Experimental Investigation of the Starting Behavior of a three-dimensional SCRamjet Intake with a Movable Cowl and Exchangeable Cowl Geometry at Different Mach Numbers

Andreas K. Flock, Ali Gülhan

German Aerospace Center (DLR) – Supersonic and Hypersonic Technology Department, Cologne, 51147, Germany

In the current work we focused our research on the intake starting process which is crucial for proper performance of Supersonic Combustion Ramjet engines. To this date there is no generally valid method to accurately predict intake starting for a certain three-dimensional SCRamjet intake configuration. Therefore we conducted starting experiments at Mach 6 and 7 in a blow down wind tunnel on a three dimensional intake model, equipped with a movable cowl and therefore variable internal contraction. Our focus was on the influence of the cowl geometry, the free stream Mach number, the angle of attack and the ratio of total temperature in the free stream to model wall temperature on intake starting. While the influence of total temperature was minor in the temperature ranges considered, the effect of angle of attack was twofold: when the intake was pitched, that the leading edge shock decreased in strength, the intake showed improved starting characteristics. For a pitch angle in the opposite direction and for increasing yaw angles, intake starting was prevented. For a decrease in free stream Mach number from 7 to 6, the starting internal contraction ratio was delayed from 1.92 to 1.73, for the v-shaped lip configuration. Exchanging the v-shaped lip with a straight lip geometry, improved intake starting and at a constant free stream Mach number of 7, the maximum internal contraction for starting moved from 1.92 to 2.12.

Nomenclature

\[ A \] cross sectional area, [m\(^2\)]
\[ H2K \] wind tunnel at the German Aerospace Center, Cologne
\[ i \] internal portion
\[ M \] Mach number
\[ o \] overall configuration
\[ p \] pressure, [N/m\(^2\)]
\[ q \] dynamic pressure, [N/m\(^2\)]
\[ Re \] Reynolds number
\[ s \] straight
\[ T \] temperature, [K]
\[ v \] velocity, [m/s]
\[ v \] v-shaped
\[ x, y, z \] local coordinates, [m]
\[ \alpha, \beta \] pitch and yaw angle, [°]
\[ \gamma \] ratio of specific heats for air

*PhD Candidate, Supersonic and Hypersonic Technology Department, Institute of Aerodynamics and Flow Technology, DLR Cologne, Student Member
†Department Head, Supersonic and Hypersonic Technology Department, Institute of Aerodynamics and Flow Technology, DLR Cologne, Member
II pressure ratio
ρ density, [kg/m³]

Subscript
cl cowl closure
CR contraction ratio
pit pitot
st static
t total condition
th throat
tot total
w wall
∞ free stream condition

I. Introduction

The Supersonic Combustion (SC) Ramjet engine is a key propulsion technology when reaching velocities exceeding a Mach number of approximately 5. In any kind of air breathing supersonic engine, the intake design is crucial for its performance and in the SCRamjet engine the intake serves as the only compression system in the engine cycle. Therefore a proper understanding of the flow phenomena within the intake and its performance is vital for successful operation of the overall engine system.

The SCRamjet research at the Supersonic and Hypersonic Technology Department is involved in the Research Training Group 1095 and an overview of its structure is given in. There are research projects, dealing with aero thermal flow phenomena in the intake, the supersonic combustion process and overall system aspects. The present work is embedded into subproject A3, which deals with the design and characterization of a three-dimensional SCRamjet intake.

The focus in the current paper is on the SCRamjet intake starting behavior. The exit flow of the intake or of a supersonic diffuser in general can either be subsonic or supersonic – the latter being the case desired and being referred to as started intake flow in the further context. Subsonic flow through the intake can lead to a severe reduction in mass flow and in overall engine performance or even loss of the vehicle.

A typical measure for starting of supersonic diffusers, was proposed by Oswatitsch and Kantrowitz. Despite the fact that Oswatitsch published his results earlier, we have the impression that Kantrowitz’s name is more widely associated with the theory and therefore we will also refer to the Kantrowitz criterion in the further context. It states, that a normal shock in front of the intake can be swallowed, as long as the flow behind the shock is accelerated right to \( M = 1 \) at the intake throat. Any further contraction would lead to a detachment of the normal shock from the intake and an intake unstart. The relation between capture area, \( A_\infty \), cross sectional area at the throat, \( A_{th} \), and free stream Mach number, \( M_\infty \), can be described by a one-dimensional flow analysis and is given via

\[
\frac{A_{th}}{A_\infty} = \left[ \frac{\gamma - 1}{\gamma + 1} + \frac{2}{(\gamma + 1)M_\infty^2} \right]^{0.5} \left[ \frac{2\gamma}{\gamma + 1} - \frac{\gamma - 1}{(\gamma + 1)M_\infty^2} \right]^{\frac{1}{\gamma + 1}},
\]

where \( \gamma \) is the ratio of specific heats for air. Furthermore an isentropic limit can be defined from a quasi one-dimensional analysis for nozzle flow, until which an intake is theoretically able to work once it was successfully started:

\[
\frac{A_\infty}{A_{th}} = \frac{1}{M_\infty} \left[ \frac{2}{\gamma + 1} \left( 1 + \frac{\gamma - 1}{2}M_\infty^2 \right) \right]^{\frac{\gamma + 1}{\gamma - 1}}.
\]

The above Kantrowitz criterion and the isentropic limit can be directly applied to fully enclosed intake geometries, but were also adopted to partially enclosed intakes. Thereto \( A_\infty \) and \( M_\infty \) are replaced by the cross sectional area, \( A_{cl} \), and Mach number, \( M_{cl} \), at the beginning of the fully enclosed part of the intake. Please note, that a fully enclosed intake consists of an internal part only, while a partially enclosed intake also has an external part (see figure 4 for further details). In the further context, the area ratios are referred to as contraction ratios (CR), while

\[
\alpha_{CR} = \frac{A_\infty}{A_{th}}
\]
is the overall contraction ratio, and

\[ i_{CR} = \frac{A_{cl}}{A_{th}} \] (4)

is the internal contraction ratio.

The Kantrowitz criterion and the isentropic limit are displayed in figure 1, along with empirical relations, that will be explained subsequently. Please note, that the reciprocal value of the internal contraction ratio is plotted, and that the horizontal axis describes the Mach number at the cowl closure position. The region above the Kantrowitz line (dotted) describes a configuration where the intake starts spontaneously, according to the Kantrowitz theory. The area, which is spanned by the Kantrowitz line and the isentropic limit (solid), is the region, where an intake does not start spontaneously, according to Kantrowitz, but where an intake could work successfully, once it was properly started.

![Figure 1. Reciprocal of \(i_{CR}\) versus Mach number at cowl closure; plotted are the Kantrowitz criterion (equation 1), the empirical equations by Sun\(^{12}\) and Wie,\(^{9}\) and the isentropic limit (equation 2); furthermore the starting internal contraction ratios for the currently investigated intake are shown.](image)

In equation 1, a quasi one-dimensional flow was assumed. However for three-dimensional intake geometries, this assumption becomes less appropriate and intake starting can occur at internal contraction ratios, higher than those indicated by the Kantrowitz theory. Therefore, the dotted line in figure 1, needs to be considered as a conservative border to determine the intake starting contraction ratio.

Various authors published research on the intake starting process and three topics will be captured in the following paragraphs: First, Sun proposed a linear empirical relation\(^{12}\) between the area ratio and \(M_{cl}\). Therefor different self starting intakes taken from experiments found in the literature, were plotted in the Kantrowitz diagram and then linearly approximated (see dashed line in figure 1).

Second, van Wie et al. investigated the intake starting behavior with a two-dimensional generic model of the internal part of the intake.\(^{9}\) They observed hard and soft versions of intake unstart, depending on the specific configuration of their generic model which had variable geometries and therefore the internal contraction ratio was adjustable. However, the difference between hard and soft unstart was not always clear. From their data, they introduced an empirical limit for the highest contraction ratios possible, similar to the isentropic limit, but taking into account viscous effects and shock losses (see dashed-dotted line in figure 1).

Third, Mölder, Tahir and Timofeev published numerous articles on intake starting.\(^{10, 11, 13}\) They stated different ways of intake starting, such as starting by overboard spillage, overspeeding, permeable walls or unsteady effects. A general approach was, to first bring the intake geometry into the region where the intake is self starting and then move towards the isentropic limit. However these measures are frequently accompanied by additional effort, such as movable parts for example. Their paper on intake starting, presented at the 2008 AIAA Space Planes Conference gives a good overview of the different techniques and mechanisms.\(^{13}\)

**II. Methods and Materials**

In this section the three following topics are going to be outlined: First, the wind tunnel facility H2K is explained. Second, the three-dimensional intake model with the integrated measurement equipment is presented, and some important vocabulary is introduced. Third, the different conditions, that were investigated
during the measurement campaign are listed, together with a time chart of a general starting experiment.

A. Wind-Tunnel H2K

We performed the experiments in the blow down wind tunnel H2K of the Supersonic and Hypersonic Technology Department at the German Aerospace Center (DLR) in Cologne. A general sketch of the wind tunnel setup along with a characteristic diagram is shown in figure 2.

![Figure 2. Schematic setup of the H2K wind-tunnel (left) along with characteristic diagram (right).](image)

First, air is heated in the electric heater up to temperatures of approximately $T_{\infty} = 700$K. Once the temperatures are reached, the 3/2 way valve is switched and the air is released through the settling chamber and Laval nozzle into the test section. The model is overflown by the free jet, before the air finally passes through the diffuser into the vacuum sphere. There are five different Laval nozzles for Mach numbers of $M_{\infty} = 5.3, 6, 7, 8.7, 11.2$, which all have a circular cross sectional exit area with a diameter of 600mm. Depending on the desired condition, test durations of about 35 seconds can be achieved.

B. Intake Model

The three-dimensional intake was designed by Hohn$^{14}$ and Riehmer$^{15}$ and a top as well as cross sectional view of the CAD model is displayed in figure 3. It was designed for a Mach 8 flight in 30km, which corresponds to a free stream pressure, temperature and unit Reynolds number of 1170Pa, 226K, and $2.95 \times 10^6 \text{m}^{-1}$, respectively. The dynamic pressure,

$$q_{\infty} = \frac{1}{2} \rho_{\infty} v_{\infty}^2,$$

at the design point is approximately $q_{\infty} = 0.53$bar.

The main ramp is inclined to an angle of $8^\circ$ while each side wall converges with $7^\circ$. Along the center line of the bottom and top walls as well as in the axially movable cowl, there are static pressure sensors, and the pressure ducts run into the casing of the psi modules. A pitot rake is positioned where the intake normally would end and the combustion chamber would start (figure 6), and which will be explained in more detail shortly. For our experiments, an adapter was attached to the intake and the captured air flow went through a honeycomb mesh and a settling chamber, before exiting through an axisymmetric throttle.$^{16}$ The length from the intake leading edge to the position of the pitot rake is 720mm and the intake throat is located at 650mm. Due to the movable cowl, the internal contraction ratio, $i_{CR}$, could be varied from 1.28 – 2.56.

In addition to the v-shaped lip, displayed in figure 3, a straight lip was manufactured and a general sketch of the two different lip configurations is displayed in figure 4. Furthermore, the lip position, $x_{\text{lip}}$, was defined as the location where the cowl closed and the internal part of the intake started. As mentioned earlier, the lip position could be varied in the $x$-direction and the relation between $x_{\text{lip}}$ and the internal contraction ratio, $i_{CR}$, is given in figure 5.

The dimensions of the intake exit area were $43 \times 65 \text{mm}^2$ with radius corners (figure 6). The pressure probes consisted of alternately distributed pitot as well as static pressure ports,$^{17}$ and therefore the static and total pressures were measured. The data of two pressure probes were corrupt during the experimental
Figure 3. Top and cross sectional view of the three-dimensional intake.

Figure 4. Sketch of intake with v-shaped (top portion) and straight (bottom portion) lip and $x_{lip}$-variable.

Figure 5. Internal contraction ratio, $i_{CR}$, plotted versus lip position, $x_{lip}$. 

5 of 12

American Institute of Aeronautics and Astronautics
campaign, and interpolated from the neighboring values. To determine a pitot pressure at the location of a static pressure port and vice versa, the respective data were interpolated from their neighboring values. Thereof, the Mach number across the intake exit height and width was calculated with the following equations: to determine whether there is super- or subsonic flow at the intake exit, the ratio of pitot to static pressure needed to be checked and if \( \frac{p_{\text{pit}}}{p_{\text{st}}} > 1.893 \), then the flow was supersonic. For supersonic flow, the relation is given via
\[
\frac{p_{\text{pit}}}{p_{\text{st}}} = \left[ \frac{(\gamma + 1)^2 M^2}{4\gamma M^2 - 2(\gamma - 1)} \right]^{\gamma/(\gamma - 1)} \frac{1 - \gamma + 2\gamma M^2}{\gamma + 1},
\]
and the Mach number needed to be calculated iteratively, for example with Newton’s Method. For subsonic flow, the following equation was directly applied to calculate the Mach number:
\[
M^2 = \frac{2}{\gamma - 1} \left[ \left( \frac{p_{\text{pit}}}{p_{\text{st}}} \right)^{(\gamma - 1)/\gamma} - 1 \right].
\]
For further information on calculating the Mach number from a pitot pressure, see for example the introductory textbook by Anderson [6, chapter 8]. Finally, the data obtained at the rake was averaged and taken as the intake exit data.

![Pressure rake, with pitot and static pressure tubes.](image)

**Figure 6.** Pressure rake, with pitot and static pressure tubes.

### C. Experimental Campaign

An overview of the different wind tunnel conditions that were investigated, is given in table 1. Two different Mach numbers were examined, and the respective Reynolds numbers were adjusted to heights, that matched a trajectory with constant dynamic pressure, \( q_\infty = 0.53 \text{bar} \). The wall temperature of the model was assumed to be constant (\( T_w = 300 \text{K} \)), and part of the campaign was to vary the total temperature of the free stream. Furthermore, the v-shaped and straight (s) lip were investigated on differences during the starting process.

The influence of pitch (\( \alpha \)) and yaw angle (\( \beta \)) on intake starting was investigated, analogously. Therefore both angles were varied separately, but also simultaneously, as indicated in table 2. Due to symmetry reasons, we varied the yaw angle in one direction only, and \( \beta \) was assigned to be positive only.

In figure 7, a sample time chart of a general starting experiment is plotted. Please note, that the only dependent variable shown quantitatively is \( x_{\text{lip}} \) (solid line), while the other variables are displayed for qualitative reasons only (broken lines). Initially the cowl is at the most upstream position, and the intake is unstarted, which is indicated by the low total pressure ratio (shortly dashed line), defined as
\[
\Pi_{\text{tot}} = \frac{p_{t,\text{exit}}}{p_{t,\infty}}.
\]

The static pressure ratio, that will emerge in the results section, is analogously defined as:
\[
\Pi_{\text{st}} = \frac{p_{\text{st,exit}}}{p_{\text{st,}\infty}}.
\]
Table 1. Overview of different test conditions (v – v-lip, s – straight lip); all for constant wall temperature, $T_w = 300K$.

<table>
<thead>
<tr>
<th>$M$</th>
<th>7</th>
<th>7</th>
<th>7</th>
<th>7</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{l,\infty}/T_w$</td>
<td>2.33</td>
<td>2.00</td>
<td>1.67</td>
<td>2.33</td>
<td>2.33</td>
</tr>
<tr>
<td>$Re \ [10^6 \ m^{-1}]$</td>
<td>3.39</td>
<td>3.39</td>
<td>3.39</td>
<td>3.39</td>
<td>4.00</td>
</tr>
<tr>
<td>lip geometry</td>
<td>v</td>
<td>v</td>
<td>v</td>
<td>s</td>
<td>v</td>
</tr>
<tr>
<td>respective height [km]</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
<td>28.2</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Table 2. Overview of angle of attack configurations that have been investigated.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$\alpha$</th>
<th>$-4^\circ$</th>
<th>$-2^\circ$</th>
<th>$0^\circ$</th>
<th>$2^\circ$</th>
<th>$4^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^\circ$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>2$^\circ$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4$^\circ$</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After the tunnel was started, the free stream static pressure adjusted within a couple of seconds, while the total temperature only slowly approached the steady state. This was due to the time response of the thermo couple in the settling chamber of the wind tunnel. Approximately 1.5s after the tunnel was started, the cowl was moved backwards with a constant velocity and consequently the internal contraction reduced. Started intake flow was indicated by the sharp increase in total pressure measured at the rake, which in figure 7 occurs at approximately 12.5s. Finally, after 29s, the cowl reached the most downstream position and the tunnel flow was stopped.

III. Results

In the results section, we will present the influence of Mach number, cowl geometry, angle of attack and total temperature on intake starting. For better understanding, the principle display of the figures, is going to be equal: the independent variable is the inner contraction ratio, $i_{CR}$, and it is plotted as the horizontal axis. In the top portion of figure 8-11, the total pressure ratio, $\Pi_{tot}$, is plotted, in the middle portion the static pressure ratio, $\Pi_{st}$, and in the bottom portion the intake exit Mach number, $M_{exit}$. These variables will be referred to as the performance parameters in the subsequent sections. As seen in figure 7, the inner contraction ratio is reduced with time, and therefore the figures need to be read from right to left. Furthermore, the configuration with the v-shaped lip at Mach 7 and no angle of attack will be considered as a reference case, and is plotted twice, to illustrate fluctuations during two experiments.

A. Cowl Shape

At first, the influence of the lip geometry on intake starting is discussed for a free stream Mach number of 7 and results are plotted in figure 8 (solid and long dashed lines). For high internal contraction ratios ($i_{CR} > 2.3$), the intake flow is subsonic and the total pressure ratio is at an insufficient level ($< 0.05$). For low internal contraction ratios ($i_{CR} < 1.9$), the intake flow is fully established and the Mach number, static
and total pressure ratio at the exit are approximately: $M_{\text{exit}} \approx 3$, $\Pi_{\text{st}} \approx 33$ and $\Pi_{\text{tot}} \approx 0.4$, respectively.

As the internal contraction ratio reduces, supersonic intake flow is established. For the straight lip the intake starts earlier (at $i_{\text{CR}} = 2.12$), than for the v-shaped lip (at $i_{\text{CR}} = 1.92$). Shortly before both configurations start, a plateau region is formed, where the flow through the intake is already supersonic ($M_{\text{exit}} \approx 2$), but where the total pressure ratio is still at a poor level ($\Pi_{\text{tot}} \approx 0.12$). The plateau region is more distinct for the straight lip, than for the v-shaped lip, but is visible for both cases.

When being at the same $x_{\text{lip}}$ position, the v-shaped cowl captures more air flow, compared to the simple straight lip geometry. Therefore the effect of overboard spillage, as explained in\textsuperscript{11} becomes more distinct for the straight lip configuration and the starting position moves to higher internal contraction ratios.

In figure 1, the internal contraction ratios for the different cowl geometries are plotted. The Mach numbers at the cowl closure position were taken from RANS simulations for the respective conditions. For both configurations, the internal contraction ratios fall within the region, where the intake would not be self starting due to the Kantrowitz theory. However, both configurations are very close to the linear fit by Sun.\textsuperscript{12}

B. Mach Number

Results for the Mach number variation are plotted along with the lip geometry results in figure 8. For the lower Mach number of 6, the intake start is delayed to lower internal contraction ratios ($i_{\text{CR}} \approx 1.72$). While the exit Mach number for started intake flow remains approximately constant, the static pressure ratio drops to about $\Pi_{\text{st}} \approx 22$ for the lower free stream Mach number. However, the total pressure ratio raises to $\Pi_{\text{tot}} \approx 0.60$. Furthermore, there is no plateau region, but the supersonic intake flow establishes rather quickly.

When looking at the Kantrowitz diagram (figure 1), the internal contraction ratio for starting is again within the region, where intake starting should not occur according to the Kantrowitz theory, but was close to the linear prediction.\textsuperscript{12} Furthermore, the effect of delayed intake starting due to lower free stream Mach number can be explained: a reduced free stream Mach number leads to a reduced Mach number at the cowl closure position as well. Moving to the left in the Kantrowitz diagram leads to a decreased internal contraction ratio for intake starting. Please note, that in figure 1 the reciprocal value of $i_{\text{CR}}$ is given and that the Mach numbers at the cowl closure position were again obtained from numerical simulations.
C. Angle of Attack

The angle of attack influence on intake starting was investigated following table 2. The display of the data follows the layout in the previous section and results for the pitch angle variation are plotted in figure 9. Please note, that a positive $\alpha$ is equal to lifting the intake nose and therefore equal to a lower deflection caused by the main ramp, and vice versa (see also figure 3 for the angle assignment).

A positive pitch angle leads to earlier intake starting, while a negative pitch angle delays intake starting. When going to pitch angles as high as $+4^\circ$, the delta in $i_{CR}$ can reach as high as 0.3. However the performance parameters for started intake flow are influenced as follows: With an increased $\alpha$, the static pressure ratio drops, while the exit Mach number and total pressure ratio increase, and vice versa. Except for the $\alpha = -4^\circ$ case, the plateau region with supersonic flow in the intake is present for all configurations.

To explain the influence of $\alpha$, one can imagine what happens to the flow when the intake is pitched: as determined earlier, by lifting the intake nose the deflection caused by the main ramp decreases, and therefore the leading edge shock loses strength. However this leads to a higher Mach number behind the leading edge shock, and in the first approximation to a higher Mach number at the cowl closure position. Analogously to the previous section, intake starting is enhanced by this higher Mach number.

Furthermore, the influence of a yaw angle variation on the intake starting behavior was investigated and results are plotted in figure 10 as dotted lines. A moderate yaw angle of $\beta \approx 2^\circ$ only marginally delayed intake starting, while further increasing $\beta$ to $4^\circ$ delayed intake starting to $i_{CR} \approx 1.8$, thus for the angles considered there is a maximum delta in internal contraction ratio of about 0.1. For symmetry reasons, the yaw angle was varied only in one direction.

When increasing the yaw angle, the deflection angle at the sidewalls, that the free stream sees behaves twofold: The leading edge shock on one side wall becomes stronger, while the shock strength on the other side wall decreases. Therefore the influence of yaw angle on intake starting is lower, but generally delays intake starting.

Finally, to better recreate the tumbling motion during a possible flight experiment, both $\alpha$ and $\beta$ were varied simultaneously and results are plotted, along with the yaw angle variation in figure 10. One can see, that the effects of improved starting due to a positive pitch angle and the effect of delayed intake starting, due to the yaw angle are to an extent super imposable. Therefore one can conclude, that during a possible tumbling motion of the SCRamjet engine in a flight experiment, there are going to be regions where intake starting is enhanced (large $\alpha$ and $\beta$‘s around zero) and regions with delayed intake starting, when compared with the initial condition $\alpha = 0^\circ$, $\beta = 0^\circ$. 

Figure 8. Starting behavior for different free stream Mach numbers and different cowl geometries.
Figure 9. Influence of pitch angle ($\alpha$) variation on starting behavior of intake; yaw angle was kept zero.

Figure 10. Influence of yaw angle ($\beta$) and of simultaneous pitch and yaw angle on intake starting for v-shaped lip at Mach 7.
D. Total Temperature

The $T_{t,\infty}/T_w$ ratio was varied from $1.66 - 2.33$, which approximately corresponds to wall temperatures of $1000K - 1400K$ for a real flight condition at $M = 7$. The influence of the temperature variation on intake starting is plotted in figure 11. A higher $T_{t,\infty}/T_w$ ratio favors intake starting to higher internal contraction ratios. In other words, for colder walls, the intake shows improved starting characteristics. For lower $T_{t,\infty}/T_w$ ratios, the plateau region with supersonic flow at the intake exit disappears. However the maximum delta in $i_{CR}$ is only around 0.04, and therefore the overall influence of total temperature to wall temperature ratio on intake starting is weak – at least in the temperature ranges considered.

![Figure 11. Starting behavior for various total temperature ratios for v-shaped lip at Mach 7.](image)

IV. Conclusion

In the current paper we presented recent insights into the starting behavior of a three-dimensional SCRamjet intake with variable internal contraction. Experiments were performed in the H2K blow down wind tunnel. The four main research topics were the influence of the i) cowl geometry, ii) Mach number, iii) angle of attack and iv) free stream total temperature to wall temperature ratio on intake starting. The air flow through the intake duct was analyzed at the intake exit area with a rake with static as well as pitot pressure ports and the performance parameters: exit Mach number, total and static pressure ratio were calculated from the measured data. The following main conclusions can be drawn from the presented results:

1. For configurations with no angle of attack, the internal contraction ratios for intake starting were found to be higher than the values predicted by the Kantrowitz theory. Therefore, the Kantrowitz line should be considered as a conservative measure, especially for high speed, three-dimensional intakes.

2. The straight cowl geometry drastically improved the starting behavior from and internal contraction ratio of 1.92 for the v-shaped lip to 2.12. This phenomenon is mainly caused by the increase overboard spillage effect for the straight cowl geometry.

3. With decreasing free stream Mach number, intake starting was reduced to lower internal contraction ratios, which corresponds to the Kantrowitz theory. However the internal contraction ratio was still within the region where intake starting should not occur.

4. Angle of attack effects were twofold: for positive pitch angles, intake starting was enhanced, while for negative pitch angles and increasing yaw angles intake starting was delayed (please note, that due to
symmetry reasons, the yaw angle was not assigned with a sign). Overall, the pitch angle influence was stronger.

5. Finally, varying the free stream total to wall temperature ratio from 1.67 to 2.33 did have a minor effect on the starting behavior.

Acknowledgments

The authors would like to thank the German Research Foundation for the support of the SCRamjet Research Training Group 1095. Furthermore we would like to thank Michael Kosbow and Marco Schmors, both from the Supersonic and Hypersonic Technology Department, for the operation of the H2K wind tunnel and the technical support.

References