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A Study on Aerodynamic Heating at Jovian Atmospheric Aerocapture. I.

by

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Abstract

The numerical simulations of drag and aerodynamic heating to the spacecraft during Jovian aerocapture have been conducted. DSMC method is used for the simulations of flow fields around the spacecraft. The transient changes of drag due to Jovian atmosphere and total heat loads to the spacecraft are obtained. The results show the estimated heat loads could be within allowable heat load when proper ablation heat shield technique is applied. Also, the results shows Jovian aerocapture could save total mass of spacecraft or could increase payload of spacecraft compared with retro-rocket blowing for space flight to Jupiter.

Keywords: Aerocapture, Aerodynamic heating, Rarefied flow, DSMC, Jovian atmosphere

1. Introduction

Jupiter is coming to next destination for manned or unmanned exploration. Pioneer X, Pioneer XI, Voyager I, Voyager II and Galileo have already reached and obtained huge amount of scientific data. The mass of Galileo and Cassini-Huygens are in total 2561 kg and 5280kg respectively. Explorations in next generation will be larger scale manned or unmanned missions due to increasee of requested instrument for Jovian exploration. Therefore, reduction of mass of explorer is one of critical problems. In fact, propellant mass of Cassini-Huygens is about 2800 kg, which is about 57% of total mass. Aerocapture is one of the hopeful techniques to reduce propellant mass which occupies significant amount of total mass of explorers.

Many researches have been conducted on aerocapture using various planetary atmospheres. However, Jovian atmosphere has not been considered because of Jovian massive gravity and consequent entry speed of 47 km/sec. The speed can never be reproduced by any

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kind of ground test facilities including hypersonic and high enthalpy wind tunnels. The only two spacecrafts, which flew through Jovian atmosphere, were Galileo and its entry capsule probe. Some researches on them are conducted in the past. Though the probe penetrated deeply into the atmosphere and data of aerodynamic heating during entry were obtained, quite few data are available in the estimation of aerodynamic heating in Jovian aerocapture.

In the present study, the numerical simulations of drag and aerodynamic heating to the spacecraft during Jovian aerocapture have been conducted. At first step orbital analysis has been conducted to obtain the trajectory of aerocapture by using Jovian atmospheric model. Typical properties along the trajectory in the orbital analysis is shown in **Table 1**. As shown in the Table, density of Jovian atmosphere in the aerocapture trajectory is quite dilute. Since the spacecraft begins to enter into atmosphere from the most outer region of Jovian atmosphere, rarefied flow analysis is requested. Also estimation of Knudsen number based on characteristic length of grid size for computation is order of 10^{-1} at the bottom of aerocapture trajectory. From the above flow condition, it is decided to use Direct Simulation Monte Carlo (DSMC) for numerical simulation[1-5]. Properties for the computation are sampled from orbit analysis conducted by Aso et al[6].

Table 1 Flow conditions at each computation point.

Time [s]	ρ [kg/m^3]	V [m/sec]	T [K]
198	1.0E-06	46,800	160
214	2.0E-06	46,700	150
229	3.0E-06	46,500	161
244	3.5E-06	46,300	157
264	3.0E-06	46,000	161
280	2.0E-06	45,800	150
298	1.0E-06	45,700	160

2. DSMC method

DSMC is very powerful numerical method for rarefied flow field. The method discretizes physical space and time based on finite difference method, and velocity space in stochastic method. In the DSMC method, flow field is divided into many small computational cells and real particles in each cell are represented by some sample particles whose physical properties are chosen under stochastic rules. It was first proposed by Bird and improved and studied for many years[1]. The method is connected with Boltzmann equation by Nambu in 1980[2].

DSMC method requires too much cost to be conducted on personal computer for large flow field which contains huge amount of molecules. Consequently, some assumptions are introduced to simplify the problem without losing essential meaning of the present study. The assumptions are as follows: 1) The flow field is axisymmetric and the spacecraft is circular cylinder as shown in **Fig. 1**. 2) The fluid is pure hydrogen (real Jovian atmosphere contains 10.2% helium). 3) Chemical reactions of dissociation-recombination are considered,

however, ionization is not considered. 4) Chemical reactions involving surface are neglected. The ablative thermal protection is most promising in such high enthalpy situation. But, surface reactions of ablator include really complicated problems which is not necessary feasibility study of aerocapture in Jovian atmosphere.

3. Physical models

3.1 Particle collisions and chemical reactions

Particle collisions occur in each cell and sample particles in the cell have some probabilities of collision each other. In principle, it is necessary to calculate all the probabilities and to let particles collide each other under calculated probabilities. In this case, the number of particle pairs, which have probabilities of collision, increase almost in proportion to square of the number of particles in the cell. Then, the cost of collision computation becomes unrealistically too large. In the present calculation, collisions between particles are calculated by Nanbu's *Maximum Collision Number Method*[7], which reduce the computation cost drastically.

For mixture gas, the method is expressed as follows:
The maximum collision probability between chemical species s and r in a cell is expressed as

$$P_{\max}(s,r)=n_r\cdot\Delta t\cdot\frac{1}{N_r}g_{\max}(s,r)\cdot\sigma_{T,\max}(s,r), \tag{1}$$

where n_r, N_r, $g_{\max}(s,r)$ and $\sigma_{T\max}(s,r)$ denotes number density of real particle of species r, number density of sample particle of species r, possible maximum relative speed between particles of species s and r and possible maximum total collision cross section between particles of species s and r respectively. Next, in order simplify above equation, we introduce $G_{\max}(s,r)$ as follows:

$$G_{\max.}(s,r)=g_{\max}(s,r)\cdot\sigma_{T,\max}(s,r) \tag{2}$$

By making use of $n_r=W_rN_r/V$, equation (1) is written as follows:

$$P_{\max}(s,r)=\frac{W_r}{V}\cdot\Delta t\cdot G_{\max}(s,r) \tag{4}$$

where, W_r denotes "weight" which means the number of real particles represented by one sample particle. However, as $P_{\max}(s,r)=P_{\max}(r,s)$, the larger of W_r and W_s should be used in place of W_r of Eq.(4). Hence, Eq.(4) could be modified as

$$P_{\max}(s,r)=\frac{\max(W_r,W_s)}{V}\cdot\Delta t\cdot G_{\max}(s,r) \tag{5}$$

Finally,

$$N_{\max}(s,s)=\frac{N_s(N_s-1)}{2}W_sG_{\max}\frac{\Delta t}{V}\quad\text{when}\quad r=s \tag{6a}$$

$$N_{\max}(s,r)=N_sN_r\max(W_s,W_r)G_{\max}\frac{\Delta t}{V}\quad\text{when}\quad r\neq s \tag{6b}$$

where $N_{\max}(s,s)$ is maximum collision number among species s and $N_{\max}(s,r)$ is maximum collision number between species s and r respectively.

Next, for any particle pairs,

$$G(s,r)=g(s,r)\cdot\sigma_T(s,r) \tag{7}$$

and the probability, P, of real collision is expressed as follows:

$$P=\frac{G(s,r)}{G_{\max}(s,r)} \tag{8}$$

Only for $N_{\max}$ pairs chosen randomly from all probable pairs, real collision occurs by using acceptance rejection method in which P is estimated by Eq.(8).

Total collision cross section $\sigma_T(r,s)$ is modelled by Variable Hard Sphere (VHS) Model[5]. Total collision cross section in VHS is given as follows:

$$\sigma_T=\sigma_{T,ref}(C_r/C_{r,ref})^{1-2\omega} \tag{9}$$

where C_r, $C_{r,ref}$ and $\sigma_{T,ref}$ is relative collision speed between two collision particles, reference collision speed and its corresponding collision cross section respectively. In Eq.(9) ω is the index of a power low temperature dependence of the coefficient of viscosity which is expressed as follows:

$$\mu=\mu_{ref}(T/T_{ref})^{\omega} \tag{10}$$

It is clear from Eq.(10) that coefficient of viscosity at only two temperatures are needed to determine ω. We rewrite Eq.(9) as follows:

$$\sigma_T=AC_r^{1-2\omega}, \tag{9'}$$

where constant coefficient A is as follows:

$$A=\frac{15\times 4\pi}{32\Gamma\left(\frac{9}{2}-\omega\right)\mu_0}\left(\frac{mkT_0}{\pi}\right)^{\frac{1}{2}}\left(\frac{4kT_0}{m}\right)^{\frac{2\omega-1}{2}} \tag{11}$$

Kinetic parameters needed to determine ω and A are transformed from database constructed by Park[8]. Chemical kinetic parameters are also given in the database

Thermally nonequilibrium is expressed by inelastic collision of Larsen-Borgnakke model[9]. Rotational relaxation probability is fixed as 0.2. Anharmonic oscillator model is used and vibrational energy is quantized by Boyd's method[10-15]. That is,

$$E_{vib}=qk\theta_{vib}\left(1-\frac{\theta_{vib}}{4\theta_D}q\right) \tag{12}$$

where E_{vib}, k, θ_{vib}, θ_D and q is the vibrational energy of the molecule, Boltzmann's constant, vibrational characteristic temperature, dissociation characteristic temperature and random integer, which satisfies the following condition, $E_{vib}+E_{rot}<E_{dis}$ respectively.

Chemical reactions are modelled with vibrationally favored dissociation (VFD) model combined with Bird's recombination model[5]. In VFD model, dissociation probability P_D is given as follows:[13]

$$P_D=\beta\frac{(E_C-E_D)^{\Psi}}{(E_C-E_V)^{\xi}}E_V^{\phi} \tag{13}$$

where, E_C, E_D, and E_V are total collision energy, the energy required for dissociation and vibrational energy respectively. In eq.(13) ϕ is an arbitrary number. It is revealed that the calculated result at $\phi=0$ show the best agreement with experimens in case of VFD model

combined with anharmonic oscillator model. Also, β, ψ and ξ of Eq.(13) are expressed as follows:

$$\beta=\varepsilon\frac{a_f\sqrt{\pi/4}(\mu/2)^{1/2-2/\alpha}}{\sigma k^{b_f}C_v T_{ref}}\times\frac{\Gamma[(\varsigma_c-\varsigma_v)/2]}{\Gamma(\psi+1)\Gamma[2-(2/\alpha)]} \tag{14}$$

$$\psi=b_f-\frac{1}{2}\left(1-\frac{4}{\alpha}\right)+\frac{\varsigma_c}{2}-1 \tag{15}$$

$$\xi=(\varsigma_c-\varsigma_v/2)-1 \tag{16}$$

where, ς_c, ς_v, a_f, b_f and μ are degree of freedom of collision pair, degree of freedom of vibration, coefficient of the forward reaction, index of temperature of the reaction and reduced mass respectively. Also $\alpha=4/(2\omega-1)$.

Post collision energy of particles are given by the simple model proposed by Haas[16)17)]. In the model energy of a mode E_m is connected with that after collision E''_m by using total collision energy E_C and reaction energy ΔE_{reac} as follows:

$$E''_m=E_m\left(1-\frac{\Delta E_{reac}}{E_C}\right) \tag{17}$$

The three body recombination is difficult to construct a good model because it depends on the dissociation process. Therefore, very fundamental recombination model by Bird is adopted in the computation[5)] as follows:

$$\frac{\sigma_R}{\sigma_T}=\frac{a_f\cdot T^{b_f}}{\frac{1}{\sqrt{\pi}}\sigma_{ref}\left(\frac{T}{T_{ref}}\right)^{1-\omega}\left(\frac{2kT_{ref}}{\mu}\right)^{\frac{1}{2}}}\cdot\frac{n_T\cdot V\cdot Q_{H_2}}{Q_H{}^2} \tag{18}$$

σ_R, n_T, V, Q and μ are cross section of recombination, number density of the third body, volume of the system, partition function of molecules and reduced mass of H-H collision respectively.

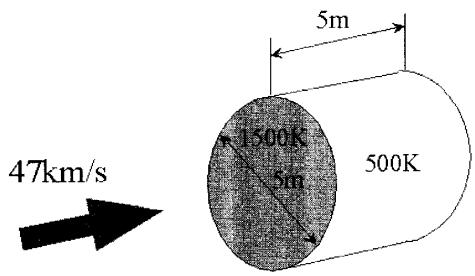

Fig. 1 Schematic of computation model.

3.2 Flow conditions

The schematic diagram of spacecraft, which is expressed by circular cylinder with diameter of 5 m and length of 5 m, is shown in **Fig. 1**. Computation conditions are given from orbital data as shown in **Table 1**. Seven locations on the orbit of aerocapture process are chosen and computation is conducted at each location. The time with **Table 1** is measured from some reference starting time when the spacecraft begins to conduct aerocapture. In the computation the flow is assumed to be steady. Colliding with the cylinder surface, particles are assumed to accommodate perfectly with the surface. Temperature of the front surface of the cylinder is assumed as 1500 K and 500 K on the side surface. Boundary condition of the cylinder is assumed to be diffusive reflection.

4. Results and discussions

About 100,000 sample particles are used for each computation. Knudsen number based on cell size is about 0.2 on the axis.

Radial distribution of heat-flux and pressure are shown in **Fig.2**. On vicinity of the axis, spike of heat flux is observed. The result is due to axisymmetric calculation. In axisymmetric computation, area of computation cell is too small in vicinity of axis. It results in underestimation of collision number. Due to smaller collision number, particles with high energy could reach to the surface with few collisions and generate spike of heat flux in the vicinity of the axis.

Representative pressure contours and temperature contour are shown in from **Figs.3** and **4**. Transient pressure distributions are shown in of **Fig.3(a)** to **3(g)**. It is clear that pressure behind bow shockwave increases as ρ_∞ increases.

Temporal changes of drag and heat load is shown in **Fig.5**. Maximum value of total heat load observed at around lowest altitude. At $t=247$ sec, heat load is about 5.5×10^9 W and drag is about 1.9×10^5 N. The total heat load and average total heat load per unit area from 180sec to 320sec are about 3.8×10^{10} J and 1.9×10^9 J/m^2 respectively.

The mass of thermal protection system (TPS) is estimated. Carbon phenolic ablator is assumed for TPS. The specific latent heat of carbon phenolic is estimated by following equation[18].

$$\Delta H=24.9-1.8\log p_w+1.1(\log p_w)^2 \quad \text{MJ/kg} \tag{19}$$

where, p_w [atm] is pressure on surface of wall. From the computational results as, p_w is on the order of 10^3 Pa, ΔH is estimated to be about 30 MJ/kg. As a result, minimum required mass of ablator is 60 kg/m^2. At the same time, it is empirically known that mass of ablator for thermal insulation is about 60 kg/m^2. As a result, total mass of ablator is estimated to be about 120 kg/m^2. Here, we assume a small spacecraft whose diameter is 1 m, though the DSMC calculation is conducted for larger spacecraft whose diameter is 5 m. Then, total mass of ablator is about 94 kg. As the trajectory analysis assumed that the ballistic coefficient of the spacecraft is 400 kg/m^2 and estimated mass of the spacecraft is 628 kg. Also the trajectory analysis concluded reduction of velocity of spacecraft to be captured in the gravitation field of Jupiter by retro-rocket is 1260 m/s. The mass reduction of propellant of 278 kg is obtained from Rocket equation if we assumed to use existing thrusters of Isp of 330 sec for retro-rocket. The required mass of propellant is quite larger than the mass of TPS. Hence, the spacecraft can increase its payload by 184 kg. As a spacecraft increase its mass, required mass of propellant increase linearly, aerocapture technique has more advantage for larger spacecraft in introduction. Those results suggest that aerocapture at Jovian atmosphere is quite useful.

5. Conclusion

A study on Jovian atmospheric aerocapture has been conducted in the present study. The numerical simulation of aerodynamic heating to the spacecraft has been conducted. DSMC method is used for the simulation of flow fields around the spacecraft. The transient changes of drag due to Jovian atmosphere and total heat loads to the spacecraft are obtained. The results show that Jovian aerocapture is quite useful.

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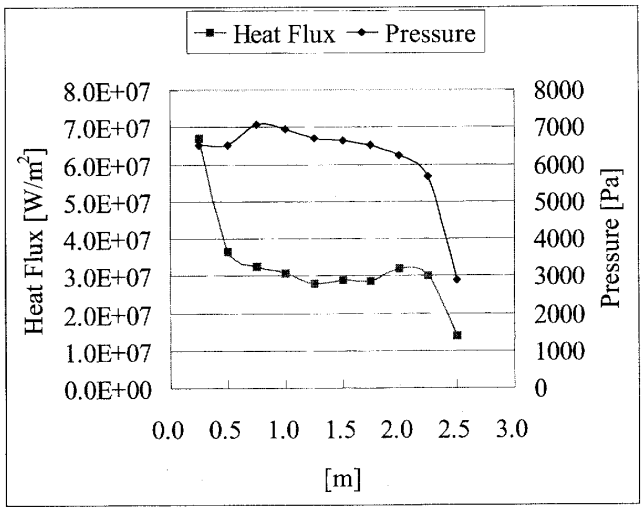
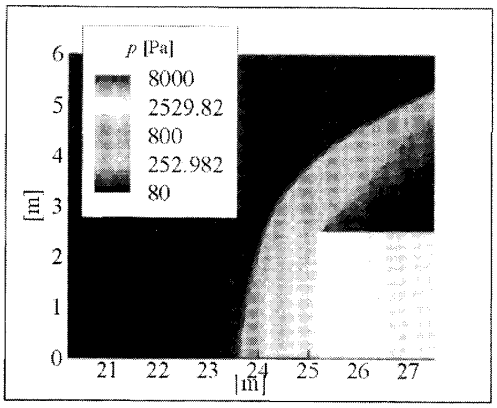
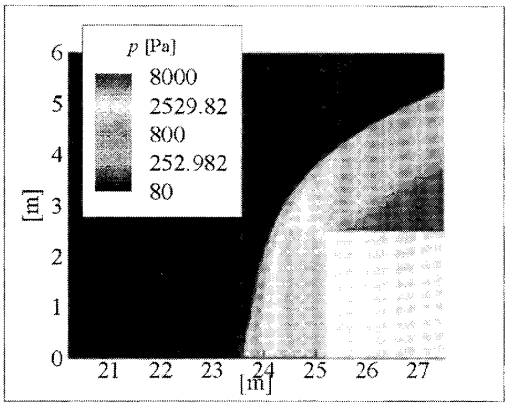


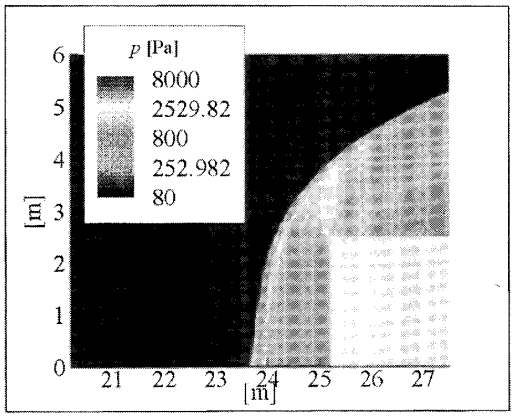
Fig. 2 Heat flux and pressure at $t=247$s.



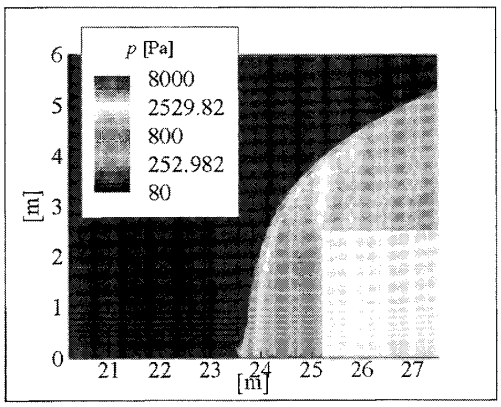
(a) $t=198$s ($H=277$km, $\rho_\infty=1.0\times10^{-6}$ kg/m^3)



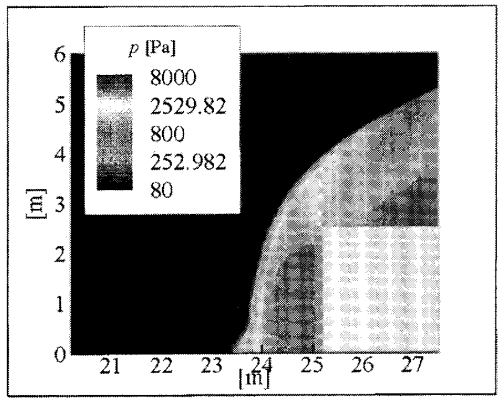
(b) $t=214$s ($H=260$km, $\rho_\infty=2.0\times10^{-6}$ kg/m^3)



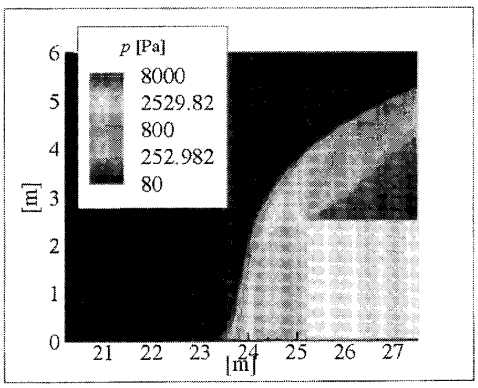
(c) $t=229$s ($H=251$km, $\rho_\infty=3.0\times10^{-6}$ kg/m^3)



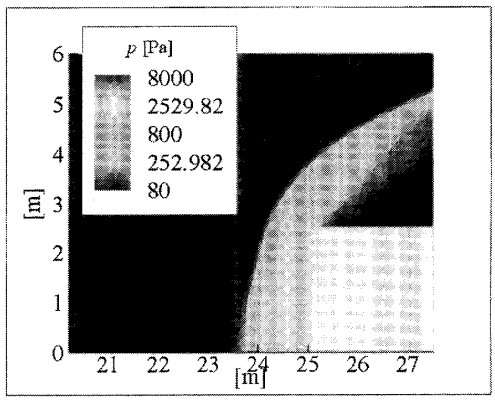
(d) $t=247$s ($H=247$km, $\rho_\infty=3.5\times10^{-6}$ kg/m^3)



(e) $t=264$s ($H=251$km, $\rho_\infty=3.0\times10^{-6}$ kg/m^3)



(f) $t=280$s ($H=261$km, $\rho_\infty=2.0\times10^{-6}$ kg/m^3)



(g) $t=298$s ($H=281$km, $\rho_\infty=1.0\times10^{-6}$ kg/m^3)

Fig. 3 Pressure distribution at each flow conditions.

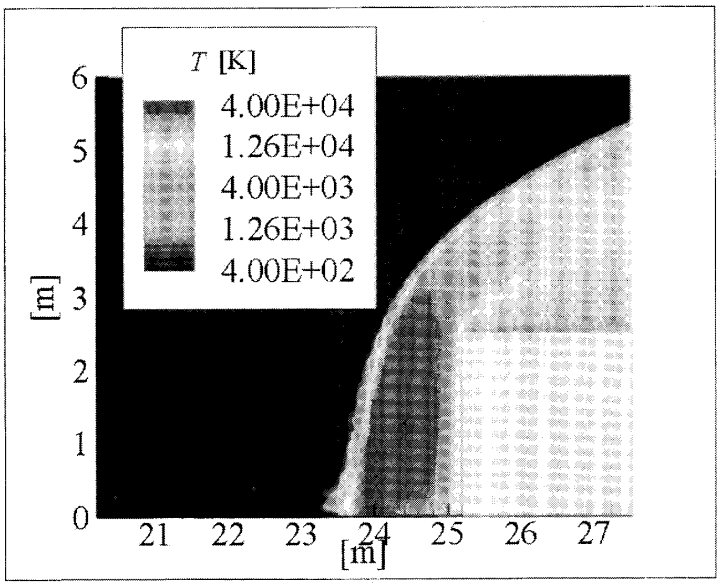


Fig. 4 Temperature distribution at $t=247$s ($H=247$km, $\rho_\infty=3.5\times10^{-6}$ kg/m^3).

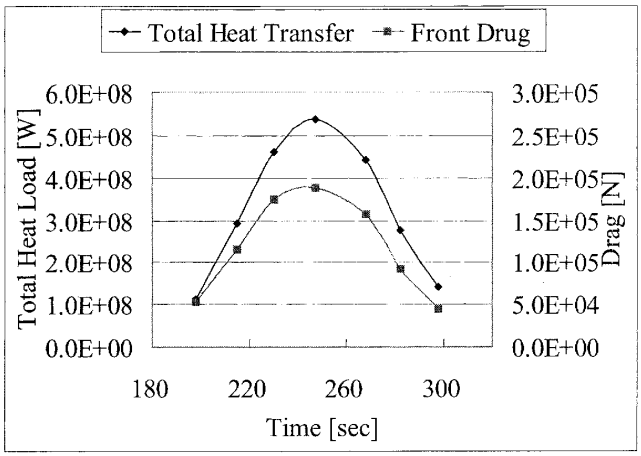


Fig. 5 Temporal changes of drag and total heat load.