High Pressure Zone Capture Wing Configuration for High Speed Air Vehicles

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Abstract

To aim at design requirements of large capacity, high lift, low drag, and high lift-to-drag ratio for high air vehicles, a new aerodynamic configuration concept, named high pressure zone capture wing (HCW) configuration is firstly proposed in this paper. By comparison with traditional lift body or waverider configurations, the new feature of the HCW configuration is to introduce a surface wing, which is upon the airframe of the vehicle and paralleled with the free stream. In high speed cruising conditions, the HCW can capture the high pressure zone compressed by the upper surface of the vehicle. Thus the lift of the vehicle can get a considerable compensation due to the large pressure difference between the upper and the lower surface of the HCW. The lift-to-drag ratio can also obtain a large improvement as a result. Besides, the increase of the volume and the weight of the vehicle will lead to higher lift of the HCW. Therefore, a self-compensation effect between the lift and the weight of the vehicle is achieved. The theoretical derivation is made in the two-dimensional condition and some three-dimensional conceptual configurations are designed. Their aerodynamic performances were as well as evaluated by computational fluid dynamics. The results clearly demonstrate the high performance of the HCW configuration. The lift and the lift-to-drag ratio of the HCW configuration are much larger compared with the configuration without HCW. Besides, the larger the volume of the configuration, the effect of the HCW will be more obvious.

Keywords: High-speed air vehicles, Aerodynamic configuration, High pressure zone capture wing, Lift-to-drag ratio

Introduction

Aerodynamic design of new high-speed vehicles is currently a hot topic of research. High-speed vehicles are mainly referred to various types of supersonic or hypersonic vehicles. Such vehicles generally use ramjet/scramjet or rocket engine. High-speed vehicles also include unpowered glider aircraft. Breguet equation [1] (Eq. (1)) shows that in cruise flight conditions, the aircraft cruising range can be estimated by the following equation:

$$R = V \cdot \left(L / D \right) \cdot I_{sp} \cdot \ln \left(\frac{W_i}{W_f} \right) \tag{1}$$

Where R is cruising distance, V is the flying speed, L/D is lift-to-drag ratio, I_{sp} is the specific impulse of the engine, W_i and W_f is the start and end vehicle loads, respectively. Eq.(1) indicates that the cruising distance is directly proportional to the lift-to-drag ratio of the vehicle. For this reason, the pursuit of high L/D is always a key issue of concern for aircraft designer. However, the aerodynamic performance of the aircraft results in a sharp decline and meets the so-called “L/D barrier” [2] with the increase of the flight speed, especially in hypersonic flight regime.

The high-speed aerodynamic vehicles can be mainly categorized wing-bodies, blended wing bodies and waveriders. The vehicles listed in reference [3] and [4] are typical wing-body configurations. These configurations consists of two parts, the body and wing. The wing uses large swept delta wing served as the main lift part and the body uses cone/cylinder combination providing sufficient capacity for the vehicle. The hypersonic test vehicle HTV-2 is a typical representative blended wing body [5]. The main features of this configuration are that the airframe and wing are fully integrated, and there are no apparent boundaries between the two parts. The upper surface arches upward appropriately to meet the volume requirements. The lower surface compresses the free stream to provide lift required for flight. With respect to the two layouts above, waveriders[6] is now recognized as the relatively good configuration whose aerodynamic performance is better. At design conditions, the shock produced at front edge attached to the vehicle. The high pressure region behind the shock wave is completely covered in the lower surface of the aircraft. Therefore, the configuration can get a larger lift-to-drag ratio. This configuration has been a focus research since Bowcutt[7] and Corda[8] got a series viscous optimized waveriders [9-16] in the late eighties. Broadly speaking, waverider can be seen as a special case of blended wing body configuration, but the compression surface (lower surface) has a strict design rule.

However, waveriders are still facing many problems in practice today. First of all, the upper surface of the standard waveriders generally parallel with the free stream or use weak expensive surface design. Its thickness is relatively thin and the volume is small. One approach to increase the volume is to increase its absolute size. Such as the conceptual vehicle proposed in the reference [9] and [10], their length are both greater than 60 meters. Obviously, the increase of the size leads to the increase of the flow area and wetted area which result in the significant increase of the drag. There is no power plant can match the drag in the stage of research. Next, one of the basic design principles is that the shock should be attached to its edge, so the leading edge must be sharp. But in the actual high-speed flight, the thermal protection must be considered. The sharp leading edge must be blunted. Recent research results show that the bluntness results in the decline of the aerodynamic performance, particularly of the lift-to-drag ratio, both in a continuous flow condition [11] and in the rarefied flow conditions [12], even with a blunted radius or thickness. In addition, waveriders are obtained through the flow stream tracing. The compression surface is so complex and non-ruled that it brings lots of difficulties in the manufacture, stability, control and other aspects.

Another method to increase waveriders volume is to modify its lower surface. As can be generated from any flow field [13], waveriders with different compression surface can be obtained by changing the reference flow field. However, the reference[14-17] shows that it can only alleviate the contradiction between lift-to-drag ratio and volume in a small range by changing the reference flow field. In addition, based on waveriders, it is also a kind of scheme to increase the volume by changing the upper surface[18] which is free stream surface or weak expansion surface to compression surface. Although this treatment can effectively increase the volume, the compression surface will produce larger drag and negative lift to make the aircraft aerodynamic performance fell sharply. Adjusting the angle of attack for cruise flight can improve aerodynamic performance, but it also make waveriders deviate from its design point which will weak the ability of riding the shock wave.

The basic function of high-speed vehicle is to realize the remote rapid transport. So the weight and volume is the two basic constraint parameters. To enhance the aerodynamic performance by adjusting the layout and optimization must be under the condition of satisfying these two indicators. Based on the discussion above, we can see that there is a strong constraint relationship between the volume, lift, drag and lift-to-drag ratio of a vehicle. Currently, the various layout schemes are designed through separating the aerodynamic performance, volume and other properties. Actually, it is a compromise and balance between the indicators or parameters. Namely, it sacrifices one or several properties in exchange for other performance improvement, and obtains a relatively optimal configuration of the overall performance.

One of the main characteristics of high speed is the emergence of shock which leads the drag of aircraft increasing dramatically. Meanwhile, the pressure after the shock rises accordingly, and the pressure is proportional to the flight Mach number. If it can effectively take advantage of this high-pressure zone, the aerodynamic performance of the vehicle would improve, maybe improve greatly. This idea has been put forward in the middle of the last century. But the research focused on the introduction of an additional shock-induced component. As a typical example, Mysliwetz [18] proposed the idea that by the introduction of revolutionary body parts hanging below the wing can induce the shock which produces high pressure acting on the wing to increase the lift. The results suggest that this device can indeed improve the lift of the wing. However, the body itself produces negative lift and drag which make the overall effect weak. Reference[19] optimized one kind of hypersonic missiles curved wing. The optimization results show that when the leading edge of the wing forward-swept is appropriate, the part can produce high pressure generated by warhead compression to increase its lift. The lift-to-drag ratio improved about 9%. This provides us a new idea. In process of the aerodynamic layout design, we can introduce some corresponding devices to capture the high pressure zone compressed by the upper surface to increase the lift of the aircraft, so that we can improve its aerodynamic performance under the demand of large volume. Based on this idea, this paper proposes a new aerodynamic concept called high pressure zone capture wing (HCW for short) aerodynamic layout.

The Principle of the HCW

As described above, in order to meet the volume requirements, the upper surface of the current high-speed vehicles usually adopts arched ways for layout design. In actual flight conditions, the free stream will be compressed by the arched upper surface. It is bound to produce a high pressure zone. The main staring point of the HCW layout design is based on this condition, through reasonable wing to make a substantial increase in lift of the aircraft. Therefore, it is especially suitable for large volume demand for the high-speed vehicles. HCW layout design can be based on shock-expansion theory. To simplify the analysis, here is an example of two-dimensional case. It can be extended to complex three-dimensional shape in practical applications. We will describe them and verify its specific effects in the following paragraphs. In addition, because the main impact of the layout is on the upper surface of the body, we mainly analyze this region. It can be combined with different lower compression surface. This paper validated vehicles combined with waveriders, and the specific results is given in the following paragraphs.

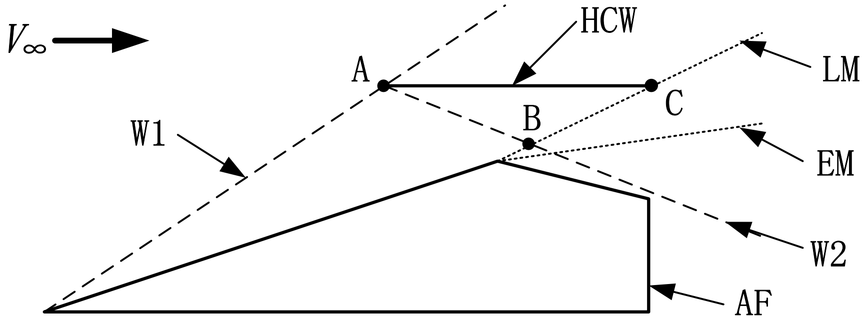


Figure 1. Diagram of the high pressure zone capture wing (HCW)

The basic principle of HCW layout is shown in figure 1. In the figure, AF as the body, use compression-expansion design to provide large volume, and volume increases along with the increase of leading compression angle. The principle of HCW producing high lift is given as follows: The high speed stream will be compressed when it flows through the leading edge of the wedge body, resulting in a shock wave W1. The shock wave angle and strength of compression are related to the stream Mach number and the leading edge wedge angle. When the stream flows through the shock wave, the pressure increases, the Mach number decreases, and the flow direction turns upwards. After continuing to flow upwards to HCW, it forms a second shock wave W2. Then the pressure increases further. On the other hand, the flow expands through the inflection point, resulting in the former Mach line and the latter Mach line. The gas pressure drops after expansion area, flowing to the downstream of the vehicle. Through the analysis of the flow process above, we can know that after the introduction of HCW, the triangle area surrounded by ABC points will form a considerable high pressure zone. At the same time, the pressure of the upper surface of the HCW is almost equal to the flow pressure. So that the pressure of the upper and lower surfaces of HCW will have a large difference which will generate a large lift on the vehicle. In addition, due to the placement of HCW is paralleling to the flow and the structure is very thin, the additional drag generated by HCW is relatively small, so the whole lift-to-drag of the vehicle can be greatly improved.

Based on the qualitative analysis above, the pressure ratio of the HCW upper and lower surface can be obtained as follows through the application of oblique shock-expansion wave theory and simple derivation.

$$\frac{P_l}{P_u}=\frac{\left[1+\frac{2\gamma}{\gamma+1}(M_1^2\sin^2\beta_2-1)\right]\left[(1+\frac{\gamma-1}{2}M_3^2)^{\frac{\gamma}{\gamma-1}}\right]}{(1+\frac{\gamma-1}{2}M_1^2)^{\frac{\gamma}{\gamma-1}}} \tag{2}$$

Where, P_l is the pressure of HCW lower surface, P_u is the pressure of HCW upper surface, γ is the specific heat ratio, M_1 is the Mach number after the leading edge shock wave, β_2 is the shock angle of the secondary shock wave generated by the stream flowing through HCW which can be derived directly by oblique shock wave equation [20], M_3 is the Mach number after the body expansion wave and it can be calculated by the following relationship.

$$\begin{cases} \nu(M)=\sqrt{\frac{\gamma+1}{\gamma-1}}tg^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)}-tg^{-1}\sqrt{(M^2-1)} \\ \nu(M_3)=\theta+\nu(M_1) \end{cases} \tag{3}$$

Where, θ is the expansion angle.

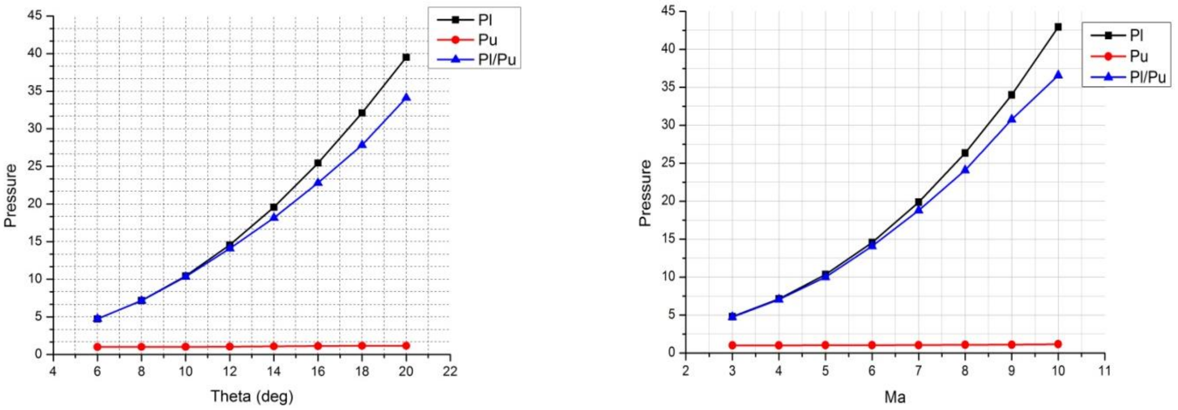


Figure 2. Pressure difference between the lower and the upper surface of the HCW with different compression angles (left) and Mach numbers (right)

According to the above formula, we calculated the pressure ratio of the HCW upper and lower surface in different frontal compression Angle (fixed to flow Mach number of 6) and different flow Mach number (fixed front compression Angle of 12 degrees), here the pressure of the upper and lower surface was normalized by the flow pressure. The results shown in figure 2 indicate that after the introduction of HCW, the pressure of its upper and lower surface will generate a big difference. The pressure difference is proportional to the leading edge compression angle and free stream Mach number. The ratio is up to tens of times. This pressure difference is bound to make the vehicle lift increase significantly.

The derivation above is just based on two-dimensional case. To validate the actual effectiveness of HCW in three-dimensional cases, we calculated several two-dimensional axisymmetric model whose body is combination of cone and cylindrical. As shown in figure 3, the body total length is given 4m and half-cone angle is 8.53°. Here is 6 different shapes as the tail height (cylinder radius) changes. The calculation conditions are as follows: stream Mach number 6, the flight attitude 30km, 0 degrees angle of attack, Euler model. The pressure contours of symmetry plane are shown in figure 4.

As can be seen from figure 4, the different combination of cone and cylinder can all make the lower and upper surface of HCW generating a big pressure difference. Besides, the pressure distribution has a huge difference for these 6 configurations. In the analysis of mutual relations between body and HCW, the volume and aerodynamic performance should be considered.

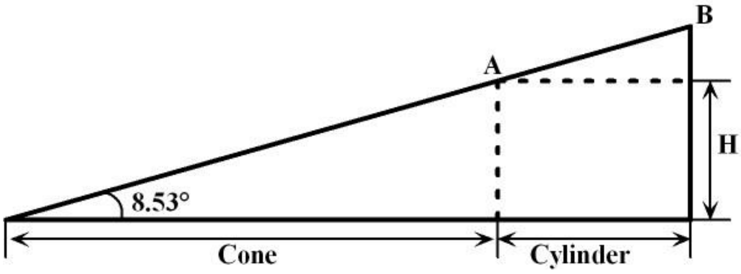


Figure 3. The symmetry plane of cone and cylinder combination

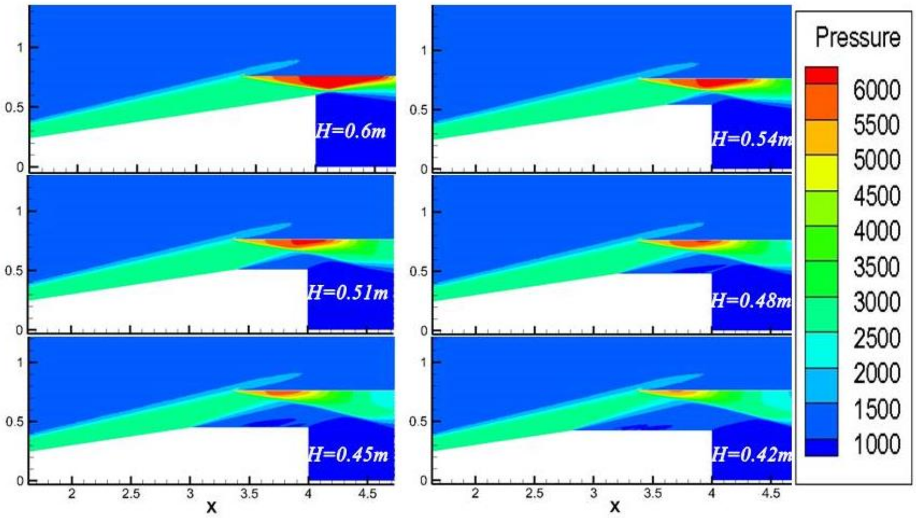


Figure 4. Pressure contours of symmetry plane in different tail height of cone and cylinder combination

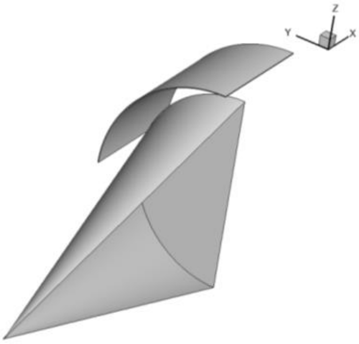
Conceptual Design Examples

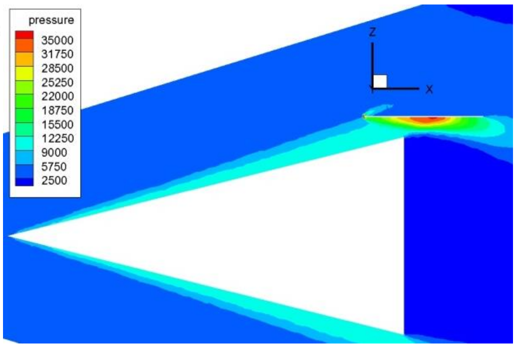
According to the planar two-dimensional and two-dimensional axisymmetric cases above, we popularize this idea to general three-dimensional cases. In order to obtain the leading edge shock wave easily, we firstly studied the relatively simple geometry of the cone and semi-cone configuration combined with HCW in their upper surfaces, and through the comparison with the conventional layout without HCW to verify the performance of the layout. Here, the design and calculation uses the following simplifications: (a) Not considering support connection means between the wing and the body, (b) using the Euler equations or laminar Navier-Stokes equations for performance evaluation, not considering the effect of turbulence, (c) HCW using relatively simple rectangular in shape. These simplified measures can make the layout design relatively simple, less computational consumption, and can seize the main advantages of HCW, namely the lift compensation effect.

Case 1: Cone

The body is a cone with the semi-cone angle of 14°, given the length of 1m. HCW is designed as half a torus whose overlooking is rectangular in shape, given the thickness of 2 mm, the length of 0.3m. The configuration is shown in figure 5.

The stream Mach number is 6, flight altitude 25 km, and the calculation model is Euler model. Since the body is axisymmetric, its lift and lift-to-drag ratio is zero with no combination HCW under zero degree angle of attack. After adding HCW, its lift force is 4233.5N, and lift-to-drag ratio increases to 1.81. As can be seen from figure 6 and figure 7, through reasonable design, the pressure distribution of HCW upper and lower surface under the condition of three-dimensional is basically the same as the results of two-dimensional theoretical derivation, and there is no high pressure leakage on both sides of HCW.





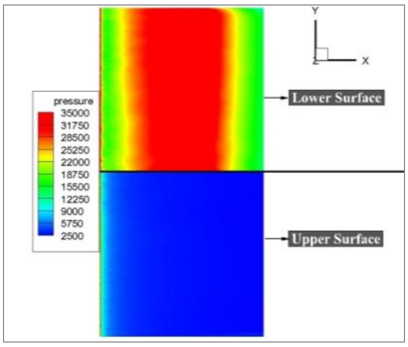
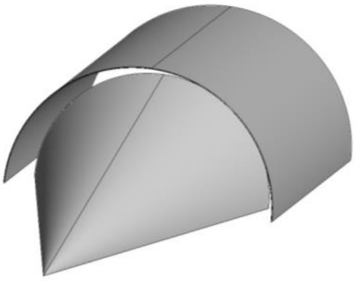


Figure 5(Left). Combination of cone and HCW configuration (half)
Figure 6(Middle). Pressure contours in symmetry plane under combination of cone and HCW
Figure 7(Right). Pressure contours comparison between the upper and lower surface of HCW

Case 2: Half cone

The body is a half cone with half cone angle of 14°，given the length of 1m. This configuration can be regarded as a simplification of HTV-2. As shown in figure in figure 8, the overlooking of HCW is rectangular in shape with a thickness of 2 mm.

The calculation conditions remain Mach number 6, flight altitude 25 km, Euler model. The body is half an axisymmetric body, whose upper surface compresses the stream, and lower surface parallel to the flow. Therefore its lift under zero angle of attack is negative, which is numerically -2.82.4N, and the drag is 1005.6N. The lift-to-drag ratio is -2.07. After adding HCW, the lift is 2773.4N, and the drag is 1081.2N. The lift-to-drag ratio increases to 2.57. The pressure distribution of symmetry plane is shown in figure 9. It is clear that there is a large pressure difference between the upper and the lower surface of HCW.



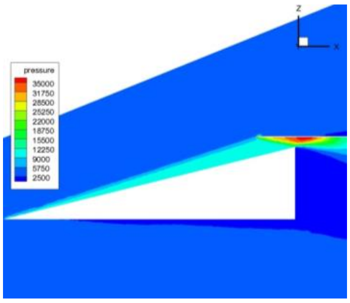
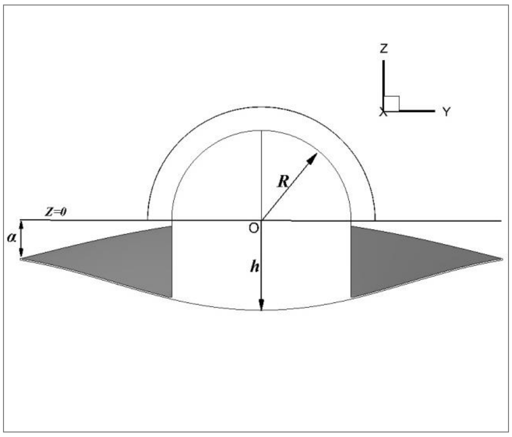


Figure 8(Left). Combination of semi-cone and HCW configuration
Figure 9(Right). Pressure contour in symmetry plane of Case 2

HCW-Waverider Wing(WW) Combination Configurations

From the simple three-dimensional configuration examples above, the main area of HCW aerodynamic layout is the upper surface. For high-speed aircraft, especially hypersonic vehicles, waveriders as the lower compression surface have good aerodynamic performance. Therefore, if the upper surface is a half cone, and the lower surface is a waverider. It can not only make the aircraft to have large volume, also can make it get better aerodynamic performance through combining with HCW. For this design idea, we analyzed the influence of HCW on several configurations with different volume.

The upper surface of the body is half cone, and the lower surface of the body is waverider. They are assembled with a certain angle of attack, given the length of 4m. The rear view is shown in figure 10. The half cone is determined by tail radius R, the assembly angle of attack is determined by the height H below the horizontal plane. In order to avoid the high pressure generated by half cone compression falling down on the waverider which can produce negative lift, the height H and tail radius are the same value. Here, R takes three different values: 0.4m, 0.6m, and 0.7m. When waverider is designed for zero angle of attack state, its front end falls on the plane Z=0. Therefore, the corresponding assembly angle of attack α is 1°, 4°, and 5.2° respectively. The thickness of waverider is 10mm, and the front uses 5mm radius arc bluntness. The overlooking of HCW remains rectangular, given the thickness of 2mm. The three-dimensional shape and three views of the configuration whose half cone tail radius is 0.6m is shown in figure 10. The calculation conditions is given as follows: stream Mach number 6, flight altitude 30km, zero degree angle of attack, the laminar flow model.



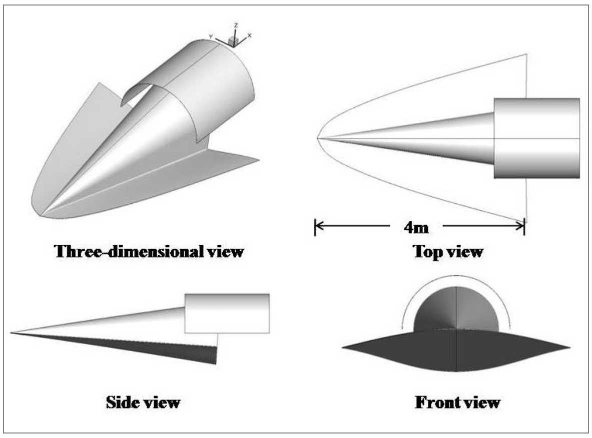


Figure 10(Left). Rear view of HCW-WW configuration

Figure 11(Right). View instances of HCW-WW configuration

The pressure contours of the three configurations symmetry plane are shown in figure 12. It can be seen that with the increase of the tail radius, the half cone angle of the upper surface and the lower surface of the assembly angle of attack increases. With the compression strengthening, the pressure of the half cone and the waverider increase. The pressure of the lower surface of HCW correspondingly increases, leading to the lift generated by HCW increasing. From the pressure distribution of the configuration section shown in figure 13, we can find that the shock is substantially attached to the leading edge. Taking into consideration the impact of thermal protection, the leading edge is blunted. Some little flow spillage takes place around the leading edge. There exists a considerable pressure difference in the upper and lower surface of the waverider which can produce large lift for the aircraft.

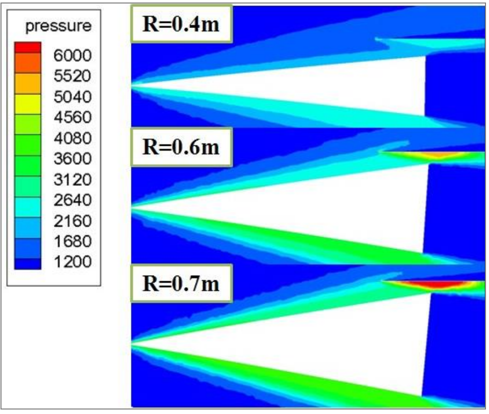
It not hard to find that in this layout design, both the HCW and waverider are wings which forms two-lifting body. In addition, the design idea of HCW and waverider has a strong similarity. They can both effectively utilize the body’s own shock. They respectively exploit the compression of the upper and lower surface. Therefore, the configuration of waverider combined with HCW can not only acquire considerable volume performance, also can achieve good aerodynamic performance.

The half cone radius change will result in the change of volume and aerodynamic performance. As shown in figure 14 and 15, the relationship between the volume and lift, drag, and lift-to-drag ratio was obtained. Here, Case1 and Case2 are respectively the configurations before and after adding HCW. What we can figure out from the figures is followed:

a) In the same volume, due to the introduction of HCW, the drag increases slightly, while the lift obtains a sharp rise. Therefore, the lift-to-drag ratio improved significantly under the same volume.

b) For configurations with different volume, with the increase of the volume, the lift generated by waverider and HCW increase dramatically, leading to the overall lift increasing. Besides, because of the increase of flow projection area, the drag also increases with the increase of volume.

c) The lift-to-drag ratio and volume are inversely related. The lift-to-drag ratio of Case1 decrease sharply with the increase in volume. While the combination of HCW can effectively slow down this trend, it decreases slowly with the increase of volume. Therefore, HCW can not only enhance the lift-to-drag ratio, also can reduce the contradiction between the volume and the lift-to-drag ratio.



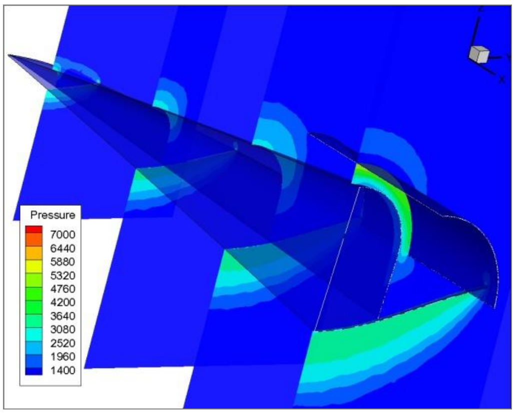
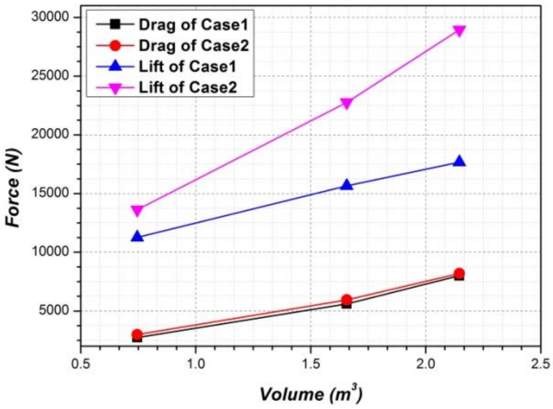


Figure 12(Left). Pressure contours in symmetry plane of different HCW-WW configurations
Figure 13(Right). Pressure contours of the HCW-WW configuration with R=0.6m



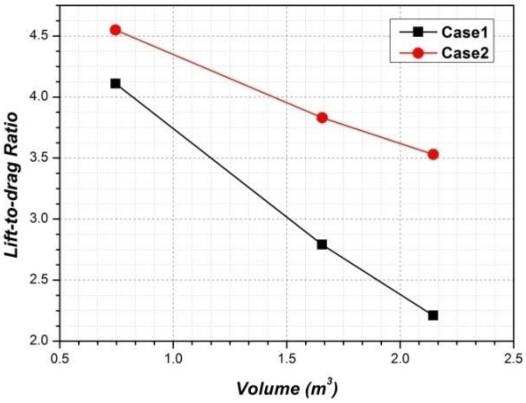
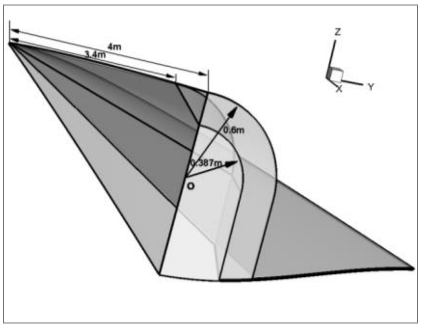


Figure14(Left). Lift and drag under different configuration volume
Figure 15(Right). L/D under different configuration volume

The effectiveness of HCW is confirmed from several conceptual configurations above. The aircraft aerodynamic performance can be effectively improved after the introduction of HCW. However, to capture the shock conveniently, the upper surface of the body is given half-cone which can produce large drag due to its huge flow projection area. According to the analysis of axisymmetric shapes, we can find out that if the upper surface of the body takes the connection of half cone and semi-cylindrical or half cone and half truncated cone, the drag and negative lift of the body can be effectively reduced. The position of HCW will be adjusted based on the upper surface. But it can still capture the high pressure effectively. Based on the waverider combined with HCW whose half cone tail radius R is 0.6m, the upper surface take the connection of half cone and half truncated cone substitute for half cone. Then analyze the effect on HCW layout of the body shape through the calculation results.

The body shape before and after modification is shown in figure 16. After modification, at the level of half cone 3.4m combined with half truncated cone, and the total length is still 4m. The tail radius of the half truncated cone is given 0.387m. Then connects to the waverider vertically, other geometric parameters unchanged. The calculation conditions are given as follows: stream Mach number 6, flight altitude 30km, zero degrees angle of attack, laminar flow calculation model.



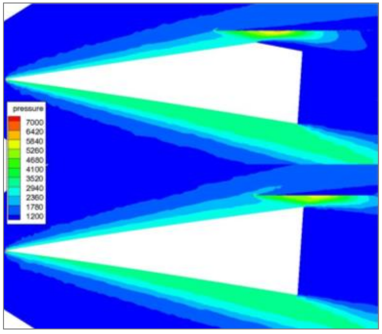


Figure 16(Left). Body shape comparison before and after modification

Figure 17(Right). Pressure contours comparison between before and after modification

The pressure contours in the symmetry plane is shown in figure 17. It is evident that the high pressure on the half truncated cone dismissed due to the expansion. Meanwhile, the position of the HCW leading edge shifts forward. The area of high pressure in the lower surface of HCW has a weak decrease.

By comparing the lift and drag of all parts of the aircraft before and after modification, as shown in figure 18, it is clear that the lift of HCW is reduced due to the area of high pressure in the lower surface of HCW is decreased after modification. The lift of the body increases sharply with the decrease of negative lift in the upper surface of the body. The overall lift of the aircraft increases by 4.4% from the original configuration (Case1). The drag of HCW is still small relative to the whole drag, and it almost remains unchanged after modification. The drag of the body is significantly reduced due to the decrease of the flow projection area of the body. The whole drag of the aircraft is decreased by 7.1% from the original configuration. On the whole, through the modification of the body, the lift increases and the drag decreases, leading to the lift-to-drag ratio improved obviously. As shown in table 2, the lift-to-drag ratio increases from 3.83 to 4.28, increased by 11.75%. The aerodynamic performance is significantly improved.

As can be seen from the example, the aerodynamic performance of the vehicle can be improved by the shape modification. However, on the other hand, the lift generated by HCW has decreased. There is a strong coupling relationship between the body and HCW. The simple modification of the body may bring the performance of HCW change as a result. Therefore, as one of the next step of work, the optimization design of the body is needed considering the coupling relationship between the two parts.

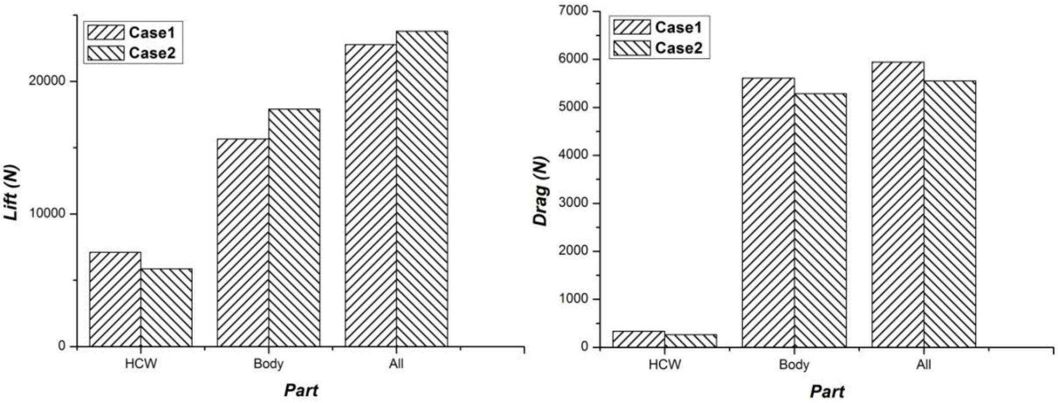


Figure 18. Lift and drag of each part before and after modification

Table 2 Aerodynamic parameters of the vehicle before and after modification

	Lift(N)	*Drag(N)*	*L/D*
Case1	22770.0	5944.0	3.83
Case2	23780.3	5552.1	4.28
Percentage Increase	+4.4%	-7.1%	+11.75%

As can be seen from the aircraft configurations above, HCW must be given thin wing structure, torus with parallel to flow, so that we can maximum reduce the drag generated by HCW. Based on the design principle, the shape of HCW can be only determined by the cross section. The cross section shape of HCW should be designed by cross section shape of the shock generated by the upper surface of the body. In the aircraft configurations above, the cross section shape of HCW is all given the semicircular shape. It is because the cross section shape of the shock generated by body is circular.

In the aircraft design above, the overlooking shape of HCW is given rectangular, and the length is given relatively long. In addition, the three dimensional effect of wing is not considered. This is simplified for analysis. The shape of HCW is given cylindrical thin airfoil with parallel to flow. The main drag of HCW is from friction. As the computational analysis mainly sues Euler equations or laminar flow model, the friction drag is relatively small, so the length of HCW we selected has little impact on the performance. Actually, although the length of HCW is long, the high pressure mainly concentrates on its front. The pressure of the latter part decreases gradually because of the expansion wave emerged in the turning point. The contribution to the overall lift of this part is very small. The long HCW may only lead to the friction increasing.

Obviously, the shape and length of HCW exists an optimal state. To validate this conclusion, we made a simple modification of HCW based on the configuration obtained in the last section. Then analyze how the shape and length of HCW influence on aerodynamic performance.

Based on the configuration obtained in the last section, we made a simple modification in HCW, considering the three-dimensional effect and expansion wave emerged in the turning point. We intercepted HCW by quadratic curves in the horizontal plane of vertical projection of the front and rear HCW. The length of HCW in the symmetric plane decreased from 2.2m to 1.7m. The shape before and after modification, and the overall configuration are shown in figure 19.

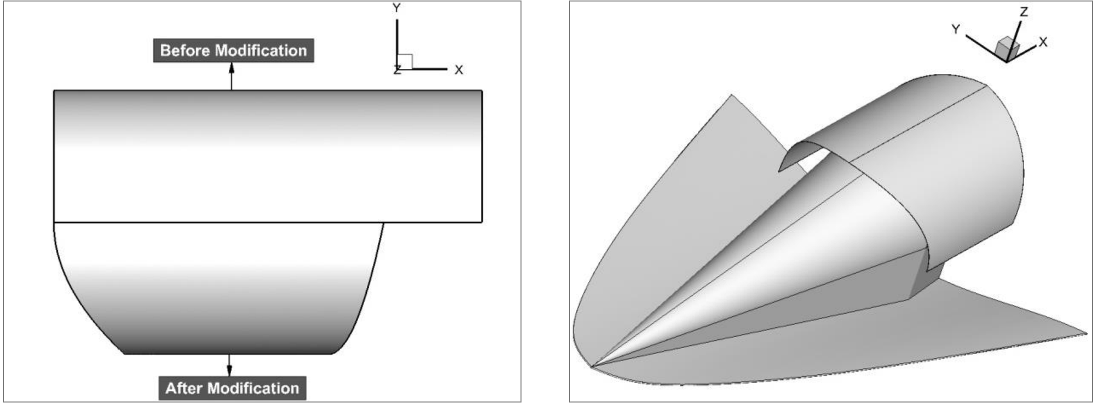


Figure 19. HCW shapes comparison before and after modification (left) and the whole shape after modification (right)

Figure 20 shows the pressure contours of the lower surface of HCW before and after modification. We can find out that the lower pressure dismissed after modification. The wet area which is related to friction drag is significantly reduced.

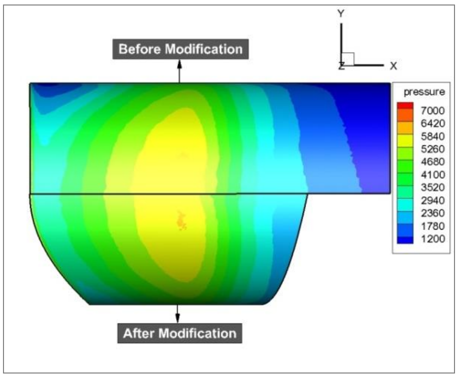


Figure 20. Pressure contours of the HCW lower surface before and after modification

The drag of each part before and after modification is shown in figure 21. Case1 and Case2 are respectively the configuration whose HCW is modified and not modified. It is clear that the modification of HCW has no influence on body. Its drag and lift remains unchanged. As shown in table 3, the pressure drag of HCW is basically the same in two configurations. The friction drag decreased significantly because the wet area is sharply reduced, leading to the whole drag of HCW decreasing. The overall drag obtained a certain degree of reduction. The pressure of the part of HCW which is cut off is relatively small, but still larger than the pressure of upper surface. The lift generated by HCW decreased. So the overall lift is also decreased. On the whole, after modification, both the lift and drag is decreased. The lift-to-drag ratio slightly increased from 4.28 to 4.29. It should be noted that the comparison is based on the laminar flow calculation model where the effect of vicious is small. If considering the impact of turbulence, the friction drag will share a large proportion. The effect of HCW modification will be more apparent. From the analysis above, we can learn that the shape of HCW can be optimized under the fixed body. The optimization design of HCW is needed in the next step.

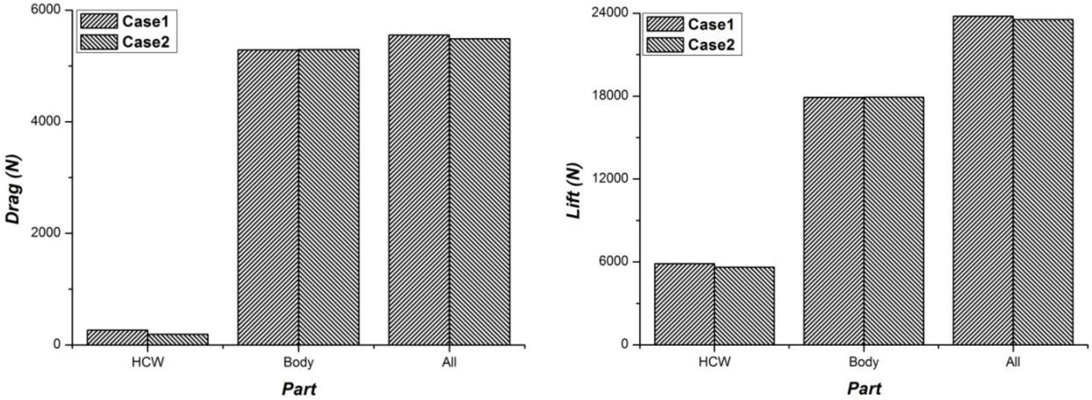


Figure 21. Drag and lift comparison of HCW, body and the whole vehicle before and after HCW modification

Table 3 Pressure drag and friction drag of two cases

	Case1		Case2	
	D_p(N)	D_f(N)	D_p(N)	D_f(N)
HCW	50.14	216.15	50.26	142.04

Table 4 Lift, drag and lift-to-drag of two cases

	Case1	Case2
Lift (N)	23780.29	23551.05
Drag (N)	5552.05	5482.38
Lift-to-drag Ratio	4.28	4.29

Further Analysis

Through the analysis of above several different bodies with HCW, we verified the validity of the HCW aerodynamic layout. In addition, we made some analysis for the shape of body and HCW. The results show that the lift and lift-to-drag ratio can be greatly improved, while the increase of drag is small. It is clear that the aerodynamic performance of aircraft can be greatly improved by introduction of HCW. But the configurations above are mainly to verify the effectiveness of improvement of aerodynamic performance. The shape of HCW and body are greatly simplified. In the actual aircraft design, many other issues will be involved. The following will be some qualitative analysis and discussion about two key problems of them.

In the analysis above, the calculation model is Euler or laminar model. But in the actual calculation, transition and turbulence will lead an increase in friction drag. Based on the analysis above, turbulence will not lead to a dramatic decline of the HCW effect. To verify the conclusion, we calculated the performance of a cone body using the $k-\varepsilon$ turbulence model. Figure 22 shows the comparison of pressure contours in the lower surface of HCW. Table 5 shows the aerodynamic performance parameters of each part and all in two calculation conditions.

As shown in table 5, under the turbulent conditions, the drag of HCW increased by 213N, the drag of cone body increased by 365N, the drag of base is reduced by almost 30N. However, we can find the pressure of HCW lower surface was higher in turbulent condition, and the lift of this part increased by 360N. On the whole, despite the promotional effect of HCW on lift-to-drag ratio decreased by about 12%, it is still very meaningful. Furthermore, the body is cone with a large cone angle. The volume ratio is big while wet area is small. The wet area of HCW shares a large proportion. For other body shape, the wet area of HCW can be reduced by reasonable optimization. The proportion of HCW friction drag to the total can be reduced.

Table 5 Comparison of aerodynamic performance between inviscid and turbulent model

	Inviscid			Turbulent		
	D(N)	*L(N)*	*L/D*	*D(N)*	*L(N)*	*L/D*
HCW	280.6	4233.5	15.08	493.6	4593.3	9.30
Body	1584.6	0	0	1949.7	0	0
Base	471.8	0	0	442.6	0	0
All	2337.0	4233.5	1.81	2886.0	4593.0	1.59

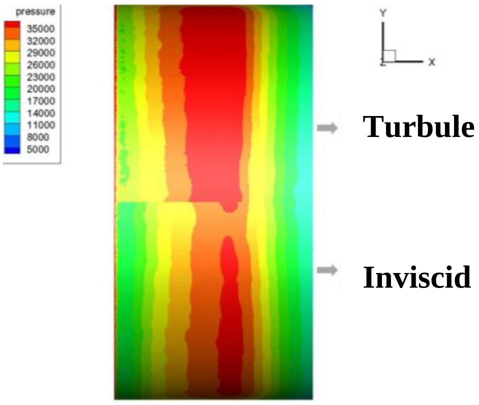


Figure 22. Pressure contours of HCW lower surface in inviscid and turbulent model

Conclusion and Discussion

According to the characteristics of high-speed vehicles and demand of high lift-to-drag and large volume, we proposed a new type with high pressure capture wing, and validated the high aerodynamic performance of this layout through some conceptual configurations. From the present calculation results, it is no hard for us to find that, after the introduction of HCW, both the lift and the lift-to-drag ratio of vehicles can get bigger. Therefore, it is a good aerodynamic layout for high-speed vehicles.

In terms of designing idea, the HCW layout and waverdier layout have some similarities. Their purposes are both to fully utilize the high pressure generated by the compression of body, improving the lift and lift-to-drag-ration. Compared to the waverider layout, the HCW layout can ease the contradiction between lift, lift-to-drag ratio with volume of the vehicle. More specifically, the increase of compression angle in upper surface can improve the volume of the vehicle. At the same time, the lift generated by HCW can be bigger. To some extent, HCW can be seen as a lift compensation device. Moreover, it can also be combined with some current good aerodynamic layout to improve the aerodynamic performance dramatically.

This paper is focused on the proposal of new HCW concept, mainly concentrating in the theoretical and conceptual analysis. In the actual design, there will be many other problems in a new aerodynamic layout. For example, the thickness of HCW will be larger along with the increase of stream Mach number considering the limitations of thermal protection and structural strength. The result is that, the effect of HCW will decrease along with the increase of stream Mach number. The main applicable range and conditions of HCW layout will be the next focus research. Besides, many other problems also should be considered, such as the off-design performance analysis, HCW shape optimization, especially when considering the friction, support device between the HCW and body and its effect on the layout, HCW structural design and analysis, and the control and stability after the introduction of HCW. All these problems will be undertaken in our research.

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