Heat transfer in supersonic separated flow of the compression corner

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Abstract. This article presents the study results for heat transfer in supersonic laminar separated compression corner flow. The study was carried out for free-stream Mach number \( M = 6 \) and the compression ramp angle in the range of \( \phi = 20° – 40° \).

1. Introduction
The configuration of two surfaces forming a compression corner is popular in hypersonic aircraft design and is relevant to study. The interaction of a shock wave generated by such a configuration with the boundary layer results in a separation region, accompanied by an increased level of power and thermal loads in the flow reattachment zone. In the case of a relatively narrow compression corner (Fig. 1, a shows a photograph of the model with the compression ramp angle \( \phi = 20° \)) this region can be three-dimensional [1 – 5]. The flow structure and the level of thermal loads for a similar compression corner model with added side walls are considered in [6].

![Figure 1. Compression corner model: a – photograph, b – diagram (dimensions are in millimeters).](image)

According to the results of surface oil flow visualization of limiting streamlines and numerical calculation data presented in [1 – 5] (Fig. 2, a and Fig. 2, b respectively), the flow inside the reverse flow zone RF is three-dimensional (on the model surface this zone is bounded by the separation line S and the reattachment line R). It can be seen that the gas moves from the central region from the junction line (marked as O) between the plate (1) and the ramp (2) towards the oncoming flow (the direction of flow oncoming to the model \( u_\infty \) is marked by the arrow at the top of the figure) to the curved separation line S and the side boundaries of the model (Fig. 2, c shows the flow in the reverse flow zone according to the numerical calculation data).

Figs. 3, a, and b present the flow structure near the separation line S and the reattachment line R respectively, constructed based on the analysis of experiment and numerical results. The flow structure is shown in the longitudinal symmetry plane of the model. \( F_2 \) gas continuously flows into the separation region from the oncoming flow, turns toward the separation line in the reverse flow zone (shown as streamline \( F_1 \)) and then flows out through the side boundaries of the separation region. There is no single separating streamline surface connecting S and R lines. Instead there is SSL surface, coming away from the R line towards the flow to infinity. The zero velocity surface is marked as ZVS. It can be seen that the
gas flow $F_3$ approaching the reattachment line $R$ has high total pressure, since it is located above the boundary layer $BL_1$ near the horizontal plate (Fig. 3, a). As a result of isentropic turn over the ramp surface in the compression fan $CF$ (Fig. 3, b) it transforms into high-pressure layer $DL$, located above the boundary layer $BL_2$. Here $C_3$ is the reattachment shock formed from intersecting characteristics of the compression fan $CF$.

![Figure 2. Flow directly near the surface of the compression corner: a – oil flow visualization of limiting streamlines, b – streamlines obtained by averaging numerical calculation data, c – general flow pattern in the separated region; 1 – plate surface, 2 – ramp surface.](image)

![Figure 3. Three-dimensional mass transfer separated flow over a compression corner: a – flow pattern near the separation line $S$, b – flow pattern near the reattachment line $R$.](image)

It may be assumed that such mass transfer flow would also be characterized by significant heat transfer in the separation region. This work focuses on determining the influence of ramp angle $\varphi$ (see the diagram in Fig. 1, b) on the heat flux magnitude in the separated region and downstream of the reattachment zone.

2. Research techniques

Test models (Fig. 1) consisted of a horizontal plate with a ramp installed at a distance $L = 50$ mm from the leading edge. Three models with the ramp angles $\varphi = 20^\circ$, $30^\circ$, and $40^\circ$ were studied (Fig. 1, b). The width of the models is equal to the length of the horizontal plate $L$. The leading edge of the model is sharp with the curvature radius $R$ of around $5 – 7$ $\mu m$. The models are made of steel and surfaces are polished.
The free-stream Mach number was $M_\infty = 6$, and the Reynolds number calculated by the horizontal plate length $L$ of the compression corner model was $Re_L = 6.1 \times 10^5$. The flow stagnation temperature was $T_0 = 390 – 403$ K in different experiments. Temperature factor of the model was $\tau_0 = T_w/T_0 = 0.73 – 0.76$.

The studies were carried out in the hypersonic wind tunnel Т-326 at ITAM SB RAS. A profiled axisymmetric nozzle with a nominal Mach number $M_\infty = 6$ and an exhaust exit diameter of 200 mm was used. Fig. 4 shows the Mach number distribution field in the middle vertical plane of the test chamber in the location of the considered models. Initial section $x = 0$ corresponds to the nozzle exit. The average Mach number in the models location $-50 \text{ mm} < y < +50 \text{ mm}$ (marked by black horizontal lines) is $M_m = 6.026$, and the standard deviation is $M_{\text{RMS}} = 0.016$ (0.2% of the average value).

The pressure in the test chamber was measured using a TDM-A-0.16 sensor (with the measurement range of $0 – 1.6 \times 10^5$ Pa and the sensor error not more than 0.2% of the measurement range). The settling chamber pressure was measured with a Metran-150-TA3 sensor (with the measurement range of $0 – 25 \times 10^5$ Pa and the sensor error not more than 0.1% of the measurement range). The maximum pressure deviation in the settling chamber from the value $p_0 = 9.68 \times 10^5$ Pa maintained during the experiment did not exceed 0.5%. The temperature in the settling chamber was measured with a chromel/alumel thermocouple (the temperature measurement error was less than one Kelvin).

Experiments included schlieren visualization of the flow and measuring the heat flux using calorimetric sensors.

Schlieren photographs were taken at a horizontal position of the knife edge; the exposure time was 18 $\mu$s.

Calorimetric heat flux sensor is made of copper sheet with a thickness $h = 0.45$ mm. The sensor diameter is 1.78 mm. A copper/constantan thermocouple with a wire diameter of 20 $\mu$m is attached to the sensor by silver solder. Thermocouple sensitivity coefficient was assumed to be 43 $\mu$V/degree. The sensor is mounted into a heat insulating frame with a diameter of 8 mm and a height of 6 mm, made of AG-4B material (with the thermal conductivity coefficient $\lambda = 0.256$ W/m·K). The sensor signal was amplified by a Z-412 amplifier manufactured by ZETLAB Company. The amplification factor was set at 1000, which provided the inherent noise level of the amplifier to be less than 2 $\mu$V. The amplified signal was recorded by an analog-digital fourteen-bit card Е14-440 manufactured by L-Card. The measurement range was set at $\pm 10$ V, which provides a measurement error of 0.05% of the range (i.e. 5 mV). The sampling frequency of each measuring channel is 10 kHz.

A total of three sensors were mounted on the horizontal plate of the model and three (for the model of $\phi = 20^\circ$ ramp angle) or two (for $\phi = 30^\circ$ and $\phi = 40^\circ$ angles) sensors – on the ramp surface. The centers of the sensors (the sensors’ location on the model can be seen in the photograph in Fig. 1, a) are located on the symmetry line of the model: on the plate – at a distance of 32 mm from the junction line between the plate and the ramp (sensor 1), 21 mm (sensor 2), and 10 mm (sensor 3); on the ramp – at a distance of 5
mm from the junction line between the plate and the ramp (sensor 4), 15 mm (sensor 5), and 25 mm (sensor 6).

T-326 wind tunnel is equipped with a test chamber, the required pressure difference between the settling chamber and the test section is provided by the ejector. The wind tunnel is launched with the model removed from the flow. The initial temperature of the model before the tunnel launch in different experiments was 291 – 295 K. During the tunnel start, before the model was inserted into the flow, the sensors on the model warmed up to 294 – 302 K (depending on the sensor location and the number of the experiment). Such heating was a result of the particular launch of the tunnel, during which the latch of the settling chamber was opened first, air started to flow into the test chamber and was heated inside the settling chamber to a temperature of about 370 K, and then the ejector was started and the flow parameters were adjusted to the required stagnation temperature $T_0$. The model was inserted into the flow by a lateral movement device. The input time was approximately 0.2 s from the moment of the model passing through the outer mixing layer boundary of the jet, exiting the wind tunnel nozzle until the model stopped in the middle of the jet.

Heat flux was determined by the formula

$$q = \rho h c \frac{dT}{dt},$$

where $q$ is the specific heat flux; $\rho$ is the density of copper; $h$ is the sensor thickness; $c$ is the copper heat capacity; $T$ is the sensor temperature; $t$ is time. The total error of determining the heat flux is estimated as 15 – 20 %.

The heat transfer coefficient was determined from Newton’s law of convective heat exchange by the formula

$$\alpha_0 = \frac{q}{(T_0 - T_w)},$$

where $T_0$ is the free-stream stagnation temperature.

The Stanton number was calculated from of heat transfer coefficient as

$$St_0 = \frac{\alpha_0}{\rho_\infty V_\infty c_p},$$

where $\rho_\infty$, $V_\infty$, $c_p$ are the density, velocity and heat capacity of air at constant pressure in the oncoming flow respectively.

3. Results and discussion

Fig. 5 presents the schlieren photographs of the separated flow over the compression corner: Fig. 5, $a - \phi = 20^\circ$, Fig. 5, $b - \phi = 30^\circ$, Fig. 5, $c - \phi = 40^\circ$. The shock wave from the leading edge of the plate $C_1$, the separation shock $C_2$, the reattachment shock $C_3$, the reverse flow zone $RF$, and the shear layer $SL$ above it are all clearly visible. The approximate position of the separation and reattachment lines is marked by points $S$ and $R$, respectively. Point $O$ marks the junction line between the horizontal plate and the ramp. The position of the heat flux sensors is indicated by white markers with corresponding numbers 1 – 6.

It can be seen that for the model with $\phi = 20^\circ$ ramp angle sensor 1 is located directly in front of the separation line, sensors 2, 3 and 4 are inside the separated region, and sensors 5 and 6 are behind the reattachment line. For the models with ramp angles of $\phi = 30^\circ$ and $\phi = 40^\circ$ sensors 1, 2, 3 and 4 are inside the separated region, and sensor 5 is behind the reattachment line.

The measurement results of heat flux sensors are presented in the table. In addition to the Stanton number for separated compression corner flow (models with $\phi = 20^\circ$, 30°, 40°) the calculated value of the Stanton number is given for comparison for the case of an attached flow around a horizontal plate with flow parameters corresponding to the experiment for the $\phi = 20^\circ$ model.
Figure 5. Schlieren photographs of the compression corner flow at the free-stream Mach number of $M = 6$: $a$ – ramp angle of $\varphi = 20^\circ$, $b$ – ramp angle of $\varphi = 30^\circ$, $c$ – ramp angle of $\varphi = 40^\circ$.

Table. Results of measuring the Stanton number on the model surface.

| Sensor | $St_0$, model $\varphi = 20^\circ$ | $St_0$, attached flow, calculated value | $St_0$, model $\varphi = 30^\circ$ | $St_0$, model $\varphi = 40^\circ$ |
|--------|----------------------------------|----------------------------------------|----------------------------------|----------------------------------|
| plate  |                                  |                                        |                                  |                                  |
| 1      | $3.4 \cdot 10^{-4}$              | $4.0 \cdot 10^{-4}$                   | $2.0 \cdot 10^{-4}$              | $3.0 \cdot 10^{-4}$              |
| 2      | $0.7 \cdot 10^{-4}$              | $3.2 \cdot 10^{-4}$                   | $3.0 \cdot 10^{-4}$              | $4.4 \cdot 10^{-4}$              |
| 3      | $0.8 \cdot 10^{-4}$              | $2.8 \cdot 10^{-4}$                   | $3.8 \cdot 10^{-4}$              | $5.9 \cdot 10^{-4}$              |
| ramp   |                                  |                                        |                                  |                                  |
| 4      | $5.2 \cdot 10^{-4}$              | $2.0 \cdot 10^{-3}$                   | $1.9 \cdot 10^{-3}$              |                                  |
| 5      | $4.2 \cdot 10^{-3}$              | $8.5 \cdot 10^{-3}$                   | $1.4 \cdot 10^{-2}$              |                                  |
| 6      | $4.1 \cdot 10^{-3}$              |                                        |                                  |                                  |

Conclusion

The following conclusions can be drawn based on the presented results. The heat transfer in the reverse flow zone $RF$ depends significantly on the ramp angle: the greater the angle, the higher the heat transfer. At the ramp angle $\varphi = 20^\circ$ the heat transfer on the plate under separated flow conditions is substantially less than on the plate without separation. At $\varphi = 30^\circ$ it is commensurable and at $\varphi = 40^\circ$ it begins to exceed the heat transfer magnitude on the plate under attached flow conditions. The obtained result confirms that the assumed mass transfer flow exists in the separation region, and therefore, this region is essentially three-dimensional and unclosed in nature. In order for the intensity of heat transfer to increase,
the mass transfer intensity also has to increase in the reverse flow zone, which indicates an increase in mass transfer in the separation region with increasing ramp angle $\phi$.

It can also be noted that the greatest heat transfer was observed on the surface of the ramp behind the flow reattachment line, which also agrees with the measurement results from paper [6].

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