Low-Density Aerodynamic Characteristics of the Upper Stage of a Launch Vehicle

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Abstract
Aerodynamic characteristics of the upper stage of a launch vehicle in high altitude of low-density regime are analysed by DSMC (Direct Simulation Monte-Carlo) method. Aerodynamic characteristics in low-density regime differ from those of continuum regime. Although the predicted aerodynamic forces of the upper stage of a launch vehicle are very small since the dynamic pressure is extremely low in low-density regime, the forces may affect motion of the upper stage of launch vehicle. Therefore, aerodynamic coefficients of the upper stage of a launch vehicle in low-density regime are presented as a function of the angle of attack for different levels of rarefaction. For validations of the DSMC code, aerodynamic coefficients of Apollo capsule are also calculated and the results agree very well with the data predicted by others. For the additional validations and applications of the DSMC code, aerodynamics of simple shapes of plate, wedge, and cone-cylinder in low-density regime are analysed.

1. Introduction

The aerodynamic characteristics of bodies are abruptly changed from continuum regime to free molecular regime through transitional regime with changing level of rarefaction of gas. The upper stage of a launch vehicle operates in the rarefied regime. In the rarefied regime, even though the characteristic length of a vehicle is not small, the Knudsen number defined as the mean free path over the characteristic length is high since the mean free path is very long. The mean free path is approximately 50 nm in ground atmospheric pressure while the mean free path is several meters in a rarefied atmosphere(120 km altitude). For the high Knudsen number regime, the Navier-Stokes equations frequently used in the continuum regime cannot be applied. Instead, Boltzmann equations based on the kinetic theory is applied in this high Knudsen number flow. The analytical approach of the Boltzmann equation is limited for a few cases. Therefore DSMC(Direct Simulation Monte-Carlo) method analyzing the Boltzmann equation using the probabilistic approach is commonly used. Smilply, the DSMC method is a particle-based numerical scheme to solve the nonlinear Boltzmann equation. In this study, the aerodynamic characteristic of vehicle shapes which in the free molecular flow regime are predicted using DSMC method. For the calculation of the flow field in the rarefied flow regime, DSMC solver SMILE(Statistical Modeling In Low-density Environment) which was developed by ITAM in Russia is used[1]. SMILE is based on the majorant collision frequency scheme, and the VHS(Variable Hard Sphere) model is applied for the intermolecular collision. For the energy exchange, Larsen-Borgnakke phenomenological model is also used. The molecules which reflect from the surface is defined using Maxwell model. The surface mesh is unstructured triangular type but remaining domain mesh is rectangular type. And parallel computation is performed using normally 8～16 processors for these analysis. SMILE is a well-known DSMC code but required more validations for understanding its capabilities and limit.

2. Applications and validations of code

2.1 Apollo capsule

The aerodynamic coefficients of Apollo capsule by Moss et al[2] are calculated to validate the ability of SMILE code to predict the aerodynamic coefficients in rarefied flow regime. Figure 1 shows the configuration of Apollo capsule using GEOM3D(the preprocessing software inside SMILE)[3]. In this calculation, the angle of attack of -25° and the flight velocity 9.6 km/s are fixed. And the variation of the flow conditions as the change of the altitude ranging from 110 km to 200 km is only considered. Figure 2 shows that calculated aerodynamic coefficients by SMILE code agree significantly with the reference calculated data in [2]. Figure 2 also shows that as the altitude increases, the axial force coefficient(CA) slightly increases, conversely, the normal force coefficient decreases and the center of pressure moves forward slightly. In this figure, legend DS3V represents the results of numerical calculation by Moss et al.

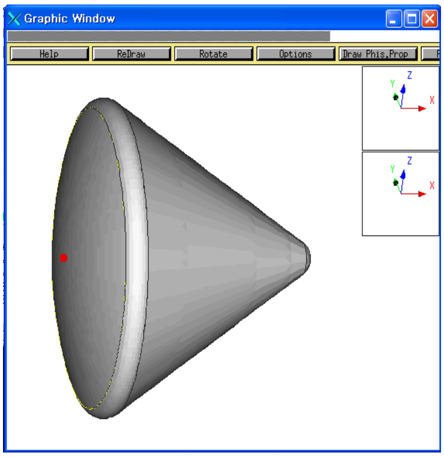


Figure 1: Apollo capsule by GEOM3D

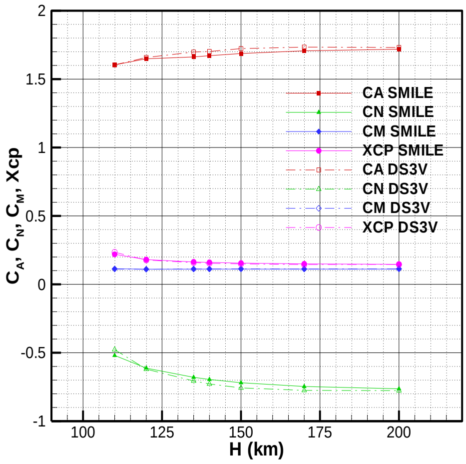


Figure 2: Aerodynamic coefficients of Apollo capsule

2.2 Blunt Plate

For the more SMILE code validation, comparison with the other DSMC analysis results(by DGS2 code) and experimental data [4] around blunt-plate is performed. The thickness of the plate is 0.06 L and Knudsen number based on plate thickness is 0.6 (altitude is about 95 km) and the free-stream Mach numbers are 7.5 and 10.7. L means a plate length. Figure 3 represents the drag coefficients with the variation of angle of attack. The flow media using in these calculations is helium. The drag coefficients of a blunt plate at small angle of attack $\alpha < 10°$ and at high angle of attack $\alpha > 30°$ have a little bit difference between experimental values and computational values. From the figure, the results of two DSMC codes have almost similar values. In figure 3, legend DSG2 represents the results of other DSMC calculation. Figure 4, 5 show density distribution around a blunt plate at free-stream Mach number M_∞=7.5 and angle of attack α =0° and 15°. The contour lines of density are not clear but having spread pattern due to air rarefaction effects.

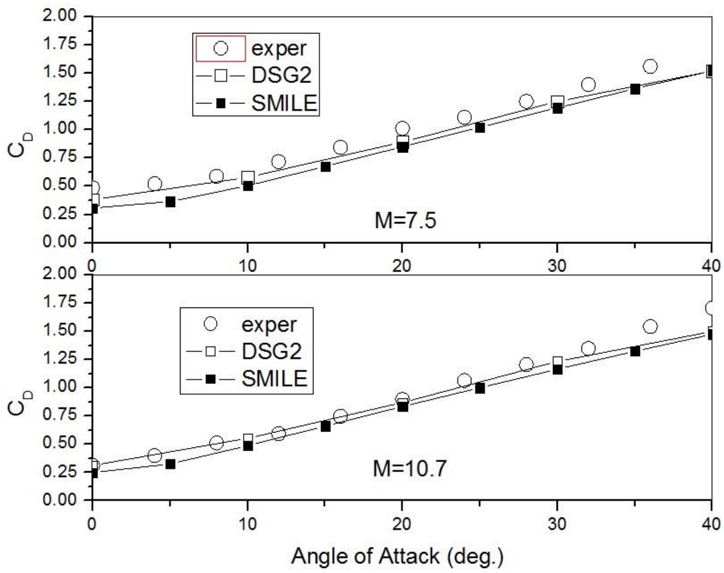


Figure 3: Comparison of drag coefficients

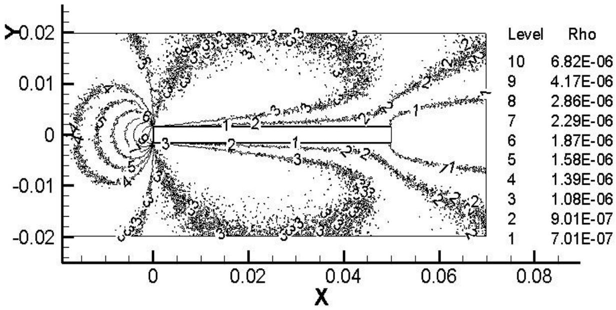


Figure 4: Density contour (M_∞ =7.5, $\boldsymbol{\alpha}$ =0 º)

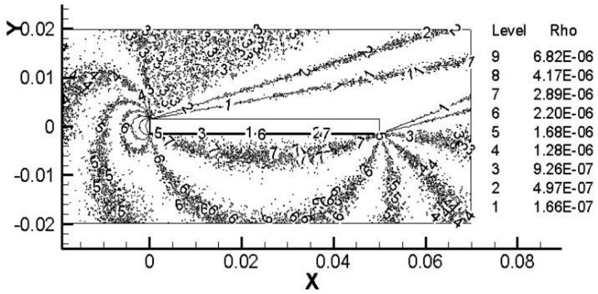


Figure 5: Density contour (M_∞=7.5, $\boldsymbol{\alpha}$ =15 º)

2.3 Cone-cylinder

Variation of drag coefficients of a cone-cylinder which has a similar shape with launch vehicle but simple shape according to degree of rarefaction of air were calculated using SMILE code. The half angle of the cone is 30º and the length of the cylinder is same as the base length of the cylinder. The free-stream Mach number equal to 5, 10 for these calculation. The Knudsen number based on cylinder base area, Kn～10^{-3} corresponds altitude of about 40 km, Kn～10^{-2} corresponds altitude of about 60km and Kn～10 corresponds altitude of about 100 km. As shown in Figure 6, the drag coefficients at high density regime (Kn is smaller than 10^{-2}) of low altitude is about 1.25～1.5 and the values not nearly change. Maybe this regime is low altitude bound region where this SMILE code cannot be more efficiently applicable. And the drag coefficients at Mach number 5 and 10 calculated by Navier-Stokes code are nearly 0.6～0.7 at altitude of 40 km. So, there may be a breaking region where the aerodynamic coefficients change abruptly between continuum and rarefied regime also. And from Figure 6, the drag coefficients are abruptly changed from moderate rarefied regime to free molecular regime through transitional regime according to level of rarefaction of air. The altitude range of transition regime in this calculation is about 60 km~100 km but the transition starting altitude is dependent on vehicle shape and size. At low density region of high altitude over 100km after the transition regime, the drag coefficients are increased to 2.0～2.5. And at high altitude where the Knudsen number is over 10, there is no severe change of drag coefficients. Figure 7 shows density distribution around the cone-cylinder vehicle at altitude of 40 km and 200 km, and the free-stream Mach number is 5.0.

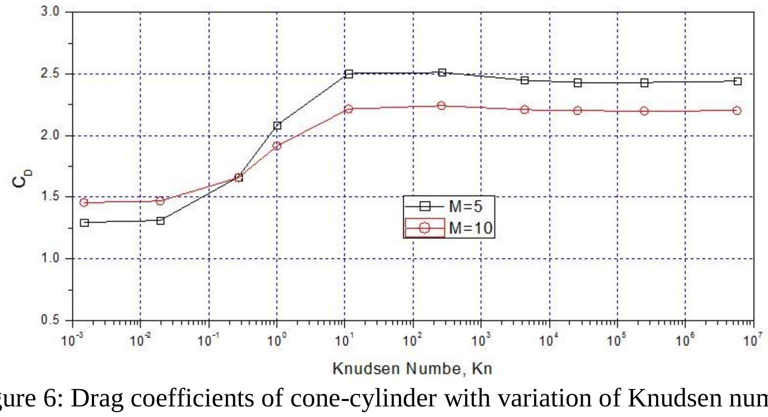
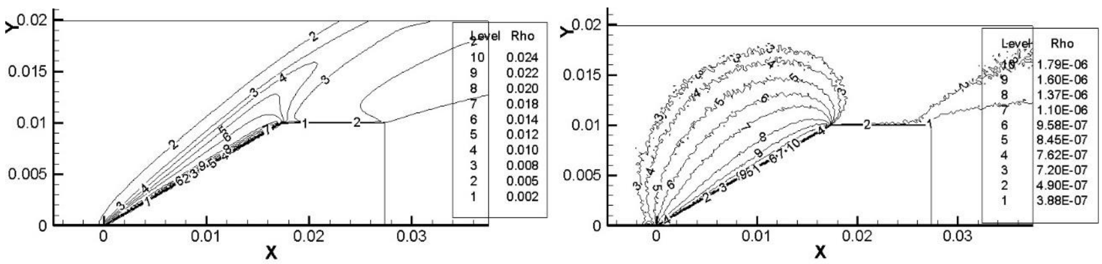


Figure 6: Drag coefficients of cone-cylinder with variation of Knudsen number



(a) Altitude 40 km (b) Altitude 200 km

Figure 7: Density contour according to altitude variation (M_∞ =5.0)

2.4 Wedge

For the more validation of SMILE code, the dependence of drag coefficients for a wedge (half angle θ=20 deg.) on the angle of attack has been analyzed. The free-stream Mach number equals to 11.8 and flow media is helium. The Knudsen number based on wedge base length is 0.3 and thickness of wedge base is 1. The base length of the wedge was taken as the reference length. As shown in figure 8, the drag coefficients which was calculated by SMILE code were compared with the other code results and experimental data [4]. In case of angle of attack smaller than 15°, the results show a little bit lager values than experimental results while the results are identical for high angle of attack. Through these calculations, it is validated that SMILE code can produce reasonable results.

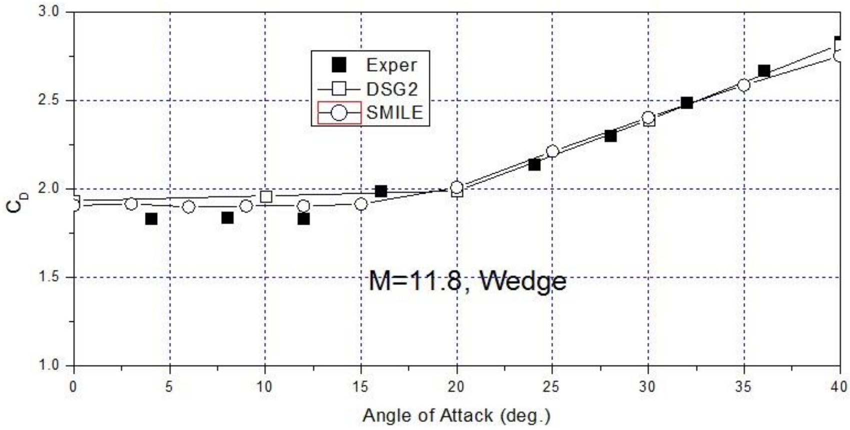


Figure 8: Drag coefficients of a wedge (M_∞ =11.8, Kn=0.3)

3. Upper stage of a launch vehicle

The launch vehicle considered in this paper is a 3-stages launch vehicle. After separation of the 1st stage rocket at altitude of about 60 km, remaining 2 and 3 stages of the launch vehicle will fly to higher altitude. We call the remaining 2 and 3 stage to the upper stage of the launch vehicle. During the upper stage of the launch vehicle ascent, it flies through very low air density region where continuum flow theory cannot be applicable. To see the rarefaction effects on the upper stage of the launch vehicle, axisymmetric shape and 3 dimensional shape are used. The configuration of the upper stage is shown in figure 9.

Figure 9: Configuration of the upper stage of the launch vehicle

The axisymmetric shape was selected to reduce the numerical calculation time and to get the quick reference data for comparison with 3 dimentional calculation data. Figure10 shows that the drag coefficients along the Knudsen number which represents degree of rarefaction of air for 3 kinds of free-stream Mach number. For this calculation, N_2 was selected as a flow media. In this figure, Kn=0.01 corresponds altitude of 60 km and Kn=4 000 corresponds altitude of 150 km. As Knudsen number increases, the corresponding altitude also increases. As shown in this figure, the drag coefficients jump to higher value at one time and then no significant change is observed at freestream Mach numbers of 3, 5. But for freestream Mach number 10 case, there is no change of drag coefficients according to variation of Knudsen number. And the drag coefficients of the vehicle is very high at low air density regime compared to drag coefficients of general launch vehicle in continuum flow region of relatively high air density. But, the predicted aerodynamic forces of the upper stage of a launch vehicle are very small since the dynamic pressure is extremely low in low-density regime. Figure 11 shows temperature (K)and pressure distribution(Pa) around axisymmetric body. From the figure, it is clear that temperature and pressure are very high at nose part and flare part near the nozzle.

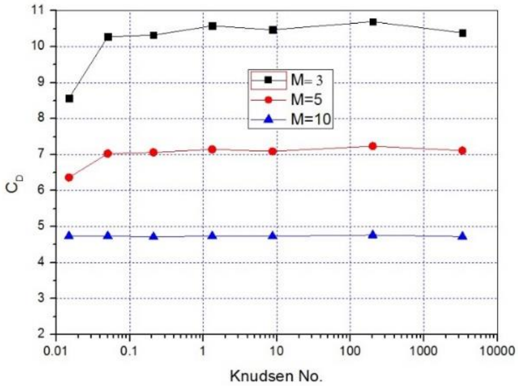


Figure 10: Drag coefficients of axisymmetric shape

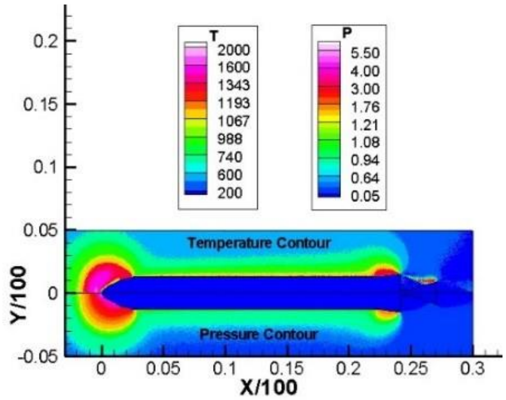


Figure 11: Temperature and pressure distribution of axisymmetric shape (M_∞ =7.0, Altitude 90 km)

To get more accurate aerodynamic coefficients of the upper stage of a launch vehicle, 3-dimensional configuration was selected but the calculation time is too long. So, the calculation at altitude below 70 km is not performed for this paper. Figure 12 shows comparison of drag coefficients between 3-dimensional and axisymmetric configuration for free-stream Mach number 5 and 10. The drag coefficients for 3-dimensional calculation are little bit smaller than those of axisymmetric calculation but nearly same value for all rarefied regime except highly rarefied region. In these calculaions, the drag coefficients nearly does not affected by level of rarefaction at highly rarified regime. Figure 13 shows that drag coefficients with the variation of Knudsen number and angle of attack at given free-stream Mach number. As the figures 12, 13 indicate, drag coefficients of the upper stage of launch vehicle in low-density regime are 6～8 times of those in atmospheric regime. Figure 14 shows variation of center of pressure as a function of Knudsen number and free-stream Mach number. Figure 15 shows the differences of normal force coefficients at different 2 kinds of altitude (80 km and 150 km) with 3 kinds of M ach number as a function of angle of attack.

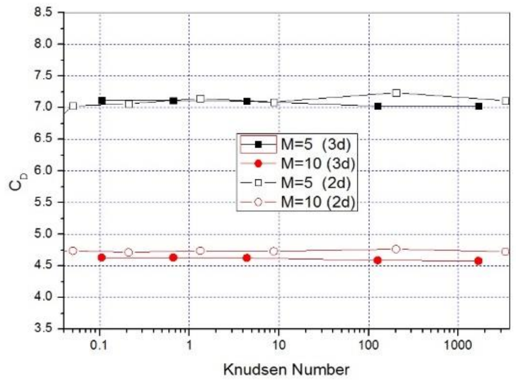


Figure 12: Comparison of drag coefficients for 3-d and axisymmetric shape

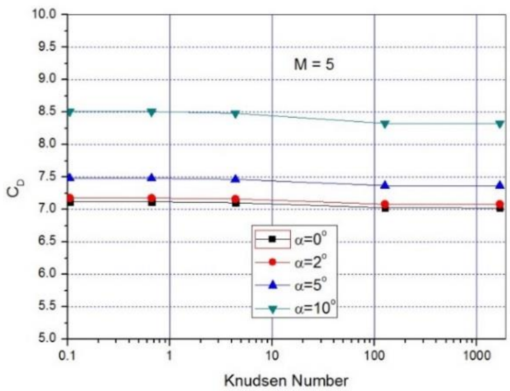


Figure 13: Drag coefficients as a function of angle of attack

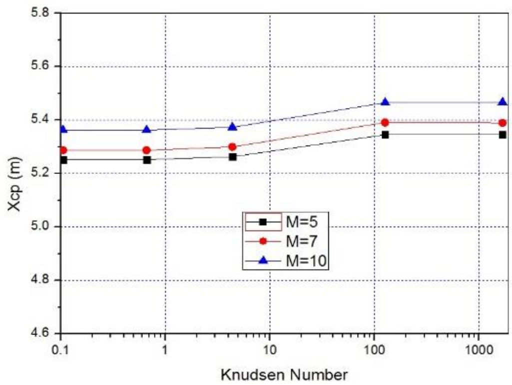


Figure 14: Location of center of pressure from nose tip

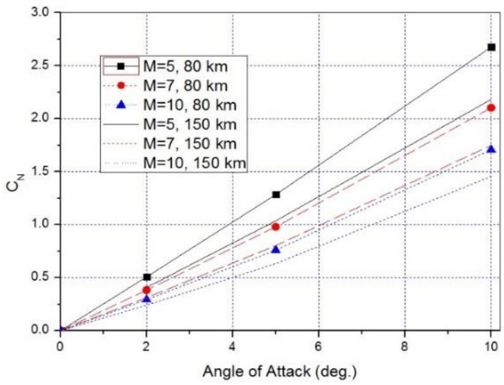


Figure 15: Normal force coefficient as a function of angle of attack

4. Conclusions

For the application and validation of the DSMC code of SMILE, aerodynamic coefficients of Apollo capsule are also calculated and the results agree very well with the data predicted by Moss et al. For the additional validations and application of the DSMC code, aerodynamics of simple shape of plate, wedge, and cone-cylinder in low-density regime are analysed and reasonable results were observed. Through several calculations, we can know that the aerodynamic characteristics, especially drag coefficients, in low-density regime very differ from those of continuum regime. Finally, aerodynamic characteristics of the upper stage of a launch vehicle in low-density regime are analysed. The predicted drag coefficients of the upper stage of a launch vehicle are very high compared to those in continuum regime. But the drag forces acting on the upper stage of a launch vehicle are very small since the dynamic pressure is extremely low in low-density regime. But the forces may affect motion of the upper stage of launch vehicle. Therefore, aerodynamic coefficients of the upper stage of the launch vehicle in low-density flow regime for the analysis of the attitude control are presented.

References

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