Analysis on Aerodynamic Performance of Single-skinned Parawing in the Hypersonic Rarefied flow

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Abstract. In consideration of the serious aerodynamic heating and overload in the return process of the space vehicles, a single-skinned parawing suitable for the whole return process is proposed, which uses lift deceleration to realize flexible reentry. A three-dimensional steady numerical simulation of the single-skinned parawing with different leading edge sweep angles was conducted by using the direct simulation Monte Carlo method, and the effects of different Mach numbers and altitudes on the aerodynamic performance of the parawing were studied in the hypersonic rarefied atmosphere. The results show that with the increase of the leading edge sweep angle, the aerodynamic performance of the parawing decreases obviously, but the ability of stall resistant is improved. The lift-drag ratio decreases monotonously with the increase of Mach number and altitude. The effect of Mach number on lift-drag ratio is not obvious, but the effect of altitude is more obvious. The maximum lift-drag ratio of parawing is 0.45 at 90 km, but only about 0.1 at 110 km. The peak heat flux always appears near the head, which will decreases obviously by decreasing the flight speed or increasing the flight altitude.

1. Introduction
The technology for the return and reentry of spacecraft has always been an important direction of development in the field of aerospace science, which can solve the problem of high cost of human space activities. There are a variety of spacecraft return schemes, in addition to the traditional circular parachute [1], large ramjet parafoil technology and solid rocket recovery technology also shine internationally. However, serious aerodynamic overload and heating can still be observed during the return process because of all of the schemes are used for the terminal recovery of spacecraft. In recent years, some new concepts for the recovery of spacecraft have been put forward by a few of foreign scholars, such as the dual-use lifting ballute [2] for orbit capture and entry, and the solar kite [3] for atmospheric reentry, which can achieve mild aerodynamic overload and heating in the process of reentry and achieve a safe soft landing with extremely low wing loading. The concept of single-skinned parawing proposed in this paper is almost similar, which has shown good performance of gliding and wind-resistant, as well as the advantages of simple structure, light weight and stable deployment characteristics. In addition, it can be controlled to very high angles of attack and adapted to a wide range of velocity from low speed to subsonic speed. Even at supersonic speed, none of the unfavorable tendencies exhibited by conventional parachutes at the speed have been shown, such as squidding and breathing, which means that a faster speed [4] for the entry or return can be realized. Therefore, the single-skinned parawing has a great prospect in the recovery of rocket and spacecraft.

The concept of single-skinned parawing (flexible wing) was first proposed publicly by Rogallo in
A preliminary investigation of the aerodynamic and control characteristics of a flexible glider similar to a parachute in construction have been made to evaluate its capabilities as a reentry glider by Rogallo [5] through a series of wind-tunnel and free-glide tests. An investigation was made to determine the behavior of parawing models at moderate to high supersonic speeds by Taylor [6]. Pressure distributions on three rigid wings simulating parawings with varied canopy curvature and leading edge sweep have been obtained for low subsonic [7], transonic [8], and supersonic speeds [9] up to a Mach number of 4.65. An investigation to study the problems of deploying parawings for the recovery of boosters and nonlifting spacecraft have been conducted by Libbey [10]. The studies of Carter [11] show that use of structure could improve the performance of a system, enhancing delivery accuracy and capability, while keeping the overall system complexity low. Computational Fluid Dynamic studies of a rigid parawing at Mach numbers from 0.8 to 4.65 were carried out by Cruz-Ayoroa [12], and the simulation results are in good agreement with the wind tunnel test results [9], which means that modern CFD methods can be used to simulate these parawing concepts and in turn help optimize them to achieve desirable aerodynamic performance.

In contrast, there are few studies on single-skinned parawing in China. It is worth noting that these studies have been limited to the low-level continuous flow region. The separation altitude of the rocket [13] is as high as dozens kilometers, and the separation speed can reach several Mach; the altitude for a reentry of space vehicle is usually lower than 120 km, of which the speed is also close to Mach 30. The flow field at these altitudes has shown an obvious rarefaction effect [14], no longer in line with the continuous medium hypothesis. If the parawing is to be applied to the whole return process of spacecraft, study on its aerodynamic performance in the hypersonic rarefied flow is very important.

The primary motivation for the study of single-skinned parawing, usually flies at a low altitude, is to examine its aerodynamic performance in a high altitude, rarefied region. A three-dimensional steady numerical simulation of the single-skinned parawing with different leading edge sweep angles is conducted by using the direct simulation Monte Carlo method, and the effects of different Mach numbers and altitudes on the aerodynamic performance of the parawing are studied in the hypersonic rarefied atmosphere.

2. Computational method and models

2.1. DSMC method
Over the past few decades, the DSMC method has become the most common computational technique for modeling complex transitional flows of engineering interest. The DSMC method simulates rarefied flow by keeping track of the motion and internal energies of simulated molecule in the flow field, where each simulated molecule represents a fixed number of real gas molecules. The molecular collisions are modeled using the VHS (variable hard sphere) molecular model which treats the molecule as hard sphere as far as the scattering angle distribution is concerned, but the collision cross section depends on the relative speed of colliding molecule. Energy exchange between kinetic and internal modes is controlled by the Larsen-Borgnakke statistical model.

In the present study, the SPARTA code based on the DSMC method is used to estimate the high altitude aerodynamic performance of parawings, which is developed with internal funding at Sandia National Laboratories. It uses a hierarchical Cartesian grid to track and group particles for 3d or 2d or axisymmetric models. Objects emedded in the gas are represented as triangulated surfaces and cut through grid cells.

2.2. Validation Process
The problem of a hypersonic rarefied flow over a flat plate was used to validate the SPARTA code employed in this study. According to Lengrand et al. [15], a flat plate of 100 mm of length and leading-edge thickness of 5 mm was tested. The results are compared with those of wind tunnel test and DAC
code based on the DSMC method.
Freestream flow conditions used for the numerical simulations are those given by Lengrand [15] and summarized in table 1.

| Parameter       | Value       | Unit |
|-----------------|-------------|------|
| Velocity        | 1504        | m/s  |
| Temperature     | 13.32       | K    |
| Number density  | $3.716 \times 10^{20}$ | m$^{-3}$ |  |
| Wall temperature| 290         | K    |
| Mean free path  | $1.6 \times 10^{-3}$ | m    |  |
| Gas             | N$_2$       |      |  |

Figure 1 and figure 2 show that the surface pressure and surface heat flux calculated by SPARTA code are compared with the results of wind tunnel test and DAC code. It can be seen that the results are basically consistent, and the results of the SPARTA code have shown better agreement with that of the wind tunnel test.

2.3. Model
Parawings are made of very loose or slack cloth whose configuration in flight is maintained by the combination of the aerodynamic forces and the reactions from the load suspension system. The canopy shape of the parawing in flight is very complicated, but the observations of parawing models in previous investigations have shown that the canopy shape could be closely represented by portions of a conical surface. With this assumption, three rigid parawing models of varying leading-edge sweep angles have been constructed.

The geometry of parawing models considered in this work is the same as that presented in Fournier and Bell [9]. Three rigid parawing models simulated a 45° basic flat planform parawing with leading-edge sweep angles of 48.6°, 52.5°, and 61.6°. These configurations resulted in one-half-circle, one-third-circle, and one-quarter-circle semispan trailing-edge curvature when viewed from downstream, which have been defined as Model 1-3, as shown in figure 4. Different curvature represents the different slackness of the canopy (by changing the leading edge sweep angle). As shown in figure 3, the length of the keel and the leading edge is 0.2 m with a radius of about 0.002 m. Considering the actual processing technology and thermal protection design, the passivation with a radius of 0.002 m has been applied to the head of the parawings. The thickness of the parawing is about 0.001 m.
Figure 3. Flat planform parawing structure diagram.

Figure 4. Geometry details of three parawing models: (a) Model 1; (b) Model 2; (c) Model 3.
3. Calculation conditions, results and analysis

Generally speaking, the flow field of the spacecraft has shown a very obvious rarefaction effect at the altitude of 90 km. According to the "reentry corridor" of the non-lift spacecraft [16], it can be determined that the flight velocity of the spacecraft at this altitude is about 28 Ma. At this time, the dynamic pressure acting on the parawing surface is only equivalent to that of 9 m/s at the sea level, which is completely bearable for the parawing. By increasing the altitude or decreasing the velocity, the dynamic pressure of freestream will be further reduced. Therefore, the aerodynamic performance of the parawings with different leading edge sweep angles at the height of 90 km and the velocity of 28 Ma was first studied; then, the effect of different Mach numbers (8-28 Ma) on the aerodynamic performance of the parawing with the best performance (Model 1) was studied at 90 km; Finally, the effect of different flight altitudes (90-110km) on the aerodynamic performance of the parawing with the best performance (Model 1) was explored at a Mach number of 28.

The flow conditions of simulation are as follows: the wall temperature is 300 K, the collision mode between molecules is VHS mode, and the collision model between molecules and object surfaces is complete diffuse reflection model. The flow conditions are set according to table 2—the atmospheric parameters of different altitudes:

| Altitude/km | Density/(kg·m⁻³) | nrho | Pressure/Pa | Mean free path /m | Temperature/K |
|-------------|-----------------|------|-------------|------------------|---------------|
| 90          | 3.4163×10⁻⁶     | 7.1162×10¹⁹ | 0.18359     | 0.0237           | 186.8         |
| 95          | 1.3934×10⁻⁶     | 2.9202×10¹⁹ | 0.07597     | 0.0579           | 188.4         |
| 100         | 5.6041×10⁻⁶     | 1.1885×10¹⁹ | 0.03201     | 0.1421           | 195.0         |
| 105         | 2.3248×10⁻⁷     | 5.0211×10¹⁸ | 0.01447     | 0.3365           | 208.8         |
| 110         | 9.7077×10⁻⁸     | 2.1440×10¹⁸ | 0.00710     | 0.7880           | 240.0         |

3.1. Effect of leading edge sweep angle on aerodynamic performance

The leading edge sweep angle of Model 1-3 is 48.6°, 52.5° and 61.6°, respectively. The larger the leading edge sweep angle is, the greater the slackness of the canopy is, indicating a larger peak lobe height. Figure 5 to figure 7 show the variation curves of lift coefficient, drag coefficient and lift-drag ratio of three parawing models at the altitude of 90 km and the velocity of 28 Ma. It can be seen from figure 5 that the parawing has a negative lift coefficient in the range of small angle of attack. The reason for this phenomenon is that the flow velocity on the upper surface is lower than that on the lower surface due to the large peak lobe height on the trailing edge of the parawing at a small angle of attack, resulting in a negative pressure difference. Considering the flexibility of the parawing surface, for which it is difficult to maintain the shape of canopy under this working condition. A local collapse is inevitable to form, indicating that the flight of the parawing at a small angle of attack is not taken into consideration for the design. Because the slackness of the canopy directly affects the flow separation in the leeward zone, the parawing with the least slackness is the first to reach the stall angle. Increasing the slackness of the canopy (by increasing the leading edge sweep angle) shifts the angle of attack for zero lift increasingly positive and reduces the lift curve slope. which is also observed in the wind tunnel test [17]. To some extent, there is a correlation between rarefied flow and continuous flow in the study of the overall aerodynamic performance of the parawing.

The variation curve of the drag coefficient of Model 1-3 with the angle of attack is basically the same. As shown in figure 6, when the angle of attack is small, the drag coefficient increases slowly, which becomes more fastly when exceeds 30°, and the drag coefficient shows a linear dependence on the angle of attack. The reason for this phenomenon is that the increase of the angle of attack leads to the increase of windward area, resulting in the increase of pressure drag as well as total drag.

It can be seen from figure 7 that the maximum lift-drag ratio of the parawing is about 0.45. When the angle of attack is less than 60°, the smaller the slackness of the canopy is, the greater the lift-drag ratio
is, but there is an opposite trend when the angle of attack is greater than 60°. A larger lift-drag ratio can be obtained by increasing the slackness of the canopy, which is directly related to the fact that the parawing with greater slackness of the canopy can obtain a larger lift coefficient at a large angle of attack.

**Figure 5.** The lift coefficient graph of the parawings.

**Figure 6.** The drag coefficient graph of the parawings.

**Figure 7.** The lift-drag ratio graph of the parawings.

**Figure 8.** The peak heat flux on surface of the parawings.
Figure 9. Heat flux distribution on lower surface of Model 1 at different attack angles: (a) $\alpha=30^\circ$; (b) $\alpha=50^\circ$; (c) $\alpha=70^\circ$.

The variation curve of the peak heat flux on surface of the parawings with the angle of attack is shown in figure 8, from which it can be seen that the peak heat flux fluctuates slightly with the increase of the angle of attack. The main reason for this phenomenon is that the peak heat flux (about 720 kW/m$^2$) mainly occurs at the head of parawings, which have the same passivation treatment. The stationary point is always near the head, which does not change with variation of the angle of attack. And there are also some errors in numerical calculation. The heat flux distribution on the lower surface of Model 1 at the angles of attack of 30$^\circ$, 50$^\circ$ and 70$^\circ$ is shown in figure 9. It can be seen that the heat flux of the lower surface is much lower than that of the leading edge, but increases obviously with the increase of the angle of attack.

3.2. Effect of velocity on aerodynamic performance

It is necessary to analyze the aerodynamic performance of the parawing in a wide range of velocity, considering the flight velocity of the spacecraft in the whole return process. The previous analysis shows that the aerodynamic performance of Model 1 with the leading edge sweep angle 48.6$^\circ$ is the best. Therefore, the Model 1 is selected for further research to study the effect of different Mach numbers (8 - 28 Ma) on the aerodynamic performance of parawing.

The variation curves of the lift coefficient, drag coefficient and lift-drag ratio of the parawing at different Mach numbers are shown as in figure 10 to figure 12, respectively, at an altitude of 90 km. It can be seen from figure 10 that at the same angle of attack, the lift coefficient decreases with the increase of Mach number, but this effect weakens obviously and finally tends to a constant value with the increase of Mach number. The stall angle increases slightly with the increase of Mach number. In contrast, the effect of the Mach number on the drag coefficient is very small. It can be seen from figure 11 that the drag coefficient decreases with the increase of the Mach number at a small angle of attack, and the effect
begins to weaken. An opposite trend begins to appear with the increase of the angle of attack, which also directly leads to the decrease of the lift-drag ratio of the parawing with the increase of the Mach number. But this effect weakens obviously with the increase of the Mach number, as shown in figure 12.

The previous results show that the peak heat flux on surface of the parawing is little affected by the angle of attack, which mainly occurs near the head of the parawing. Figure 13 shows the variation curve of the peak heat flux on surface of the parawing at $\alpha = 50^\circ$. The red line is the data fitting curve, and the function of fitting curve is $y = 1.69092 \times 10^{-9} \cdot x^3$, which is in good agreement with the experimental results and also consistent with Fan Jing's theory that the aerodynamic heat flux at the stationary point is proportional to the cubic power of the freestream velocity. Therefore, the aerodynamic heat flux can be significantly reduced by reducing the flight velocity of the parawing.

3.3. Effect of altitude on aerodynamic performance

According to the variation curve of the flight velocity in the whole return process of spacecraft [17], it can be found that the spacecraft basically maintains a constant velocity above 90 km, so the effect of different altitudes on the aerodynamic performance of parawing at a Mach number of 28 is also studied

![Figure 10](image1.png)  
**Figure 10.** The lift coefficient graph of the parawing at different Mach numbers.

![Figure 11](image2.png)  
**Figure 11.** The drag coefficient graph of the parawing at different Mach numbers.

![Figure 12](image3.png)  
**Figure 12.** The lift-drag ratio graph of the parawing at different Mach numbers.

![Figure 13](image4.png)  
**Figure 13.** The peak heat flux on surface of the parawing at $\alpha=50^\circ$. 
in this paper. The higher the flight altitude is, the lower the gas density is, and the more obvious the rarefaction effect is.

The variation curves of lift coefficient, drag coefficient and lift-drag ratio of the parawing at different altitudes (90-110 km) are shown in figure 14 to figure 16, respectively. At the same Mach number, the lift coefficient decreases obviously with the increase of altitude, and this trend is more and more obvious with the increase of the angle of attack. The maximum lift coefficient of the parawing at 90 km is almost twice that at 100 km. On the contrary, the drag coefficient shows an opposite trend as shown in figure 15, which increases with the increase of altitude, but this trend weakens obviously and finally will tend to a constant value. The similar results had been obtained from the simulation of a flat plate [14]. The lift-drag ratio of parawing decreases with the increase of altitude due to the continuous decrease of lift coefficient and the increase of drag coefficient, but it is worth noting that the angle of attack corresponding to the maximum lift-drag ratio is gradually decreasing, which means that to obtain a better aerodynamic performance, a smaller angle of attack is necessary for the parawing at a higher altitude.

Figure 17 shows the variation curve of peak heat flux on surface of the parawing at $\alpha = 50^\circ$. It can be seen that with the increase of altitude, the aerodynamic heat flux acting on the parawing decreases significantly due to the thinner gas. Therefore, as long as the dynamic pressure is big enough, the parawing needs to open as soon as possible, the higher the altitude, the thinner the air and the smaller the aerodynamic heat flux. At the same time, the lift can also control the increase of the vertical velocity, reduce the dynamic pressure and aerodynamic heating effect, as well as avoid overload and ablation of structure.
4. Conclusions
A three-dimensional steady numerical simulation of the single-skinned parawing with different leading edge sweep angles was firstly conducted by using the direct simulation Monte Carlo method, and the effects of different Mach numbers and altitudes on the aerodynamic performance of the parawing were studied in the hypersonic rarefied atmosphere. Increasing the slackness of the canopy (by increasing the leading edge sweep angle) shifts the angle of attack for zero lift increasingly positive and reduces the lift curve slope. The maximum lift-drang ratio of the parawing decreases by about 20%, while the stall angle increases by about 10° when the sweep angle changes from 48.6° to 61.6°. At the same altitude, the lift-drang ratio of parawing decreases with the increase of Mach number, and finally tends to a constant value; at the same Mach number, the lift-drang ratio of parawing decreases with the increase of altitude. Generally speaking, the effect of Mach number on lift-drang ratio is not obvious, while the effect of height is very obvious. The peak heat flux always appears near the head, which will decreases obviously by decreasing the flight velocity or increasing the flight altitude. Therefore, as long as the dynamic pressure is big enough, the parawing will be opened as soon as possible, the higher the altitude, the thinner the air and the smaller the aerodynamic heat flux. At the same time, the lift can also control the increase of the vertical velocity, reduce the dynamic pressure and aerodynamic heating effect, as well as avoid overload and ablation of structure.

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