Aerodynamic Performance Analysis of a Curved-channel ABLE Airfoil in Supersonic Continuous and Hypersonic Rarefied Flows

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Abstract. An airfoil, equipped with a curved-channel ABLE, is a good alternative to increase the lift-to-drag ratio. For this purpose, a curved-channel artificial blunted leading edge (ABLE) was applied to several supersonic/hypersonic symmetrical airfoils to analyse the aerodynamic performance in low-altitude supersonic continuous flow and high-altitude hypersonic rarefied flow during the process of re-entry into the atmosphere. The compressible Navier–Stokes equations were solved using the finite volume method to analyse the aerodynamic performance and determine the optimal curved-channel ABLE airfoil for supersonic continuous flow. Thereafter, the drag reduction and lift increment efficiency of the optimal ABLE airfoil were analysed in the hypersonic rarefied flow. The variation in the aerodynamic performance of the ABLE airfoil with the Knudsen number and freestream Mach number was determined using the direct simulation Monte Carlo (DSMC) method. The results showed that with suitable ABLE configuration and parameter values, the concept of ABLE can help reduce the drag coefficient, improve the lift coefficient, and obtain a better lift-to-drag ratio in both continuous and rarefied flows without considerable aerothermal penalty. However, the drag reduction effect of the curved-channel airfoil in the rarefied flow is much lower than that in the continuous flow, because of the lower proportion of the wave drag in the total drag, and the overall aerodynamic performance is significantly deteriorated because of the rarefaction effect of the atmosphere.

1. Introduction
The lift-to-drag ratio (L/D) of supersonic and hypersonic vehicles, such as space shuttles and re-entry vehicles, significantly affects performance criteria such as the cross range, manoeuvring requirements, and payload mass fractions, as well as their economic viability. The drag acting on supersonic/hypersonic vehicles can be classified into three categories: 1) skin friction drag, 2) drag due to lift, and 3) zero-lift bluntness (wave) drag. The skin friction drag is due to the fluid viscosity and is a function of the total wetted surface area of the vehicle, and the drag due to lift includes the induced drag and the wave drag component[1]. During re-entry, the vehicles first fly in a hypersonic rarefied flow and then in a hypersonic or supersonic continuous flow. This requires the vehicles to have an optimal aerodynamic performance under both the flow conditions.

For supersonic or hypersonic continuous flows, Gupta and Ruffin introduced the concept of a curved-channel artificial blunted leading edge (ABLE) to reduce wave drag under the condition that the channel is sized such that a choked flow condition exists. This concept allows for a hollow channel
to be opened in the airfoil while cruising at supersonic/hypersonic speeds. The channel thickness should be sufficiently small, a normal shock should exist in front of the channel, and the flow should enter the channel subsonically. They studied the aerodynamic characteristics of the ABLE airfoil, such as the force coefficient, lift-to-drag ratio, and maximum heat transfer rate by conducting Navier–Stokes simulations. The ABLE concept helped reduce wave drag, slightly increase the skin friction drag, reduce the total drag, and increase the lift-to-drag ratio while keeping the same aerothermal load level as that of a no-channel airfoil[1-4].

Two types of ABLE concepts have been proposed: a flow-through channel ABLE and a curved-channel ABLE. The latter has a shorter channel, opened toward the nose of the vehicle or the leading edge of the airfoil and exhausted near the leading edge. With the channel opened, a part of the high-pressure surface of the nose or the leading edge of the airfoil is removed, thus reducing the wave drag. In addition, the jet-flow acting on the upper part wall results in a significant lift increment. Thus, the lift-to-drag ratio is improved. The flow-through channel ABLE airfoil has a lower total drag, and the flow expanding over the channel lip significantly increases the lift relative to the baseline geometry; the curved-channel ABLE has more advantages compared with the flow-through channel ABLE, such as better volumetric efficiency, lower internal structural/thermal load penalties, and lower viscous drag penalties.

It is reasonable to apply the curved-channel ABLE to re-entry vehicles as the leading edge of the airfoil for high-altitude hypersonic rarefied flows. Figure 1 shows the typical parameter–time maps of an unmanned space vehicle (USV)[5], from which the heat flux occurring in the stagnation point region when re-entering the earth’s atmosphere can be read. During re-entry, a space shuttle undergoes a relatively significant aerothermal heating at altitudes in the range of 60–110 km, where the flow regime includes free molecular and transitional regions.

![Figure 1. Time–altitude, time–velocity, and time–heat flux maps of an unmanned space vehicle.](image)

This condition demands a new understanding of the aerodynamic performance of airfoil/vehicles. This can be done by applying the ABLE concept, as it is ideal for the near-space flow domain where the gas is no longer consistent with the continuous medium hypothesis. This paper reports a study that extends the application range of the ABLE concept. We studied the feasibility of the previous curved-channel ABLE concept applied to several classical supersonic/hypersonic symmetrical airfoils and verified the efficiency of the ABLE concept under flight conditions where gas rarefaction dominates the flow regime. If the ABLE concept can help reach the design point and increase the lift-to-drag ratio, a vehicle can exhibit a better control performance in terms of the flight time, flight speed, and vehicle range and even improved fuel efficiency. The heat transfer rate at the leading edge is a function of the flight speed, and therefore, by controlling the flight speed, we can limit the heat flux during re-entry.
This study focused primarily on reducing the wave drag force and increasing the lift force as a means of increasing the lift-to-drag ratio, aiming to establish the feasibility of the ABLE concept by quantifying the aerothermal and aerodynamic performance under a wide range of flow domain. This concept can be applied to any airfoil used on a supersonic/hypersonic vehicle, but for simplicity, we selected some basic symmetric airfoils. First, the curved-channel ABLE concept was applied to four classical supersonic/hypersonic symmetric airfoils in a low-altitude continuous flow, and the optimal airfoil geometry was determined by conducting Navier–Stokes simulations. The optimal airfoil was further evaluated in a high-altitude rarefied flow using the direct simulation Monte Carlo (DSMC) method. The Knudsen number and freestream Mach number were considered to characterize the aerodynamic performance of the airfoils employing the ABLE concept.

2. Simulation configuration and method

2.1. Model building

The concept of curved channel ABLE was first proposed by Gupta and Ruffin[3]. At the beginning, with the hypothesis of a negligible lateral flow, four groups of typical two-dimensional hypersonic or supersonic airfoils and corresponding ABLE airfoils derived from the previous baseline longitudinal symmetry blunted diamond airfoil[3] were considered. Relative to a non-channel airfoil, taking advantage of the ABLE concept is expected to help reduce the total drag. To avoid significantly increasing the wetted area, which will result in an increased skin-friction drag, the channel is made to slope downward near the leading edge of the airfoil. The curves for the channel walls need to follow those of the lower and upper channel walls to match the external (baseline geometry) slopes at their end points; the upper channel wall exit location is the design input. Figure 2 shows the geometric parameters of the airfoils. Here, \( C \) is the chord length, \( L \) is the channel length, \( t \) is the channel height, \( R \) is the leading-edge bluntness radius of the airfoil, and \( R_n \) is the leading-edge bluntness radius of the channel.

![Figure 2](image)

(a) Outline shape of no-channel baseline diamond airfoil; (b) that of curved channel ABLE baseline diamond airfoil.

| Table 1. Two-dimensional airfoil shapes. |
|------------------------------------------|
| airfoil     | Configuration of symmetrical airfoils | Curved channel ABLE |
| diamond     |                                        |                     |
| biconvex    |                                        |                     |
| quadrangle  |                                        |                     |
| hexagon     |                                        |                     |

*The quadrilateral airfoil a/b is taken as 4/5; hexagonal airfoil a/b is 3/5.*

It is convenient to nondimensionalize these parameters with \( L=10\%C \) and \( t=4\%L \) to ensure a sufficient expansion of the flow inside the channel and with \( R_n=0.8\%L \) to reduce the leading-edge heat...
flux. For convenience, the following terminology is used to describe the airfoil. B-RN represents a symmetric curved-channel ABLE biconvex airfoil, which can be abbreviated as ABLE biconvex airfoil. NC, RN, D, B, Q, and H represent the no-channel baseline airfoil, round-nose curved-channel ABLE airfoil, diamond airfoil, biconvex airfoil, quadrangle airfoil, and hexagon airfoil, respectively.

Table 1 gives the configuration diagrams of the four typical supersonic symmetrical airfoils and the corresponding ABLE airfoils. The models are ensured to have the same main parameters as those of the baseline model, the only difference is that they have different two-dimensional plane shapes.

2.2. Simulation approach

The aerodynamic performance in the continuous flow was predicted using the commercial software Fluent. To this end, the k-ω turbulence model and density-based solver were used, and the compressible Navier–Stokes equations were solved using the finite volume method. The aerodynamic calculation is slightly affected by the grid. In this study, based on existing experience and for sufficient accuracy and efficiency, the near-wall and fore body grids were refined to some extent to ensure shock capturing capability.

A better alternative for practical applications is the open-source DSMC method called SPARTA, which has been well established by Sandia National Labs for rarefied and hypersonic conditions. This simulation approach is a particle method that does not rely on the continuous medium hypothesis. In the computational kernel, a large number of particles were simulated to represent real gas molecules, each having its velocity and internal energy. The grid generation has good flexibility because the DSMC method is computationally stable.

Based on previous experience, we take the grid dimension as $\Delta x \sim (1/3)\lambda$, which is called ‘one third of the mean free path’, and $\lambda$ is the local mean free path of the gas molecules in the grid. Thus, a relatively ideal grid division can be obtained.

Currently, two main molecular models are used in the DSMC methodology: the variable hard sphere (VHS) model and the variable soft sphere (VSS) model. The only difference is that the deflection angle in the VHS model is given by:

$$ x = 2\cos^{-1}(b / d)^{1/\alpha} $$

In the other model, it is given by:

$$ x = 2\cos^{-1}(b / d) $$

Here, $\alpha$ is a coefficient between 1 and 2.

The complete diffuse reflection model is an inelastic collision model that takes the temperature of the object surface as the equilibrium condition. The distribution function of the diffuse reflection particles is given by:

$$ f(C_r) = n_r \left(\frac{m}{2\pi kT}\right)^{1.5} \exp\left(-\frac{m}{2\pi kT}C_r^2\right) $$

Moreover, the Knudsen number ($Kn$) is defined as:

$$ Kn = \frac{\lambda}{L} $$

The mean free path is a function of the pressure, viscosity, and most probable molecular velocity. Various models have been proposed to describe [6]. $L$ is the characteristic length.

Besides $Kn$, the rarefaction parameter $\delta$ is another quantity that is also used to describe the flow regime and is defined in [7] as:

$$ \delta = \frac{\sqrt{\pi} \ L}{2 \ \lambda} = \frac{\sqrt{\pi} \ 1}{2 \ \ Kn} $$
3. Simulation validation

Table 2 gives the flow conditions used in the following test cases.

| Flow domain                | $V_\infty$(m/s) | $T_\infty$(K) | $n_\infty$(m$^{-3}$) | $\lambda$(mm) |
|----------------------------|-----------------|---------------|----------------------|--------------|
| supersonic continuous flow | 708             | 300           |                      |              |
| hypersonic rarefied flow   | 1504            | 290           | 1.05×10$^{21}$       | 1.6          |

3.1. Simulation validation

For validation in the first case, some comparisons of the force coefficients are made between the computational results of this study and the reference ones given in under the same flow condition. Figure 3 shows the corresponding plots. The drag and lift coefficients are in good agreement, with the maximum relative error of the lift–drag ratio reaching 11.16%. This discrepancy may be due to the systematic error in the simulation and the error in the numerical calculation when the lift-to-drag ratio was calculated using the lift and drag coefficients. Nevertheless, to some extent, the comparison results verify the validity of the method used for simulating the continuous flow.

![Figure 3](image)

**Figure 3.** (a) Comparisons of $C_l$ and $C_d$ between the results obtained in this study and the experimental results obtained in [8]; (b) Comparison of $L/D$.

3.2. Validation in the case of hypersonic rarefied flow

For validation in the second case, a test model proposed in [8] was employed. The test model was defined by the following parameters: the length of the flat plate was 100 mm and the thickness was 5 mm. The VHS and specular diffusive reflection models were used. The computational grid used in the simulation is a 2D structural grid, and the simulation is performed in an orthogonal domain around the plate. The inflow boundary is defined on the left side of the domain, whereas the outflow boundary is defined on the right.

![Figure 4](image)

**Figure 4.** (a) Comparison of pressure between computational results of this study, the wind-tunnel experimental ones in [9], and DAC results in [10]; (b) Comparison of heat flux.

Referring to the low-density wind-tunnel experimental results in [9] and DAC (another DSMC method) results in [10], the pressure and heat flux distribution along the flat-plate upper surface are
compared, as shown in figure 4. The results are in good agreement. Moreover, the results obtained using SPARTA are in better agreement with the wind tunnel experimental results; however, the heat flux readings are not predicted accurately enough by the DAC software. Previous studies[11,12] have verified SPARTA, and the reliability and validity of the computational kernel have been proven.

4. Results and discussion

4.1. Aerodynamic performance of airfoils in continuous flow

The influence of channel parameters on the aerodynamic performance in continuous flows has been preliminarily studied. The first set of results in continuous flow were obtained using Fluent with a free-stream Ma number of 2.4 and an altitude of 12 km. These simulation tests can be viewed as modelling the low-altitude supersonic continuous flow around the airfoils. Figures 5(a)–6(c) show the computed results of the force coefficient and lift-to-drag ratio.

![Figure 5](image)

**Figure 5.** (a) $Cl$; (b) $Cd$; (c) $L/D$ of the different airfoils and ABLE airfoils.

The lift coefficient of the airfoil increases linearly with the increase in the angle of attack, and the variation in the drag coefficient with the increase in the angle of attack first gradually increases and then rapidly increases. When the angle of attack reaches 4°, the drag coefficient increases more obviously, because with the increase in the angle of attack, the windward area increases, on which the pressure acting is greater than that on the leeward area. This also makes the lift-to-drag ratio to increase first and then decrease. Overall, among the four groups of investigated models, except in the cases of the ABLE quadrilateral airfoil and ABLE hexagonal airfoil, the curved-channel ABLE concept helps reduce the drag and increase the lift; moreover, the maximum lift-to-drag ratio increases by approximately 24%. This can be attributed to the sloping down of the curved channel near the leading edge, which reduces the high pressure acting on the stagnation point region; moreover, the jet force on the upper surface of the airfoil generates a positive normal force, resulting in an increased lift.

![Figure 6](image)

**Figure 6.** (a) Trace lines of the ABLE hexagonal airfoil; (b) that of the ABLE diamond airfoil.

The drag coefficient of the ABLE hexagonal airfoil is slightly greater than that of its baseline no-channel model. The lift coefficient and drag coefficient of the ABLE quadrilateral airfoil are lower.
than those of the baseline no-channel model; when the angle of attack reaches 4°, the lift coefficient of the ABLE quadrilateral airfoil is approximately 69.49% that of the no-channel one. To further analyse the possible reason for the abnormal characteristics, the trace lines near the outflow of the ABLE hexagonal and ABLE diamond airfoils are simulated, as shown in figure 6. Compared with the ABLE diamond airfoil, the leading edge of the ABLE hexagonal airfoil has a greater semi-apex angle and a thicker leading edge, resulting in a larger projected area in the x-direction at the outlet where the channel slopes down. The resulting jet force acting on this area induces a certain force in the x-direction and then converts to a drag part, leading to an increase in the total drag. However, the other ABLE airfoils generate a lower chordal force at the outlet, which is insufficient to increase the total drag.

Figure 7. (a) Flow field contours of the ABLE quadrilateral airfoil near the tail edge; (b) Flow field contours of the baseline non-channel quadrilateral airfoil near the tail edge.

Figure 7 shows the results of the flow field contours near the tail edge of the ABLE quadrilateral and baseline no-channel airfoils. Because of the influence of jet-flow to flow field on the outlet of the channel, the expansion wave at the rear edge is weakened, resulting in a reduced low-pressure area, and the differential pressure between the upper and lower surfaces of the airfoil is reduced. This decreases the lift and drag coefficient of the ABLE quadrilateral airfoil.

The results confirm that the current configuration of the ABLE quadrilateral and ABLE hexagon airfoils may not reach the ideal design point. Therefore, we need to modify and optimise the shapes and parameters. Referring to figure 5(c), with such designs, the ABLE diamond airfoil exhibits an optimal aerodynamic performance in supersonic continuous flow with a maximum increase in L/D of approximately 25% at α=4°. Therefore, it is selected as the baseline airfoil for further analysis in hypersonic rarefied flow.

4.2. Aerodynamic performance of airfoils in rarefied flow

Taking the optimal case in the continuous flow as the diamond and ABLE diamond airfoils for further research, we obtained a series of results in rarefied flow using SPARTA under flow conditions based on an altitude of 70–90 km during re-entry. These simulations are intended for modelling the high-altitude hypersonic rarefied flow around the airfoils. With one of the parameters held constant, the effects of Mach and Knudsen Numbers, which represent different heights and air densities, on the aerodynamic performance are quantified.

First, the force coefficient and lift-to-drag ratio are computed with $Ma=22$ and 28, respectively, while maintaining an altitude of 80 km (with the Knudsen Number kept constant); the molecular density is $3.8317\times10^{15}/m^3$, and $Kn$ is 0.044 with the slip-flow dominating the flow. The slip-flow starts to appear when $Kn$ is greater than 0.01, as the gas becomes more and more rarefied; the flow is characterised to be in the transition and free molecular regimes when $Kn$ reaches 0.1 and 10, respectively [13].

Figure 8 shows the aerodynamic parameters of the airfoils. The variations in $Cl$, $Cd$, and $L/D$ with the angle of attack appear to be largely the same as those under the continuous flow condition, indicating there might be some similitude between the continuous and rarefied flows. With the
increase in the angle of attack, the drag coefficient does not increase as much as it did under the continuous flow condition. This is because the flow regime is so rarefied that the freestream flows around the airfoil more smoothly, resulting in a lower differential pressure between the upper and lower surfaces of the airfoil relative to the one in the continuous flow.

![Figure 8](image)

**Figure 8.** (a) Cl and Cd of baseline diamond airfoil and ABLE diamond airfoil; (b) L/D of airfoils.

At a certain Knudsen number, both Cl and Cd decrease with the increase in the Mach number. The ABLE concept can still yield reduced drag and increased lift and L/D ratios. Although the drag reduction ratio is only approximately 2.6%, the lift increment ratio reaches approximately 8–10%, thus increasing the L/D ratio. Table 3 gives the force coefficient values.

Under a such rarefied flow condition, for α=4°, the skin friction drag of the ABLE airfoil at 22 Ma reaches up to 75.12% of the total drag, with the wave drag ratio being less than 25%. With the curved-channel ABLE concept, the skin friction drag coefficient increases by only 3.35%, while the reduction ratio of the other drags (including the wave drag) increases by 20.08%. However, because of the much lower proportion of the wave drag, the drag reduction performance of the airfoil is much weaker when utilising the curved channel in the rarefied flow. Moreover, the drag reduction and lift increment rates hardly vary with Ma at any given angle of attack. In addition, because of the obvious rarefaction effect, the lift-to-drag ratio of the ABLE airfoil is much lower than that under the continuous flow condition. This is consistent with that reported previously [14, 15]: The maximum lift-drag ratio of a waverider reaches 7.5 when flying at an altitude of 30 km; however, at 90 km, the result calculated using the DSMC is only 0.3, which is much lower than that calculated under the continuous flow condition.

**Table 3.** Force coefficients with an angle of attack of 4° at 22 Ma.

|                | Skin friction drag | Other drags(including wave drag) | Total drag |
|----------------|-------------------|----------------------------------|------------|
| Original airfoil | 0.151             | 0.050                            | 0.201      |
| ABLE airfoil    | 0.156             | 0.040                            | 0.196      |
| Δ(∗)           | 3.35%             | −20.08%                          | −2.49%     |

Considering the airfoils with α=4°, parameters as listed in table 4, Cd does not change considerably for the ABLE airfoil; however, Cl and L/D increase to a great extent, and the lift-to-drag ratio increases by more than 12% while the maximum heat flux increases no more than 8% compared with the baseline airfoil. From this, we can conclude that the ABLE airfoil with a bluntness radius Rn=0.8%L, which is reasonable for continuous flows, meets the required design for increasing L/D while maintaining a relatively low heat flux increment in the rarefied flow.

**Table 4.** Heat flux and force coefficient with an angle of attack of 4° at 22 Ma.

|                | Qmax (×10^6) | Cd   | Cl   | L/D  |
|----------------|--------------|------|------|------|
| Original airfoil | 1.001        | 0.201| 0.075| 0.373|
| ABLE airfoil    | 1.080        | 0.196| 0.082| 0.418|
| Δ(∗)           | 7.89%        | −2.49%| 9.33%| 12.06%|
By analysing the pressure contour distributions of the diamond airfoil and the corresponding ABLE airfoil in figure 9, we can preliminarily reveal the aerodynamic characteristics of the ABLE airfoil in the rarefied flow. With the curved channel, most of the wall where the stagnation-region high pressure acts is removed, resulting in a suction high pressure at the throat of the channel, which is slightly greater than the stagnation pressure, and there is no obvious leading edge shock wave interaction like that in the continuous flow. Compared with the pressure distribution contour in the continuous flow given in [8], we find that the shock waves in the rarefied flow are very weak and relatively concentrated at the leading edge; the shock waves are very close to the airfoil surface, and the shock layer region is very narrow under the action of hypersonic airflow. Within the scope of the angle of attack studied, in the continuous flow, the lift coefficient is always greater than the drag coefficient; however, in the rarefied flow, the lift and drag coefficients decrease, with the drag coefficient being greater than the lift coefficient, resulting in a significant reduction in the lift-to-drag ratio.

For the second test, a shuttle is subjected to varying flow conditions at different flight heights across a typical trajectory. This requires understanding the effect of air density ($Kn$) on the aerodynamic performance of the airfoil. In fact, the lower the density, the greater the value of $Kn$.

![Figure 9](image_url)  
**Figure 9.** (a) Flow field of the diamond airfoil; (b) that of curved-channel ABLE airfoil.

Figure 10 shows the variation in the aerodynamic performance parameters with $Kn$. At the same $Ma$, with the increase in the Knudsen number, the lift and drag coefficients both first rapidly increase and then gradually increase, and the lift–drag ratio decreases gradually. The Knudsen number shows no obvious effect on the drag reduction and lift increment efficiency.

![Figure 10](image_url)  
**Figure 10.** (a) $Cl$ and $Cd$ of airfoils with different $Kn$; (b) $L/D$ of airfoils with different $Kn$.

However, compared with the influence of the Mach number, the effect of curved channel on the increment in the lift-to-drag ratio presents a decreasing trend with the increase in the Knudsen number.

5. Discussion and Conclusions

We investigated a set of two-dimensional supersonic/hypersonic symmetrical airfoils and corresponding curved-channel ABLE airfoils in this study. The continuous and rarefied flow fields around the ABLE airfoils during re-entry were simulated by solving the Navier–Stokes equations and using the DSMC method, respectively. The simulation results show that:

1. In a supersonic continuous flow, creating a curved channel can help reduce the drag and increase the lift and effectively improve the lift-to-drag ratio. A curved-channel ABLE diamond airfoil provides an optimal aerodynamic performance relative to the other airfoils tested.

2. In a hypersonic rarefied flow, because of the relatively low proportion of the wave drag in the total drag, the drag reduction performance of the channel is relatively insignificant. However, the lift
increment performance and the lift-to-drag ratio can still be effectively improved. Because of the rarefaction gas effect, the airfoil aerodynamic performance is seriously deteriorated compared with that in the continuous flow.

(3) Under the same Knudsen number, the lift and drag coefficient of the airfoil decrease with the increase in the Mach number, and the effect of the channel on the aerodynamic performance remains largely unaffected by the Mach number.

(4) Under the same Mach number, the lift and drag coefficient increase with the increase in the Knudsen number, while the Knudsen number has a relatively obvious influence on the channel effect: the increased lift-to-drag ratios decrease with the increase in the Knudsen number.

To summarize, we verified the feasibility of the previous curved-channel ABLE concept applied to several classical supersonic/hypersonic symmetrical airfoils. There might exist some differences and similarity between continuous and rarefied flows. Therefore, we verified the efficiency of the ABLE concept under flight conditions where the gas rarefaction dominates the flow regime. The paper provides insights into the requirements of the new design.

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