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Aerodynamic Drag of Hypersonic Astrotrain

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A WISH TO NEXT GENERATION

In a new century people need new dreams. One of them is the development of Astrotrain. This train, which is magnetically levitated and driven by the linear-motor, runs in an evacuated tube with hypersonic speed. It is named Astrotrain because it runs in an artificial space. Frank P. Davidson[1] of MIT has the opinion that the transportation system by Astrotrain is one of the most possible macro-engineering projects of the twenty-first century. Astrotrain will bring most of the earth's metropolitan area within one hour of commuting time from each other. The realization appears to be only a matter of investment decisions of the next generation of our planet.

The design speed of the linear-motor train MLU002, which is a prototype of commercial train in Japan, is 500 km/h.[2] It is levitated by superconducting NbTi magnet. The aerodynamic drag D of the train is proportional to $p_\infty U^2$, where p_∞ is the pressure of undisturbed air and U is the train speed. Since D is proportional to U^2, the speed of MLU002 is limited to 500 km/h. Astrotrain runs in the evacuated tube. If $p_\infty \rightarrow p_\infty/1,000$ and U $\rightarrow$ 10U, then D $\rightarrow$ D/10; the drag is one tenth even at the train speed of 5,000km/h. Since we wish that the first Astrotrain run in the narrow Japan Islands, its speed is chosen to be 6,200km/h (Mach number 5) in this paper. Figure 1 shows the case when we enjoy a trip of 1,000 km. It takes 12.6 minutes. Acceleration is set equal to that of gravity.

RAREFIED FLOW AROUND ASTROTRAIN

Figure 2 shows the model of Astrotrain with an ellipsoidal nose. Our previous model was a simple cylinder with a flat nose.[3] We can expect a large reduction of the pressure drag by this improved model. Rarefied flow around the model is calculated by use of the Monte Carlo direct simulation method.[4] The molecular collision is treated by the collision number scheme.[5] Gas is a monatomic one. The viscosity is assumed to be proportional to the

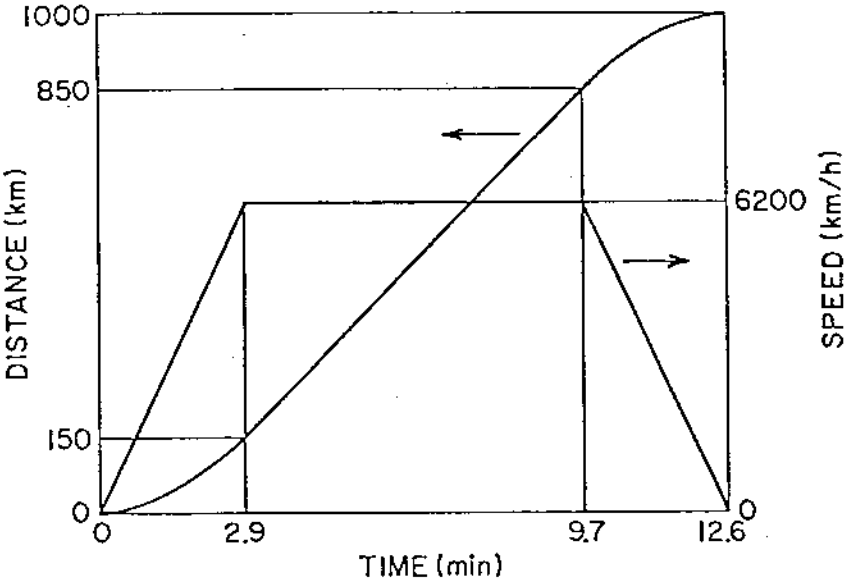
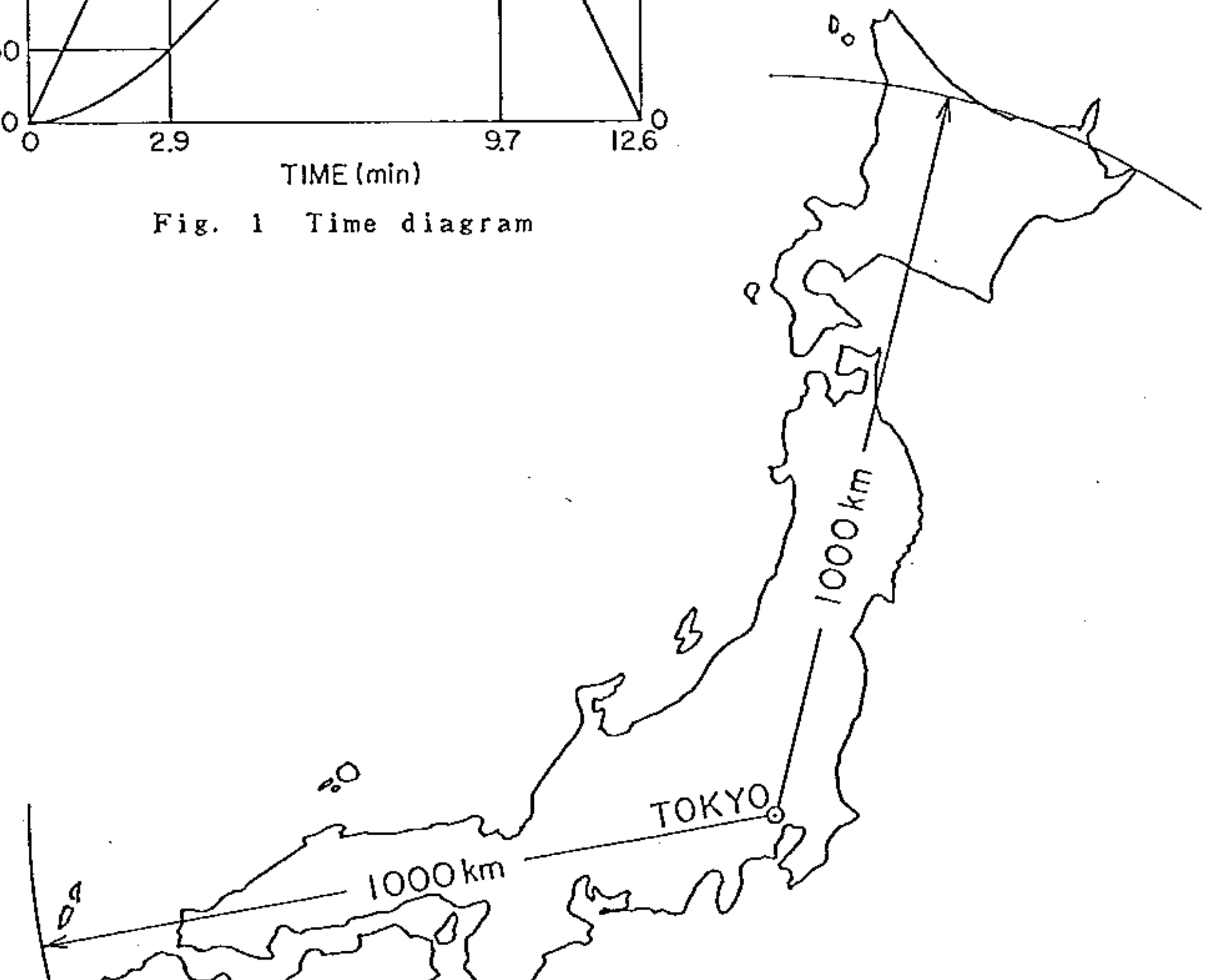


Fig. 1 Time diagram



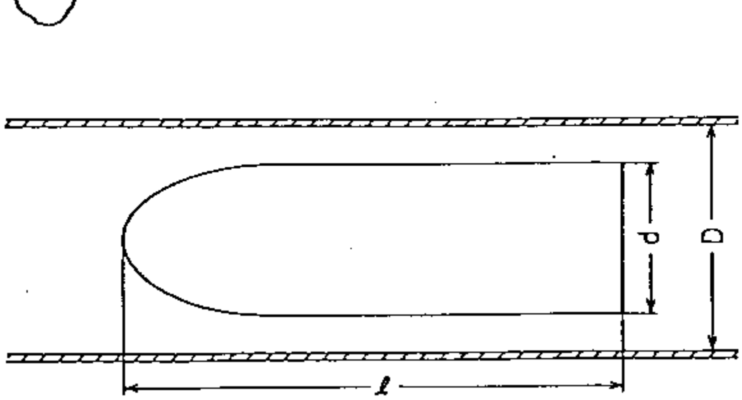


Fig. 2 Model of Astrotrain

temperature. The train runs with the Mach number M_∞ in the undisturbed gas of the density ρ_∞ and temperature T_∞. The computations are performed for the following conditions.

(a) Mach number $M_\infty (= U/\sqrt{\gamma R T_\infty}) = 5$

(b) Knudsen Number, $Kn (= \lambda_\infty / D) = 0.1, 0.01$

(c) Diameter of train, $d = (2/3)D$

(d) Length of train, $\ell = 5d, 10d, 15d$

(e) Aspect ratio of nose ellipsoid, 2:1

(f) Temperature of tube wall is T_∞.

(g) Temperature of train wall is equal to T_∞ except the nose. Along the nose it is

$$T_w = T_\infty (1 + 0.5(\gamma - 1) M_\infty{}^2 \sin^2\theta)$$

where θ is the angle between the axis of the tube and the tangent to a generating line of the ellipsoid. It is equal to the stagnation temterature T_0 at the top of the nose ($\theta = 0$) and to T_∞ at the junction point ($\theta = \pi/2$).

A. Flow field Here we show only the results for $\ell/d = 5$. The velocity fields for $Kn = 0.01$ and 0.1 are shown in Fig. 3. The velocity vectors are those observed by a passenger in the train. The flow in the gap between the train and tube is of the Couette type. The velocity slip is large for $Kn = 0.1$. The density contours are in Fig. 4, in which the spacing of ρ/ρ_∞ is 0.2. The bow shock is much more curved than the shock appeared in case of the flat nose.[3] The density field behind the train is the same whether the nose is ellipsoidal or flat. The temperature contours are in Fig. 5.

B. Drag coefficient The total drag D is the sum of the pressure drag D_p and the skin friction drag D_f. Let us introduce the drag coefficients C_D, C_p, C_f by dividing D, D_p, D_f by $\rho_\infty U^2 A/2$, where $A (= \pi d^2/4)$ is the cross-sectional area of the train. Figure 6 shows C_p and C_f for $Kn = 0.01$ as a function of ℓ/d. The data for the flat nose are also included. The value of C_p for the ellipsoidal nose is much smaller than that for the flat nose whereas C_f hardly depends on the nose shape. The coefficient C_f is a linear function of ℓ/d, and C_p is independent of ℓ/d, i. e.

$$C_f = 0.357(\ell/d) + 0.283, \quad C_p = 0.613 \qquad (1)$$

If ℓ/d is large, the second term of C_f can be neglected. We can then say that C_f is proportional to ℓ/d. Table 1 shows the data for the ellipsoidal nose. The coefficient C_N is a contribution to C_D from the part of the nose. It is about double C_p. Table 2 is

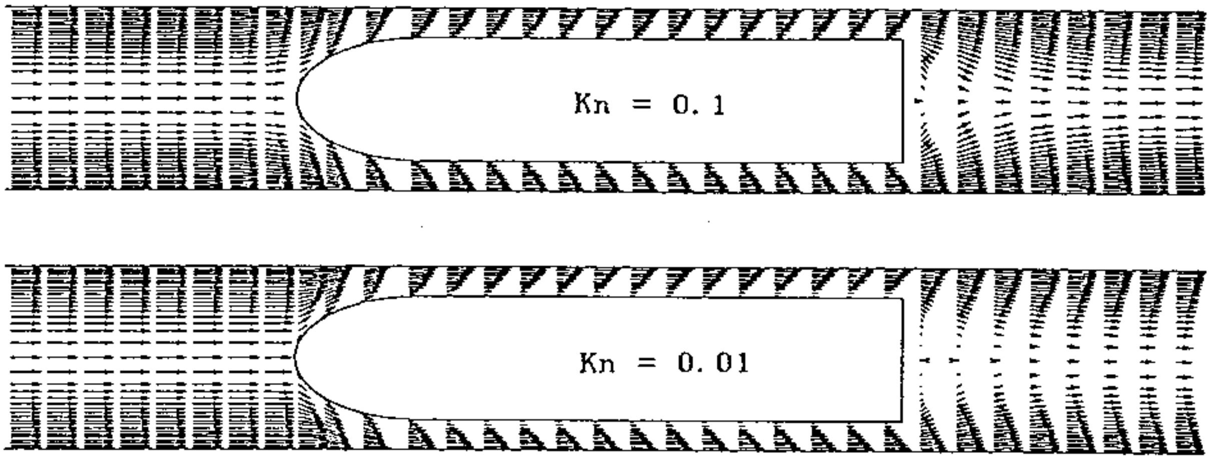


Fig. 3 Velocity field (M_∞ = 5)

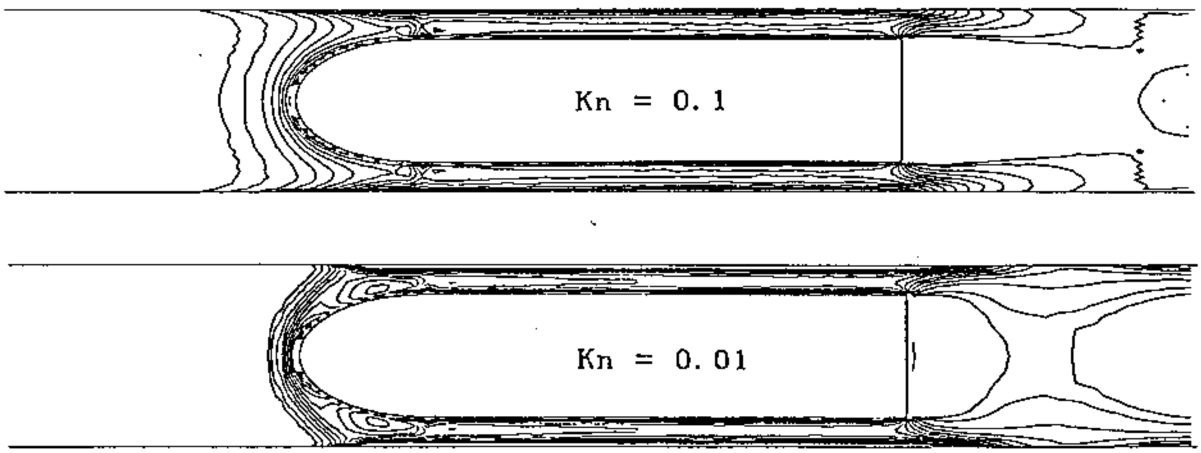


Fig. 4 Density contours (M_∞ = 5)

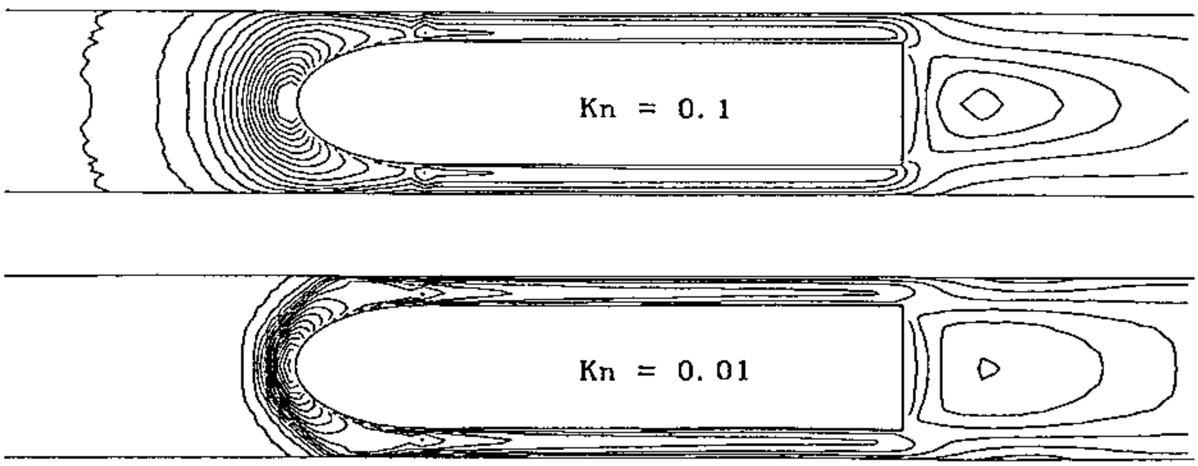


Fig. 5 Temperature contours (M_∞ = 5)

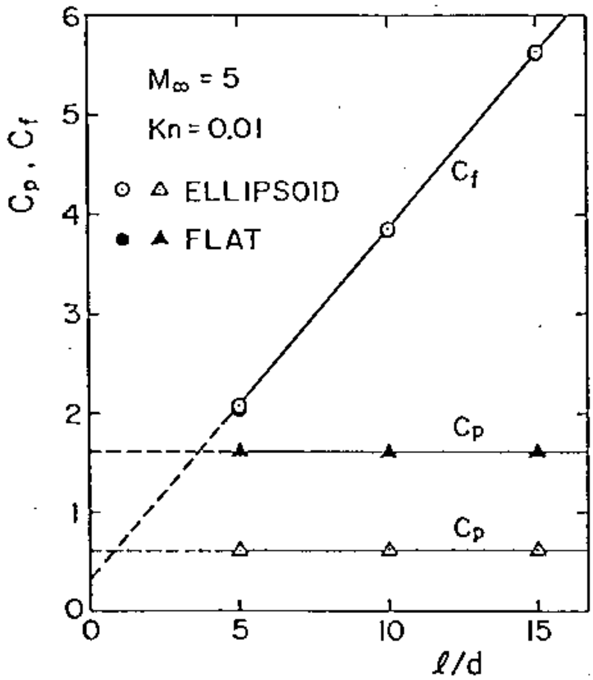


Fig. 6 Drag coefficients

Table 1 Drag coefficients (Ellipsoidal nose)

Kn	ℓ/d	C_p	C_f	C_D	C_N
0.1	5	0.884	5.410	6.295	2.036
0.01	5	0.614	2.075	2.689	1.158
0.01	10	0.612	3.853	4.465	1.152
0.01	15	0.614	5.640	6.253	1.158

Table 2 Drag coefficients (Flat nose)

Kn	ℓ/d	T_w	C_p	C_f	C_D
0.1	5	T_∞	1.978	5.205	7.183
0.01	5	T_∞	1.660	1.915	3.576
0.1	5	T_0	2.298	5.309	7.607
0.01	5	T_0	1.612	2.038	3.650
0.001	5	T_0	1.570	1.561	3.130
0.01	5	T_0	1.612	2.038	3.650
0.01	10	T_0	1.605	3.826	5.431
0.01	15	T_0	1.603	5.605	7.217

the data for the flat nose. Two cases of $T_w = T_\infty$ and T_0 are considered. The effect of T_w on C_D is small at Kn = 0.01. Note that the continuum data of Kn = 0.001 can be obtained by the Monte Carlo direct simulation method.

C. Drag of Astrotrain   The value of C_D is necessary for the design of Astrotrain. Tentative design parameters are: U = 6,200km/h (M_∞ = 5), D = 3m, d = 2m, ℓ = 200m, and p_∞ = 0.001 atm, where p_∞ is the pressure of the residual air in the tube. The parameters M_∞ and d/D are the same as before. The values of ℓ/d, Kn, and γ for the present Astrotrain are

$$\ell/d = 100,\ Kn = 0.000022,\ \gamma = 1.4 \qquad (2)$$

We estimate C_D for condition (2) from the results in Sec.B as follows. Since ℓ/d = 100, we obtain from eq. (1)

$$C_f = 35.98,\ C_p = 0.613 \qquad (3)$$

for Kn = 0.01, and γ = 5/3. The effect of Kn on C_f and C_p has been examined for the train model of ℓ/d = 5 with the flat nose. The data are in Table 2. These coefficients decrease slowly with Kn. The values of C_f and C_p at Kn = 0.001 are, respectively, 0.7659 and 0.9739 times those at Kn = 0.01. It is most probable that both C_f and C_p are independent of Kn for Kn$<$0.001. Using these correction factor, we have, from eq. (3)

$$C_f = 27.56,\ C_p = 0.597 \qquad (4)$$

for Kn = 0.000022 and γ = 5/3. The correction for γ is made as follows. The modified Newtonian theory tells that the drag coefficient C_D (= $C_f + C_p$) of the disk, sphere, and cylinder is proportional to $(\gamma + 3)/(\gamma + 1)$ for hypersonic flows.[6] We use this rule. Multiply the sum of C_f and C_p by 1.048, and the final C_D for condition (3) is 29.51.

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