Effects of Cowl Lip Angle on Starting Performances for a Mixed-Compression Two-Dimensional Axisymmetric Hypersonic Inlet

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Abstract: The third quasi-uniform B-spline was adopted to design the cowl profiles with various cowl lip angles. Starting performances were simulated by the numerical method and the results showed that the starting processes for different cowls can be classified into two types. In the first type, the inlet starts when the opened large-scale separation zone is swallowed; in the second type, the opened separation zone enters the internal contraction region to form a closed separation zone, which is then swallowed to enable the start. In addition, inlets with small and large cowl lip angles exhibit the first and second types of the starting process, respectively. Moreover, there is an optimal cowl lip angle to achieve the best starting performance. For the inlet investigated herein, the starting Mach number is the lowest when the cowl lip angle is 9°. In addition, as the internal contraction ratio increases, the optimal cowl lip angle gradually decreases and the starting performance deteriorates.

Keywords: hypersonic inlet; cowl lip angle; starting performance; large-scale separation bubble

1. Introduction

Hypersonic aircrafts powered by scramjet engines have recently been attracting significant attention among scholars [1,2]. The scramjet directly uses the oxygen in the environment to achieve supersonic combustion and generates thrust, which results in high specific impulse and economic advantages [3–6]. As a key component, the inlet is used to capture and compress air, and then sent the airflow to the combustion chamber. A well-designed inlet is one that can capture adequate airflow with high total pressure recovery performance and low distortion [7,8]. However, when an unstart emerges, the inlet experiences rapid reductions in captured airflow and total pressure recovery performance, which further results in thrust decline or even engine flameout [9–11]. Considering that the inlet unstart has led to numerous flight test failures, it should be investigated in detail [12–15].

Several factors contribute to inlet unstart; irrational geometric parameters are one of the most important factors among these [16]. As a key parameter in inlet design, the internal contraction ratio (ICR) is one of the main factors affecting the starting performance. Ogawa [17] found that inlets with high internal contraction ratios struggle to achieve self-start. Thus, assistant start means are utilized for such inlet to enable a start. Kantrowitz [18,19] assumed that a normal shock wave exists at the entrance of the one-dimensional isentropic-compression inlet and calculated the critical self-start contraction ratio according to the isentropic relation, viz., the Kantrowitz criterion, as shown below.

$$\left(\frac{A_i}{A_*}\right)_{\text{Kantrowitz}} = \frac{1}{M_{\infty}} \left[\frac{(\gamma + 1)M_{\infty}^2}{(\gamma - 1)M_{\infty}^2 + 2}\right]^\frac{\gamma - 1}{2\gamma - 1} \times \frac{\gamma + 1}{\gamma + \frac{2\gamma - 1}{2\gamma - 1}}$$

where \(A_i\) is the entrance area, \(A_*\) is the throat area, \(M_{\infty}\) is the freestream Mach number, and \(\gamma\) is the specific heat ratio.
According to the Kantrowitz criterion, starting performance is determined by the Mach number and the internal contraction ratio. For a given Mach number, the starting performance of the inlet declines with an increase in the internal contraction ratio. However, many experimental and numerical results show that the inlet with an internal contraction ratio greater than the critical ICR can also start [16,20]. This contradiction can be attributed to the fact that Kantrowitz assumes that a normal shock exists at the entrance. However, a weak oblique shock stands at the entrance due to the cowl lip angle design. This discrepancy indicates that the cowl lip angle has a significant effect on the inlet starting performance. Van Wie [20] found that the cowl length, height, and lip angle can affect the critical internal contraction ratio. Liu [21] proposed an assistant restarting method by introducing a rotating cowl for a supersonic inlet. The results indicated that the starting performance could be improved by increasing the cowl rotating angle. The result undertaken by Ramprakash [22] indicated that the starting ability was independent of the cowl rotation rate. The stability boundary and buzz evolution process were analyzed by Wen [23,24] for a hypersonic inlet with translating/rotating cowl. Teng [25] studied the influence of the cowl sidewall on starting ability of a generic rectangular hypersonic inlet. The results indicated that the increased cowl sidewall sweepback expanded the inlet flow spillage window, thus effectively restarting the inlet. Chen [26] investigated the effect of the cowl convergence angle on the supersonic isolator flow behavior, and found that there was an optimal cowl convergence angle to achieve the best starting ability. Jae [27] studied the flow through a supersonic inlet with a moveable cowl under various attack angles. The results demonstrated that the vehicle angle of attack could be varied over a wide range without choking. Moreover, based on a simplified hypersonic inlet, Yue [28] observed that inlets with various cowl lip angles can generate cowl lip shocks with different intensities, thus affecting the starting performance. Liu [29] numerically studied the starting performance of a simplified inlet and reported that there was an optimal cowl lip angle to achieve the best starting performance. However, the underlying flow mechanism needs to be further investigated.

In hypersonic flow, the airflow was pre-compressed by the forebody. The effecting law of cowl lip angle on starting performance may vary for the inlets with various forebody configurations. Therefore, the forebody should be considered in the cowl lip angle study, and the effect of the cowl lip angle for the mixed-compression forebody/inlet configuration on the starting performance needs to be further investigated [30]. Moreover, the underlying mechanism by which the cowl lip angle impacts the starting process is still unclear.

In this study, a mixed-compression hypersonic inlet was analyzed to determine the effect of cowl lip angles on starting performances. The parametric approach is applied to design the cowl profiles and acquire the inlet configuration with different cowl lip angles. Then, the numerical simulation method was used to calculate the starting processes. Subsequently, the inlet with ICR = 1.9 was considered to analyze how the cowl lip angle affects the inlet starting processes. Finally, the effect laws of the cowl lip angle on the starting ability of the inlets with various ICRs were studied, which can provide guidance for the cowl design.

2. Inlet Configuration and Parametric Design of the Cowl
2.1. Researched Model

Figure 1a illustrates the studied model, where $x$ is the flow axis, $r$ is the radial axis, and $R$ is the radius of the body at the throat section. According to the flow characteristics, the forebody/inlet is divided into three parts: the conical AB section is the wall of the conical shock dependence area, the wall BF is the external compression section, and the wall FD and cowl CE co-create the internal contraction section. The total contraction ratio (TCR) and the ICR of the inlet are defined by Equations (2) and (3). The inlet is designed for a flight height, flight Mach number (denoted by $Ma$), and angle of attack of 25 km, 6.0, and $0^\circ$, respectively. Figure 1b shows the Mach number contour of the inlet with TCR = 6.0 and ICR = 1.9 under design point. As illustrated, when the airflow passes
through the cone tip, a conical shock generates and intersects with the leading edge of the cowl, achieving “shock-on-lip”. Then, a series of compression waves are generated by the external compression wall to isentropically compress the airflow. Finally, the airflow is captured by the cowl and further compressed by the cowl lip shock and its reflected shock in the internal contraction section. In conclusion, the freestream within the circle of radius \( r_c \) experiences a series of compressions and finally flows to the ring-shaped throat.

\[
\text{TCR} = r_c^2 / r_e^2 - r_d^2
\]

\[
\text{ICR} = (r_c + r_f) \sqrt{\left( r_c - r_f \right)^2 + \left( x_c - x_f \right)^2 / \left( r_e^2 - r_d^2 \right)}
\]

2. Inlet Configuration and Parametric Design of the Cowl

2.1. Researched Model

Figure 1. Studied model and Mach number contour under design point: (a) Schematic of the inlet configuration and flow structure; (b) Mach number contour.

2.2. Parametric Design of the Cowl

The parametric design of the cowl should be performed under certain geometric restraints. To ensure that the mass flow ratio \( (\varphi) \) remains constant, the positions of the start-point C and the end-point E of the cowl are unchanged. To ensure the smooth transition of the cowl and the downstream isolator, the cowl curve should keep horizontal at the throat. As shown in Figure 2, a third quasi-uniform B-spline curve is adopted to perform the parametric design of the cowl configuration (blue curve). The cowl is determined by the control polygon \( CF_1F_2E \) (denoted by red lines). The fixed points C and E are the start and end points of the cowl, respectively. Point \( F_1 \) can move along the extended line of \( CF_1 \), where the angle between line \( CF_1 \) and the horizontal direction is denoted as \( \delta \). Point \( F_2 \) can move along the horizontal direction, and its radial coordinate is identical to that of Point E, thereby ensuring that the cowl is horizontal at E. In this study, the distances from C to \( F_1 \), and from E to \( F_2 \) are denoted as \( L_1 \) and \( L_2 \), respectively. With a given group of \( L_1, L_2, \) and \( \delta \), a corresponding cowl curve can be acquired. Under the proposed parametric design, \( \delta \) is the cowl lip angle. To simplify the study, \( L_1 \) and \( L_2 \) are set as 0.32\( R \) and 0.25\( R \), respectively, and the inlet configurations with different cowl lip angles are acquired by changing the value of \( \delta \).
waves obtained by the numerical method are almost the same as the experimental results, was selected for the current study. The first cell height of the medium grid is 0.02 mm, considering the axial symmetry of the model, the 2D flow field in a symmetry plane was considered the computational domain. The boundary layer grid was set up to accurately simulate the near-wall airflow. Moreover, to accurately simulate the complex shock system, the density-based solver was utilized to solve the Reynolds-averaged Navier-Stokes equations. Considering the large-scale separated flows in the flow field under the unstarting state, the SST k-ω model was selected as the turbulence model. By combining the advantages of the k-ε model in calculating the far field and k-ω model in near-wall region flows, the SST k-ω model satisfactorily simulates the boundary layer and separated flows. The ideal gas model was used as the airflow model and the Sutherland law was adopted to calculate the viscosity. Figure 4 shows the inlet computational domain and grid. Considering the axial symmetry of the model, the 2D flow field in a symmetry plane was considered the computational domain. The boundary layer grid was set up to accurately simulate the near-wall airflow. Moreover, to accurately simulate the complex shock system in the flow field, the grids in the cone tip, cowl lip, and internal contraction section are dense. A grid independence study was undertaken in a previous work, three grid scale, i.e., coarse (200 × 120), medium (300 × 180), and refined (400 × 240) grids were set [31]. The results show that the wall pressures calculated by the medium and refined grids are similar, and the differences in the mass flow ratio and total pressure recovery coefficient (σ) are both below 0.05%. Considering the computing accuracy and cost, the medium grid was selected for the current study. The first cell height of the medium grid is 0.02 mm, which results in a y+ below 1 in the main portion of the wall. Moreover, the expansion ratio of the grid is 1.12. The far field pressure was considered as the inlet condition of the computational domain, the outlet was taken as the pressure outlet, and the compression wall and cowl were assumed to be non-slip adiabatic walls. The experiment data of the inlet flow field with a complex shock system obtained by Herrmann were adopted to validate the accuracy of the current numerical method. The geometric configuration of the test model and the experimental conditions of the wind tunnel could refer to in Ref. [32]. In addition, the current grid setting and numerical method were employed to simulate the test process. Figure 5 shows the schlierens of the flow fields obtained by the experiment and the current numerical simulation. As can be seen, the locations and shapes of the shock waves obtained by the numerical method are almost the same as the experimental results.
demonstrating the reasonability of the proposed numerical method for calculating the inlet flow field.

![Inlet computational domain and grid.](image)

**Figure 4.** Inlet computational domain and grid.

![Schlierens comparison.](image)

**Figure 5.** Schlierens of the flow fields obtained by the current numerical method and experimental result.

### 4. Results and Discussion

#### 4.1. Two Types of Starting Processes under Different Lip Angles

The numerical method is utilized to calculate the starting process of inlets with different cowl lip angles. The results show that there are two different starting processes depending on the cowl lip angle. In this paper, the inlets with $\delta = 3^\circ$ and $10^\circ$ are considered to analyze the two starting processes. First, the inlet with $\delta = 3^\circ$ is used to introduce the first type of starting process. Figure 6 shows the Mach contours of the flow fields under typical freestream Mach numbers during the starting process. When the incoming Mach number is 3.0, the airflow chokes at the throat. Subsequently, a high-pressure signal propagates upstream, which leads to a large-scale separation bubble at the entrance. The separation shock makes the incoming flow deflect in advance, and forms a supersonic spillage above the cowl lip, thus easing the choke at the throat. In addition, complex shock systems, such as the cowl lip shock and the reattached shock, leads to significant flow loss. Note that the inlet is in the unstarting state. Since the separation shock induced by the separation bubble is upstream of the cowl lip and results in spillage, the separation zone is called the opened separation bubble. When the incoming Mach number increases from 3.0 to 5.9, the separation shock approaches the cowl lip gradually, and the spillage decreases accordingly. However, the opened separation zone continues to exist in this process, and the separation point remains almost unchanged. In particular, at $Ma = 5.9$, the separation shock intersects the cowl lip, and the spillage almost disappears. As the Mach number increases to 6.0, the separation bubble suddenly disappears, and an unblocked supersonic flow is formed in the duct. Obviously, the inlet enters the starting state.
Figure 6. Mach number contours during the first type of starting process ($\delta = 3^\circ$).

Figure 7 shows the mass flow ratio and total pressure recovery coefficient at the throat during the first type of starting process. The definition of mass flow ratio is expressed in Equation (4), where $\dot{m}$ is the mass flow at the throat, $\rho_\infty$ and $v_\infty$ represent the density and velocity of the freestream, $A$ is the inlet capture area. The total pressure recovery coefficient is the ratio of the total pressure at the throat ($TP_t$) to the total pressure of the freestream ($TP_\infty$), which is expressed in Equation (5). At $Ma = 3.0$, the inlet shows poor flow capture capability because of the spillage induced by the separation bubble. In addition, because of the large-scale separation zone, the total pressure recovery coefficient is also low. Moreover, the mass flow rises gradually with the increasing Mach number; however, owing to the increase in the shock intensity, the total pressure recovery coefficient decreases further. When the Mach number increases from 5.9 to 6.0, the two parameters increase significantly (as denoted by the arrows in Figure 7), and the inlet enters the starting state.

In summary, the first type of starting process can be described as follows. Owing to the low incoming Mach number, an opened large-scale separation bubble is formed in the entrance and a supersonic spillage is generated. When the Mach number increases till the separation shock reaches the cowl lip, even a marginal increase in the incoming Mach number would enable the inlet to enter starting state. During this starting process, the mass flow and total pressure recovery coefficient rise sharply as the inlet enters the starting state.

$$\phi = \frac{\dot{m}}{\rho_\infty v_\infty A}$$  \hspace{1cm} (4)

$$\sigma = \frac{TP_t}{TP_\infty}$$  \hspace{1cm} (5)

Figure 7. Distributions of the mass flow ratio and total pressure recovery coefficient during the first type of starting process ($\delta = 3^\circ$).

Next, the inlet with $\delta = 10^\circ$ is considered to analyze the second starting process, for which the Mach contour is shown in Figure 8. At Mach numbers of 3.0 and 4.2, an opened separation zone exists in the flow field, and the flow characteristics are the same as those of the inlet with $\delta = 3^\circ$. When the Mach number increases to 4.3, the separation zone greatly shrinks and moves downstream. At this time, the separation shock impinges on the cowl, and the spillage disappears completely. Under this state, the separation bubble forms a closed recirculation zone in the duct, therefore called a closed separation zone. With the further increase in the Mach number, the position of the closed separation zone...
gradually travels downstream. When the Mach number reaches 4.7, the closed separation zone completely disappears and a supersonic flow forms in the duct.

**Figure 8.** Mach number contours during the second type of starting process ($\delta = 10^\circ$).

Figure 9 shows the changes in the mass flow ratio and total pressure recovery coefficient at the throat during the second type of starting process. When the Mach number is low, an opened separation zone exists, and the two parameters are both low as well. At $Ma = 4.3$, the closed separation zone is formed, the mass flow ratio increases significantly, and the total pressure recovery coefficient also rises sharply (as denoted by the arrows in Figure 9). With a further increase in the incoming velocity, the mass flow ratio increases linearly, and the total pressure recovery also improves. When the Mach number increases from 4.6 to 4.7, the inlet enters the fully-starting state. At this time, the mass flow ratio shows no significant increase; however, the total pressure recovery coefficient rises sharply again.

**Figure 9.** Distributions of mass flow ratio and total pressure recovery coefficient during the second type of starting process ($\delta = 10^\circ$).

In summary, the second type of starting process can be described as follows. When the incoming Mach number is low, the opened separation zone is formed in the flow field. When the Mach number increases to a certain value, the separation zone enters the internal contraction section and forms a closed one. With a further increase in the Mach number, the separation zone shrinks and moves downstream. As the Mach number increases further, the closed separation zone disappears, and the inlet enters the fully-starting state. In this starting process, the mass flow ratio rises sharply only when the closed separation zone is formed. In contrast, the total pressure recovery coefficient increases significantly at two separate instances: once, when the closed separation zone is formed, and for the second time, when the inlet enters the fully-started state.

Van Wie [3] reported that an inlet could be deemed to be in the starting state when the internal flow does not affect the flow capture ability. On this basis, the inlet with $\delta = 10^\circ$ can be considered as entering the starting state at $Ma = 4.3$. However, a large-scale separation bubble still exists in the duct. Moreover, the separation, reattachment, and reflected shock waves induced by the separation bubble dramatically increase the flow loss, which differs significantly from the fully-starting state. Generally, whether a flow field can be regarded as a starting one can be judged based on two aspects: the flow structure and the inlet
Van Wie [3] reported that an inlet could be deemed to be in the starting state when the inlet wall enters the starting at \( Ma = 4.57 \), exhibiting the best starting performance. Figure 10 shows the fully-starting flow field (flow field A) and the flow field with a closed separation zone (flow field B) at \( Ma = 4.3 \), where the inlet wall are remarked by blue lines, the streamlines are denoted by black lines, and the wave system are represented by red lines. The fully-starting flow field was obtained according to the hysteresis principle by decreasing the incoming Mach number from a high value to 4.3. As shown in Figure 10a, when the inlet is fully-starting, the airflow capture capability is not affected by the internal flow, and the cowl lip shock impinges on the compression wall, forming a small-scale separation bubble. As displayed in Figure 10b, the internal flow also does not affect the flow capture performance. However, a comparatively large-scale separation bubble is formed in the internal contraction section. Meanwhile, the position where the separation zone is located forms an aerodynamic throat, and the separation zone induces complex shock systems that significantly increase the flow loss. Furthermore, the separation bubble scales of the two flow fields vary considerably. Therefore, in view of the flow structure, the flow field with the closed separation zone cannot be considered as a starting flow.

![Figure 10. Structures of the two flow fields (\( \delta = 10^\circ \)) at Ma = 4.3 for (a) Flow field A and (b) Flow field B.](image)

Table 1 shows the aerodynamic parameters at the throat of the two flow fields, where \( Ma_t \) and \( p_t \) represent the mass-average Mach number and static pressure at the throat, and \( p_{\infty} \) is the static pressure of the freestream. Though the two flow fields have identical mass flow ratios, the total pressure recovery coefficient of flow field A is significantly greater than that of flow field B. In addition, the airflow in flow field B obviously decelerates, resulting in a relatively high-pressure rise. For the combustion chamber, when a closed separation zone is formed, the airflow parameters differ significantly from those of the fully-starting state, so the engine may not work normally even though the mass flow meets the requirements. Thus, the flow field B is still deemed to be at the unstarting state. Therefore, for the inlet with \( \delta = 10^\circ \), the starting Mach number (\( Ma_s \)) is 4.7.

<table>
<thead>
<tr>
<th></th>
<th>( \varphi )</th>
<th>( \sigma )</th>
<th>( Ma_t )</th>
<th>( p_t/p_{\infty} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow field A</td>
<td>0.725</td>
<td>0.4114</td>
<td>1.50</td>
<td>23.86</td>
</tr>
<tr>
<td>Flow field B</td>
<td>0.725</td>
<td>0.7753</td>
<td>2.30</td>
<td>13.33</td>
</tr>
</tbody>
</table>

4.2. Effect of Cowl Lip Angle on the Starting Performance

Figure 11 shows the starting Mach number distribution of the ICR = 1.9 inlet with different lip angles, where the abscissa and ordinate represent the cowl lip angle and starting Mach number, respectively. The blue and green dots represent the first and second types of starting processes, respectively. The inlet experiences the first type of starting process at a small cowl lip angle, and the second type at a large cowl lip angle. In addition, the cowl lip angle has a significant influence on the starting performance. When the cowl lip angle is small, the inlet starts at a high Mach number, showing a poor starting ability. With the increase in the cowl lip angle, the starting Mach number decreases gradually. The inlet with \( \delta = 9^\circ \) enters the starting at \( Ma = 4.57 \), exhibiting the best starting performance. However, the starting ability deteriorates with the further increase in the cowl lip angle,
which implies that excessively small or large cowl lip angles will lead to unsatisfactory starting performances. There is an optimal cowl lip angle to achieve the lowest starting Mach number, which is denoted by $\delta_{\text{opt}}$ in this study.

![Starting Mach number distribution of the inlet with different cowl lip angles.](image1)

**Figure 11.** Starting Mach number distribution of the inlet with different cowl lip angles.

To determine the underlying reason for the sharp rise of the starting Mach number at excessively small cowl lip angles, the wall pressure distributions during the starting process of the inlet with $\delta = 0^\circ$ are analyzed, as shown in Figure 12. When the inlet Mach number increases from 4.0 to 6.4, an opened separation zone appears in the flow field, and the separation point remains unchanged. However, owing to the increase in the incoming dynamic pressure, the wall pressure in the duct increases continuously, even exceeding $70p_\infty$. This indicates that the inlet struggles to swallow the separation zone under the effect of the strong cowl lip shock, thereby resulting in a poor inlet starting performance [33].

![Wall pressure distributions during the starting process of the inlet with $\delta = 0^\circ$.](image2)

**Figure 12.** Wall pressure distributions during the starting process of the inlet with $\delta = 0^\circ$.

Excessively large cowl lip angles would also result in a poor starting performance. Figure 13 shows the wall pressure distribution during the starting process of the inlet with $\delta = 12^\circ$. At $Ma = 4.0$, the separation point is located near $x/R = 3.7$, with an opened separation zone in the flow field. However, when the inlet Mach number increases to 4.5, the separation zone enters the internal contraction section and forms a closed separation zone. In this flow field, with a further increase in the incoming Mach number, the separation zone keeps retreating, and the pressure in the duct keeps increasing to resist the increasing incoming dynamic pressure. The closed separation bubble is hard to be swallowed owing to the large contraction ratio of the duct, thereby leading to a high starting Mach number.
2.2 Effects of the cowl lip angle on starting performance of inlets with various ICRs. Each point in the figure represents the starting Mach number of the inlet at a specific ICR and cowl lip angle, with the inlets on the same line having the same ICR. As can be seen, ICR has no obvious effect on the starting ability for the inlets with small lip angles. However, for the inlets with large lip angles, the starting performance is greatly determined by ICR, exhibiting a trend of deteriorating starting performance with increasing ICR. For example, when the cowl lip angle is $0^\circ$, the starting Mach numbers of inlets with ICR = 1.8 and 2.2, respectively, are 6.5 and 6.4. However, when the cowl lip angle reaches $12^\circ$, the Mach numbers of inlets with ICR = 1.8 and 2.2 are 4.6 and 6.8, respectively, which is a large difference. In addition, for a given ICR, the inlets with excessively large or small lip angles exhibit poor starting performance. In other words, there is an optimal cowl lip angle to achieve the best starting ability among the researched ICR range. Figure 15 shows the distribution of the optimal cowl lip angle and the corresponding $Ma_s$ for the inlets with different ICRs. With an increase in ICR, the optimal cowl lip angle decreases gradually, and the starting performance of the inlet deteriorates. For example, for the inlet with ICR = 1.8, the cowl lip angle corresponding to the low start Mach number is $10^\circ$, and the inlet enters the starting state at $Ma = 4.26$. However, for the inlet with ICR = 2.2, the optimal cowl lip angle is $6^\circ$, and the corresponding start Mach number is 5.51.

**Figure 13.** Wall pressure distributions during the starting process of the inlet with $\delta = 12^\circ$.

**Figure 14.** Effects of the cowl lip angle on starting performance of inlets with various ICRs.
2. Xiong, B.; Fan, X.Q.; Wang, Y. Parameterization and optimization design of a hypersonic inward turning inlet.


References


