RESULTS are given of an investigation of heat transfer on the flat surface of a blunted half-cone, washed at zero angle of attack by a helium flow at high Mach number (up to 23.5). A correlation is given for the experimental data obtained over a wide range of Mach numbers ($M_{\infty} = 3-23.5$) and Reynolds numbers ($Re_{\infty a} = 10^4 - 3.5 \cdot 10^5$, where $a$ is the nose radius).

A blunted half-cone can be considered as a schematic lifting body of a hypersonic aircraft. It was shown in [1-3] that two narrow longitudinal zones with intense heat transfer form on the leeward surface of the half-cone. The enhanced heat transfer in these zones is due to flow separation and thinning of the boundary layer near the reattachment lines because of the transverse gas flow. The heat flux to the leeward surface of the half-cone reaches a maximum value approximately at the angle of attack for which the lift-to-drag ratio reaches a maximum. If the leeward side is a plane surface, this occurs for $\alpha \approx 0$, while if the leeward surface is convex, it occurs for $\alpha \approx \theta$, where the angle of attack $\alpha$ is calculated from the flat surface, and $\theta$ is the half-angle of the cone.

Local heat transfer enhancement on the leeward surface also occurs on other lifting bodies: on triangular and rectangular wings [4-7], on bodies which are a combination of a half-cone and a half-cylinder afterbody [8], and on models of an orbiting vehicle [9].

It was shown in [2, 3, 5] that heat-transfer enhancement on the leeward surface of a half-cone only occurs at quite large Reynolds numbers, in excess of some critical value of $Re$. These results were obtained at comparatively small Mach number values (up to $M_{\infty} = 6$). It is shown in this paper that for large values of $M_{\infty}$, typical of re-entry of space vehicles, and for quite large Reynolds numbers, zones of enhanced heat transfer also form on the top surface of a half-cone.

§1. In wind tunnels using air as the working substance it is difficult to obtain large values of Reynolds and Mach numbers simultaneously, since this requires a very high stagnation chamber pressure. With constant stagnation pressure and constant working-section static temperature, which cannot be lower than the condensation temperature, the Reynolds number decreases as the Mach number increases: $Re_{\infty} \sim M_{\infty}^{-6}$. When helium is used, because of its low condensation temperature, there is no need for heating over a wide range of Mach numbers $M_{\infty}$. For constant stagnation pressure and temperature and with helium, $Re_{\infty} \sim M_{\infty}^{-2}$. Thus, when helium is used the Reynolds number decreases more slowly with increase in Mach number than when air is used. However, the question remains unresolved as to whether results obtained in helium can be carried over to conditions of flight in air.

The tests were carried out in two helium wind tunnels with conical nozzles. The gas was not heated in the small helium tunnel. Flow visualization tests were carried out in this tunnel at $M_{\infty} = 12$ and 17.5, and the stagnation pressure $p_0$ near the model was measured, using total pressure probes. The heat-transfer investigations were carried out at $M_{\infty} = 17$ and 23.5 in a large tunnel with helium heated up to stagnation pressure $T_0 = 600-773^\circ K$. Both wind tunnels were of the blowdown type. The flow in the working section was established in approximately 0.01 sec. The test duration was 1-2 sec.
The models had the form of a blunted half-cone with vertex angles \( \theta = 15 \) and 24.5°. The Reynolds number was varied both by varying the stagnation pressure \( P_0 \) and by changing the model size. The Reynolds number \( Re_\infty \), based on the undisturbed flow parameters, was varied from 10^4 to 2 \cdot 10^5 for Mach number \( M_\infty = 17 \) and from 4.6 \cdot 10^4 to 6.4 \cdot 10^4 at \( M_\infty = 23.5 \). Results of investigations of heat transfer on a half-cone in an air flow at Mach numbers from 3 to 8 and \( Re_\infty \) from 10^4 to 3.5 \cdot 10^5 were also used in this paper.

The method of temperature-sensitive coatings was used to measure the heat-transfer coefficient. Fusible heat-indicators with critical temperatures \( t_c = 40 \) and 65°C and fusible liquid-crystal compositions with a low critical temperature \( t_c \) (from 29 to 45°C) were used. The liquid crystals were applied in a very thin layer (on the order of 1-2 \( \mu \)) to the model surface, and this was especially important when short duration tests were performed.

At large Mach numbers (\( M_\infty = 12-23.5 \)), and also for low Mach numbers, the gas flows from the convex surface of the half-cone to the flat surface, because of pressure drop. The crossflow meets the longitudinal flow coming from the blunted nose. The gas flowing over the upper surface is stagnated, leading to separation of the boundary layer near the lateral edges (Fig. 1). The flow reattaches on longitudinal lines located between the edge and the line of symmetry. Here flow spread lines \( R \) are formed.

The measurements taken with the total head probes showed that there are two sharp drops of stagnation pressure \( p_0 \) between the shock wave and the flat surface: at the boundary of the high-entropy layer, formed with flow over the blunt nose, and at the edge of the viscous layer (separation region). From the measurements of stagnation pressure \( p_0 \) we can determine approximately the boundaries of the high-entropy layer and the separation region. These boundaries were also observed for small Mach number \( M_\infty = 5 \) by a laser knife-edge method [10] (Fig. 2, transverse section \( x/a \approx 6 \), 1) separation zone, 2) boundary of the high-entropy layer, 3) shock wave). Near the spread lines \( R \) the viscous layer has minimum thickness. This is the basic reason for increased friction and heat transfer.

At zero angle of attack the thickness of the separation zone is on the same order of magnitude as that of the boundary layer at the line of symmetry (in the attached flow region), and the flow is like secondary flow in the boundary layer. At large angles of attack a separated zone develops whose thickness is considerably greater than that of the boundary layer in unseparated flow.

At larger Mach numbers longitudinal zones of intense heat transfer form on the top surface of the half-cone behind the blunted nose. They are located near the flow spread lines. The heat-transfer coefficient in these zones is larger than at the edges or at the line of symmetry. Figure 3 shows a photograph of the flat surface of the half-cone, obtained at a time of 0.9 sec after the start of the test with \( M_\infty = 17 \) and \( Re_\infty a = 2 \cdot 10^5 \). The dark regions on the photographs are the intense heat-transfer zones, where the heat-indicator has melted.

Fig. 1

Fig. 2

Fig. 3