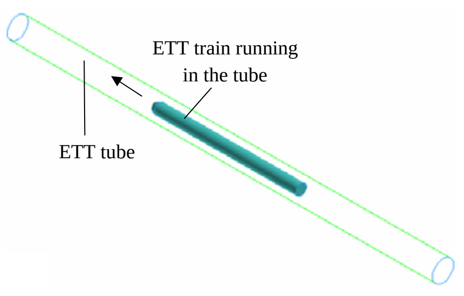
where the gas density ρ=[0.000 122 5, 0.122 5] (kg/m^3), the speed of train V=[50, 300] (m/s), the characteristic length L=6 m, and viscous coefficient μ=[1.421 6, 1.789 4] (×10^{-5} Pa·s) [12-13]. Hence the minimum Reynolds number, min{Re} is given by the expression:

$$\min\{Re\} = \frac{\min\{\rho VL\}}{\max\{\mu\}} = \frac{0.000\,122\,5 \times 9.8 \times 50 \times 6}{1.789\,4 \times 10^{-5}} = 20\,127.$$

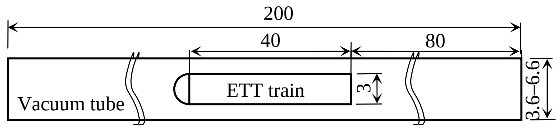
Since the minimum Re number is much more than 2 000, the flow is considered turbulent.

2.2. Model geometry

The geometry of the model used for calculating the aerodynamic drag is shown in Fig. 1. In the model, the ETT train is columned, with a diameter of D_1=3 m, body length 40 m and a semi-spherical front. The distance from the train front to the inlet of the vacuum tube is 80 m, and the distance from the train tail to outlet is also 80 m. The entire tube length is 200 m, and the tube diameter D_0 used for calculating the aerodynamic drag is 3.6, 4, 5, 6 and 6.6 m.



(a) 3D figure of the model geometry



(b) Model geometry with size indication

Fig. 1 Model geometry (unit: m)

2.3. Grid meshing by Gambit tool

The meshing of the model geometry as appropriate on the basis of the blockage ratio was accomplished using Gambit software tool. The geometry of the model in this paper is assumed to be axis symmetric. In order to simplify the calculation and accelerate convergence, a half flow field calculation region is considered. A sketch of model grid meshing is shown in Fig. 2.

For simplicity, we assume a frame of reference in which the train is stationary, and the gas is in motion.

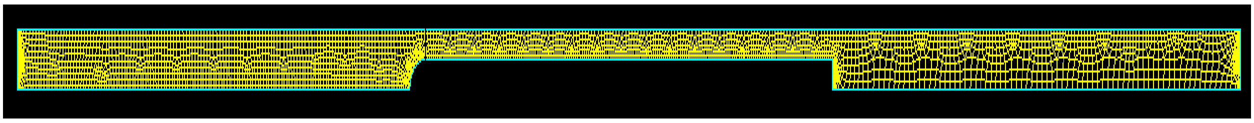


Fig. 2 2D model grid meshing

2.4. Solver settings in FLUENT 6.3

The main solver settings in FLUENT 6.3 are as follows:

- Solver: Pressure-based
- Space: 2D
- Formulation: Implicit
- Time: Steady
- Velocity formulation: Green-Gauss Cell Based
- Energy Equation: Not included
- Viscous mode: k-ε (2 equation)
- k-ε model: Standard
- Near-wall treatment: Standard wall functions
- Operating pressure: 0 Pa
- Boundary conditions: Velocity-inlet and outflow
- Temperature: 300 K
- Modified turbulent viscosity: 1.789 4×10^5 kg/(m·s)

3. Calculation and analysis

The aerodynamic drag imposed on ETT train is calculated according to the following equation:

$$F = C_\mathrm{d} \cdot S / 1\ 000,$$

where C_d is the drag coefficient obtained from FLUENT simulation, in N/m^2; S is the train section area: S=3.14×1.5^2=7.065 m^2.

When the air pressure intensity in ETT tube is 10 132.5, 1 013.25, 101.325, and 10.132 5 Pa, different aerodynamic drags on the trains running in tubes under different blockage ratios and at different speeds are calculated and listed in Tables 1, 2, 3, and 4, respectively.

From Table 1, when the internal diameter of tube, D_0 is 6 m, the blockage ratio α =0.25 and train speed

V=300 m/s, the aerodynamic drag F=46.165 kN, which is within the traction capacity range of common trains. It indicates that as long as the blockage ratio is less than 0.25, the ETT train can run at a subsonic speed only when the air pressure in ETT tube is reduced to 1/10 (about 10 000 Pa) of standard atmosphere pressure.

From Table 2, when the internal diameter of tube D_0 is 5 m, the blockage ratio α=0.36 and train speed V=300 m/s, the aerodynamic drag F=31.156 kN, which is also within the traction capacity range of common trains. It indicates that as long as the air pressure intensity in ETT tube is reduced to 1/100 (about 1 000 Pa) of standard atmosphere pressure, the tube internal diameter of 5 m can meet the requirement that the ETT train runs in subsonic range; namely the blockage ratio is increased to 0.36. However, it should be noted that an aerodynamic drag of 31.156 kN is still high for an ETT train. Thus, if we want to reduce tube section or increase blockage ratio, the air pressure intensity in tube must be reduced further.

From Table 3, when the inside diameter of tube D_0=3.6 m, the blockage ratio α=0.69 and train speed V=300 m/s, the aerodynamic drag F=15.550 kN, which is also within the traction capacity range of common

Table 1 Aerodynamic drags on trains running in ETT tubes at 10 132.5 Pa

V (m/s)	D_0=6.6 m, α=0.21		D_0=6 m, α=0.25		D_0=5 m, α=0.36		D_0=4 m, α=0.56		D_0=3.6 m, α=0.69	
	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)
50	163.66	1.156	174.05	1.23	1 227.00	8.669	2 991.06	21.132	6 103.28	43.120
100	666.82	4.711	706.98	4.99	4 914.19	34.719	1 1964.51	84.529	24 409.64	172.454
150	1 513.39	10.692	1 605.89	11.35	11 065.65	78.179	26 934.85	190.295	54 914.42	387.970
200	2 711.40	19.156	2 876.36	20.32	19 691.71	139.122	47 879.68	338.270	97 614.76	689.648
250	4 261.52	30.108	4 518.48	31.923	30 775.73	217.431	74 805.10	528.498	152 511.70	1 077.495
300	6 223.30	43.968	6 534.28	46.165	44 316.75	313.098	107 712.74	760.991	219 607.63	1 551.528

Table 2 Aerodynamic drags on trains running in ETT tubes at 1 013.25 Pa

V (m/s)	D_0=6.6 m, α=0.21		D_0=6 m, α=0.25		D_0=5 m, α=0.36		D_0=4 m, α=0.56		D_0=3.6 m, α=0.69	
	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)
50	14.91	0.105	15.73	0.111	121.96	0.862	298.79	2.111	611.04	4.317
100	61.56	0.435	64.56	0.456	488.71	3.453	1 195.22	8.444	2 442.81	17.258
150	141.11	0.997	147.41	1.041	1 100.58	7.776	2 689.46	19.001	5 494.82	38.821
200	252.74	1.786	264.63	1.870	1 958.03	13.833	4 781.57	33.782	9 767.52	69.008
250	398.41	2.815	417.08	2.947	3 060.89	21.625	7 471.81	52.788	15 259.89	107.811
300	577.63	4.081	604.17	4.268	4 409.91	31.156	10 760.15	76.020	21 972.78	155.238

Table 3 Aerodynamic drags on trains running in ETT tubes at 101.325 Pa

V (m/s)	D_0=6.6 m, α=0.21		D_0=6 m, α=0.25		D_0=5 m, α=0.36		D_0=4 m, α=0.56		D_0=3.6 m, α=0.69	
	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)
50	1.31	0.009	1.38	0.010	12.13	0.086	29.92	0.211	61.40	0.434
100	5.47	0.039	5.70	0.040	48.57	0.343	119.60	0.845	245.07	1.731
150	12.61	0.089	13.14	0.093	109.38	0.773	269.01	1.901	550.89	3.892
200	22.74	0.161	23.71	0.168	194.60	1.375	478.16	3.378	978.82	6.915
250	36.06	0.255	37.53	0.265	304.23	2.149	747.04	5.278	1 528.80	10.801
300	52.53	0.371	54.56	0.385	438.33	3.097	1 075.68	7.600	2 200.92	15.550

Table 4 Aerodynamic drags on trains running in ETT tubes at 10.132 5 Pa

V (m/s)	D_0=6.6 m, α=0.21		D_0=6 m, α=0.25		D_0=5 m, α=0.36		D_0=4 m, α=0.56		D_0=3.6 m, α=0.69	
	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)	C_d	F (kN)
50	0.07	0.001	0.09	0.001	1.22	0.009	3.07	0.022	6.40	0.045
100	0.36	0.003	0.42	0.003	4.84	0.034	12.08	0.085	24.80	0.175
150	0.96	0.007	1.06	0.008	10.85	0.077	26.89	0.190	55.46	0.392
200	1.83	0.013	2.02	0.014	19.23	0.136	47.89	0.338	98.60	0.697
250	3.14	0.022	3.31	0.023	30.25	0.214	74.72	0.528	153.96	1.088
300	4.44	0.031	4.74	0.034	43.61	0.308	107.81	0.762	221.65	1.566

trains. It indicates that as long as the air pressure intensity in ETT tube is reduced to 1/1 000 (about 100 Pa) of the standard atmosphere pressure, the tube inside diameter can be reduced to 3.6 m [14]. That is, the blockage ratio is increased to 0.69, and the ETT train can run in the whole subsonic range.

From Table 4, for blockage ratio α=[0.25, 0.69] and train speed V=[50, 300] (m/s), the aerodynamic drag is F=[0.001, 1.566] (kN). It indicates when the air pressure intensity in ETT tube is reduced to 1/10 000 (about 10 Pa) of the standard atmosphere pressure, for blockage ratio in any feasible range, the aerodynamic drag is reduced to a quite low level. For the ETT system, when the blockage ratio is greater than 0.7, the structure of ETT train and tube section will become unreasonable. On the other hand, when the blockage ratio is less than 0.2, the overmuch ETT tube section redundancy will make the ETT system uneconomical. Thus, this paper suggests α should be in the range of 0.2–0.7 as a reasonable value for the blockage ratio of ETT system. Nevertheless, this does not necessarily imply that this value is the optimum.

4. Conclusions

The diameter of the column ETT train in the geometry model used for calculating the aerodynamic drag in this paper is 3 m, which is close to the size of carriage of the current international standard railway. When the tube internal diameter is increased to 4 m and the air pressure in the tube is 10 Pa, aerodynamic drag on the ETT train reduces. However, the increase in the diameter of ETT tube not only increases the construction costs of the ETT system, but also the costs associated with creating and maintaining the required vacuum surroundings. Therefore, it is recommended that the internal diameter of the ETT tube should not exceed 4 m.

In the case of an air pressure of 10 000 Pa in the ETT tube, if the blockage ratio α is very small, such as 0.25, the aerodynamic drag on ETT train in subsonic range is also in the range of the train traction capacity. However, an increase of α increases the aerodynamic drag on an ETT train beyond the capacity range of traction that train can provide. Since a blockage ratio 0.25 is too small for ETT, the air pressure intensity in the future ETT system should be less than 10 000 Pa. This means that the blockage ratio of ETT should be more than 0.25, so that the air pressure intensity in ETT tube can be further reduced so as to keep the aerodynamic drag on ETT train at a low level.

When the air pressure in ETT tube is 10 Pa, the aerodynamic drag on trains running in subsonic range (up to 300 m/s) will not go beyond the train traction capacity. When the air pressure is less than 10 Pa, ETT train running in a subsonic range will run in the surroundings almost without resistance.

From the above reasons, two important conclusions are obtained:

(1) Reasonable internal diameter of a subsonic ETT tube should be in the range of 2 to 4 m.

(2) Reasonable air pressure in the subsonic ETT tube should be in the range of 1 to 1 000 Pa.

At the same running speed, the higher blockage ratio means the smaller tube section. As a result, the cost of the ETT tube construction and the cost of creating vacuum surroundings and maintaining vacuum will be low, but the vacuum degree in ETT tube need to be higher. The higher vacuum degree means higher cost in creating and maintaining vacuum. Thus, the optimum values of blockage ratio and vacuum degree needs to be determined by further analysis and comprehensive economic comparison.

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