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The interaction of shock waves near a cylinder normal to a blunted plate

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Abstract

An experimental study of the interaction of shock waves near a cylinder perpendicular to a blunted plate was carried out. The experiments were made in the Ludwig wind tunnel at Mach number $M_\infty=5$ and different Reynolds numbers $Re_{\infty L}$ in the range from $0.6 \cdot 10^7$ to $4.0 \cdot 10^7$. The heat fluxes to the model surface, measured using Temperature Sensitive Paint (TSP), were analyzed. The influence of the plate blunting radius and the distance of cylindrical obstacle from plate leading edge on the gas flow are studied.

Keywords: *shock waves interference, heat transfer, Ludwieg wind tunnel, temperature sensitive paint (TSP)*

Nomenclature

Latin
D – Diameter of cylindrical cowl
L – Length of the plate
M – Mach number
r - Leading edge bluntness radius
Re – Reynolds number
St – Stanton number
X - Axis and distance from plate leading edge

Superscripts
0 – Angular degree

Subscripts
0 – Related to cowl position
c - Related to cylinder
L - Related to plate length

1. Introduction

The problem of a flow around a cylindrical obstacle installed on flat plate attracted the close attention of researchers in the 1960s [1]. The flow near a cylinder located on a sharp plate at a large distance from its leading edge was studied. The main features of the flow structure were revealed, sharp peaks of heat flux and pressure were found on the plate in front of the cylinder and on the cylinder itself. It was found that the three-dimensionality of the flow in front of the cylinder leads to a significant increase in the peak values of heat flux and pressure compared to the two-dimensional case.

In connection with the development of air intakes for high-speed aircraft, the problem of a flow around a cylindrical obstacle regains interest, which stimulates the resumption of research [2]. Indeed, the entrance edges of compression wedge and cowl of the air intake should have some blunting to restrict the temperature of intake structure. On the other hand, a flat air intake usually contains the side walls to eliminate the lateral overflowing of compressed gas. The leading edges of the side walls should also have some blunting. The distance of the entrance edges of the wedge and cowl from the leading edge of the side walls may be small. This restricts the size of the separation zone that is formed in front of the cylindrical blunting, and can lead to significant changes in the distribution of heat flux and pressure compared to what was observed previously with free separation of the boundary layer at a large distance from the leading edge of the plate. Thus, there is the

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problem of the interaction of cylindrical shock waves that are formed near a blunted plate and a cylindrical obstacle at different distances from the plate leading edge.

Model configuration is shown in Fig. 1. Vertical plate 2 with a cylindrical leading edge 6 of 10 mm diameter *D* is installed on a horizontal plate 1 having variable leading edges of bluntness radius *r*. Distance X_0 of vertical plate leading edge from horizontal plate leading edge can be varied in a wide range. To determine the state of undisturbed boundary layer on a horizontal plate, some experiments were also carried out without a vertical plate. Leading edge blunting radius of the plate was changed by replacing the front insert 3. Side fences 5 were installed to prevent gas overflowing from the bottom surface of the plate to its top (working) surface. A horizontal plate with thermoinsulating insert 4 made of AG-4 fiberglass was used in heat transfer studies.

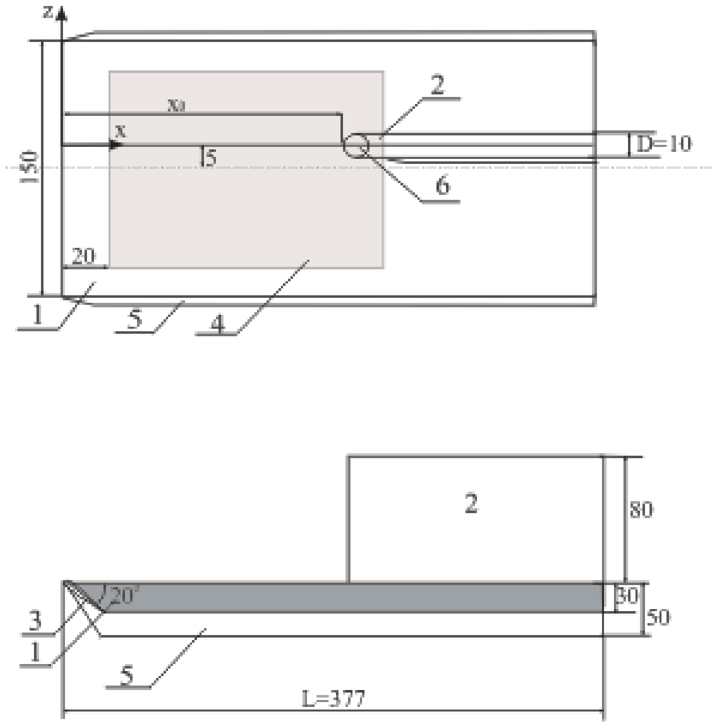


Fig 1. Model schematic: *1* – horizontal plate, *2* – vertical plate with cylindrical leading edge, *3* – changeable front insert, *4* – thermoinsulating insert, *5* – side fence, *6* – cylinder

The experiments were carried out in the UT-1M wind tunnel, which operates in Ludwig tube mode, at Mach number M_∞=5 and two values of total temperature T_0. Experiments without a vertical plate were performed at $T_0 \approx$ 600K ($T_w/T_0 \approx 0.48$). In experiments with a vertical plate the temperature was reduced to $T_0 \approx$ 450K ($T_w/T_0 \approx 0.60$) to eliminate the model overheating in the zones of the most intensive heat transfer. The Reynolds number Re_L calculated by the model length L=377 mm and the parameters of free stream were varied in the range from approximately $0.6 \cdot 10^7$ to $4 \cdot 10^7$ by changing the total pressure (from 16 to 65 bar) and the stagnation temperature (450 K and 600 K). The duration of the steady flow parameter is 40 ms. The output diameter of the nozzle is 300 mm.

The heat transfer coefficient from the gas to the model surface was measured using a thin luminescent coating sensitive to temperature – Temperature Sensitive Paint (TSP) [3]. To realize this method, the investigation surfaces of the model were made of a material with low thermal conductivity – of AG-4 fiberglass.

2. Flow structure

The flow pattern in the presence of horizontal plate blunting is shown in Fig. 2. The leading edge of horizontal plate generates a bow shock wave, behind which a high-entropy layer is formed. Next, the flow separates from the surface of the horizontal plate in front of a cylindrical obstacle on S_1 line and reattaches to the cylinder front surface on R_2 line, then separates secondly from the cylinder on S_2

line and reattaches to the surface of the plate on R_1 line. Inside the primary separation region $S_1R_1S_2R_2$, a narrow secondary separation region 5 is formed. On a far distance from the cylinder, the flow separated from the plate on S_1 line, after turning, reattaches directly to the surface of the horizontal plate on R_1 line. The $S_1R_1S_2R_2$ vortex formed in front of the cylinder is split: one branch propagates along the head shock wave of the vertical plate, the other along the side surface of vertical plate.

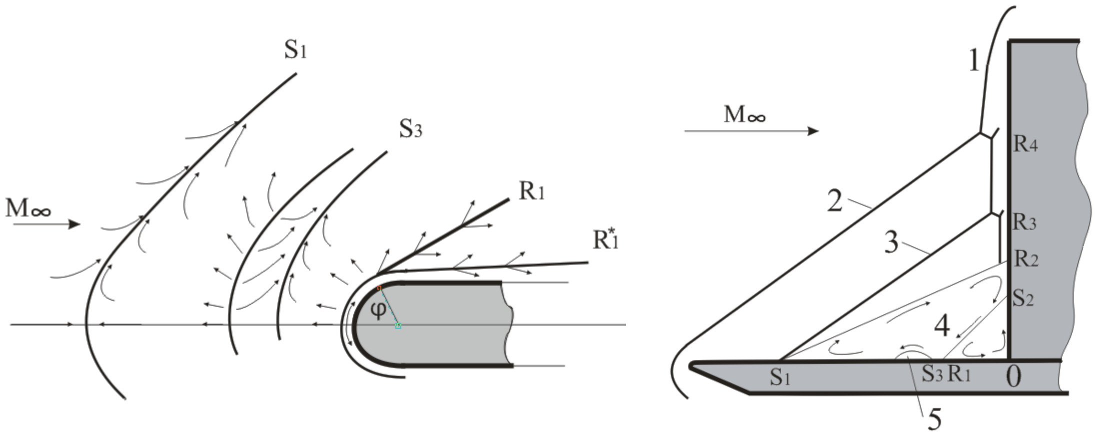


Fig 2. Flow structure: *a)* – streamlines on horizontal; *b)* – vertical flow cross-section; *1* – bow shock wave of the cylinder; *2* – bow shock wave of horizontal plate; *3* – separation shock; *4* – primary separation; *5* – secondary separation; S_1, S_2, S_3 – separation lines; R_1, R_2, R_3, R_4 – reattachment lines

Three specific zones are formed on the front surface of the cylinder in which the local heat transfer intensification can take place: the zone of attachment to the cylinder of a flow separated from the plate (R_2); the zone of incidence of separation shock (R_3) and the zone of incidence on the cylinder of the plate bow shock wave (R_4). The location of these zones depends on the shape of the bow shock wave of the plate, as well as on the shape and on the length of the separation zone.

3. Heat transfer on the plate

The specific features of heat transfer on horizontal plate surface in the presence of a vertical plate are shown in Fig. 3. Here, St_r is calculated for a turbulent boundary layer on a sharp plate at the point X_0/D=15, and St_c – for the critical line of isolated infinite cylinder of D=10 mm diameter.

Fig. 3b shows that at X_0/D≈4.3 the boundary layer laminar–turbulent transition ends, i.e. the zone of interaction of vertical plate bow shock with the boundary layer of horizontal plate is in the turbulent zone. Behind the primary separation line S_1 (Fig. 3, a), the heat transfer is enhanced due to the pressure increase behind the separation shock. Further (in front of the line S_3) there is a narrow zone of low heat transfer. It is formed due to the formation of a secondary separation zone (zone 5 in Fig. 2) inside the primary separation zone. The heat transfer coefficient reaches a maximum at the end of the zone of primary separation, on R_1 line. The zone of maximal heat transfer has the shape of a semi-ring. In Fig. 3, c the maximal Stanton number in this semi-ring is represented depending on the central angle φ. In accordance with the shape of the streamlines (see Fig. 2), the zone of maximal heat transfer is split close to the side cylinder lines: one branch propagates along the bow shock wave of the cylinder, and the other – along the side surface of the vertical plate.

From Fig. 3, b, it can be seen that the maximum value of the Stanton number on the plate near the cylindrical obstacle is an order of magnitude higher than the similar value in undisturbed region and is close to the Stanton number calculated for the front surface of the cylinder in undisturbed flow. Therefore, in figure 3, c and in the following figures, the peak values of St are related to the value of St_c.

An influence of plate leading edge bluntness on the maximum value of Stanton number in front of the cylinder at large distance of its position from the leading edge (X_0/D=15) and large Reynolds number $Re_D=9.1\cdot10^5$ is shown in Fig. 4. This configuration is characterized by the facts that the zone of plate bow shock incidence on the cylinder is significantly displaced from the plate, the state of the boundary layer in front of the cylinder is not changed (it is turbulent) and the structure of the gas flow on the plate in front of the cylinder is determined mainly by the high-entropy layer (HEL) created by the plate leading edge. At small blunting (up to r/D=0.05), the effect of blunting on heat transfer is insignificant, since the HEL is absorbed by the boundary layer before the reaching of cylinder location zone. A further blunting increase significantly reduces the heat transfer in front of the cylinder because of the decrease of total pressure on external boundary of separation zone near cylinder base, which leads to a decrease of velocity gradient on reattachment line R_1. Finally, starting from blunting radius of $r/D\approx$0.2, a further blunting increase has a weak effect on heat transfer. This is caused by the fact that unabsorbed HEL reaches the cylinder location zone, and a further blunting increase has no effect on the total pressure and other flow parameters near the base of the cylinder. A similar effect was observed in the studies of the flow in the zone of oblique shock falling on a blunted plate [4].

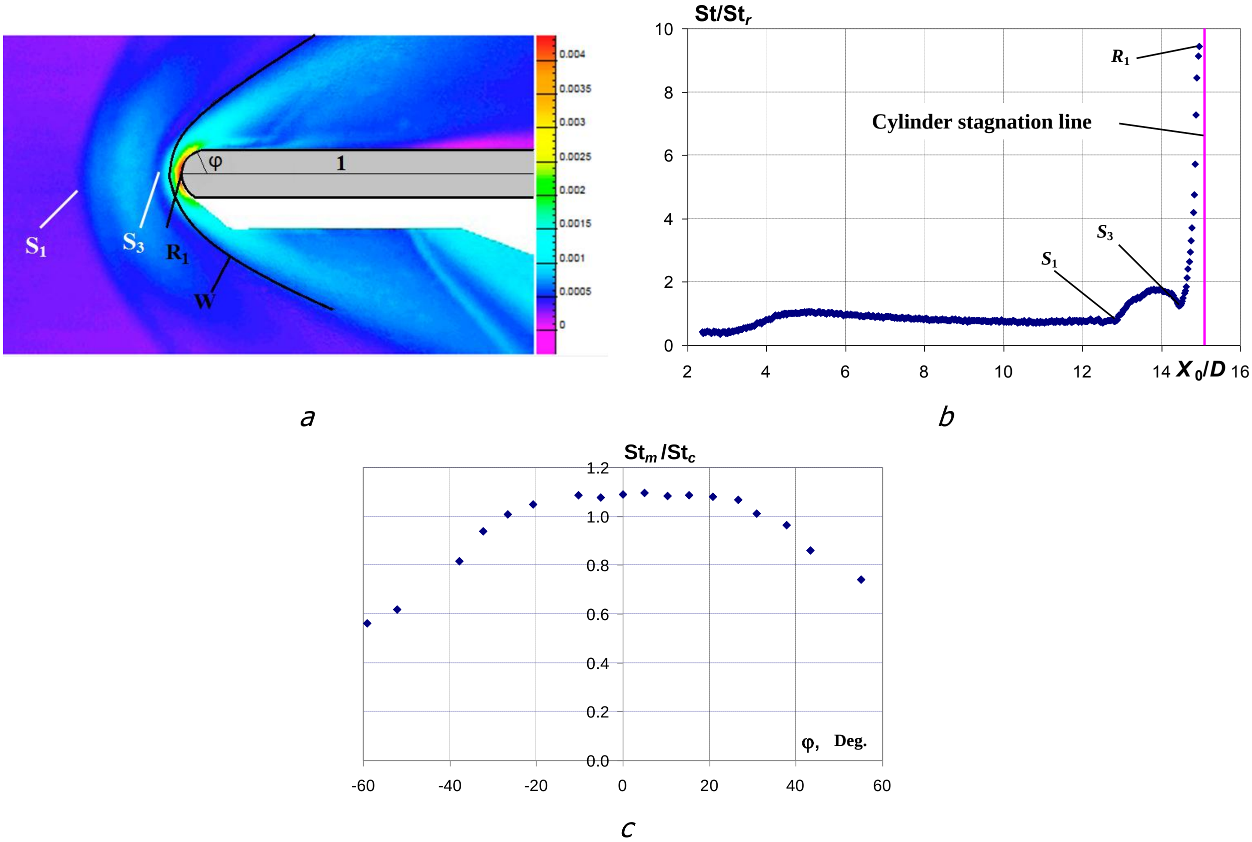


Fig 3. St number distribution on horizontal plate at X_0/D=15, $Re_D=9.1\cdot10^5$ and r/D=0.2: *a)* – heat flux pattern (*1* – vertical plate, *W* – its bow shock wave calculated without viscosity effect, scale on the right shows St values; *b)* – St/St_r distribution on a symmetry line ($St_r=0.46\cdot10^{-3}$), *c)* –St/St_c distribution along the reattachment line R_1 ($St_c=3.87\times10^{-3}$)

An influence of the distance of cylinder position from the plate leading edge on heat transfer is investigated. As the cylinder approaches the leading edge, the flow at the base of the cylinder becomes more complex: the free separation goes into the separation with a fixed starting point; this increases the angle of separation zone inclination. On the other hand, on the blunted plate, at the base of the cylinder the pressure increases and the Mach number decreases with X_0 decrease. It is interesting that in many flow regimes there is not pronounced tendency of a decrease of St_m/St_c ratio as X_0/D tends to the zero (Fig. 5). In this connection, the additional experiments were performed for small X_0/D=0.5, 1.0 and 2.0. Quantitative data were not obtained since the surface near the leading edge has not thermo-insulating insert, and Temperature Sensitive Paint was applied on the steel surface. However, the qualitative results of these experiments indicate that maximum heat transfer coefficient continues to increase at the approach to the leading edge. Evidently, this effect is caused by the thinning of the boundary layer in the zone of reattachment line R_1 in front of the cylinder, similarly to the case of non-separated flow on the plate.

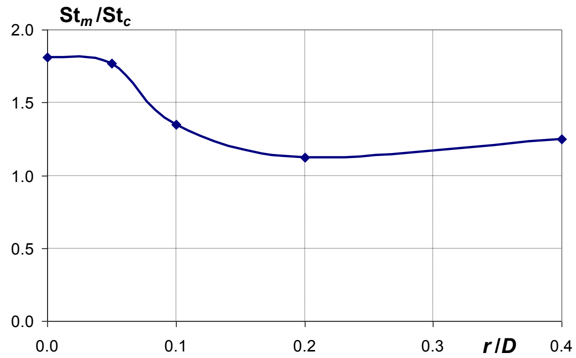


Fig 4. An effect of plate bluntness radius on maximum St value ahead of cylinder (in R_1 zone) at X_0/D=15 and Re_D=9.1·10^5

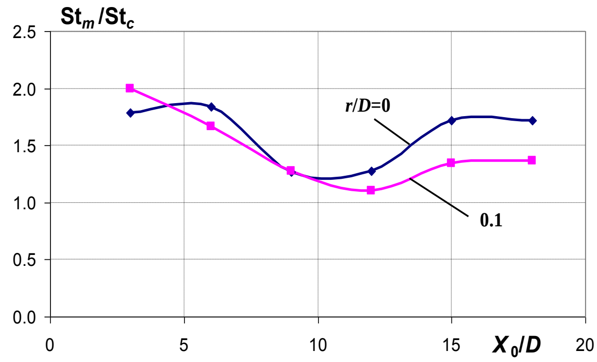


Fig 5. An effect of the distance of cylinder position from plate leading edge on maximum St value at Re_D=2.7·10^5

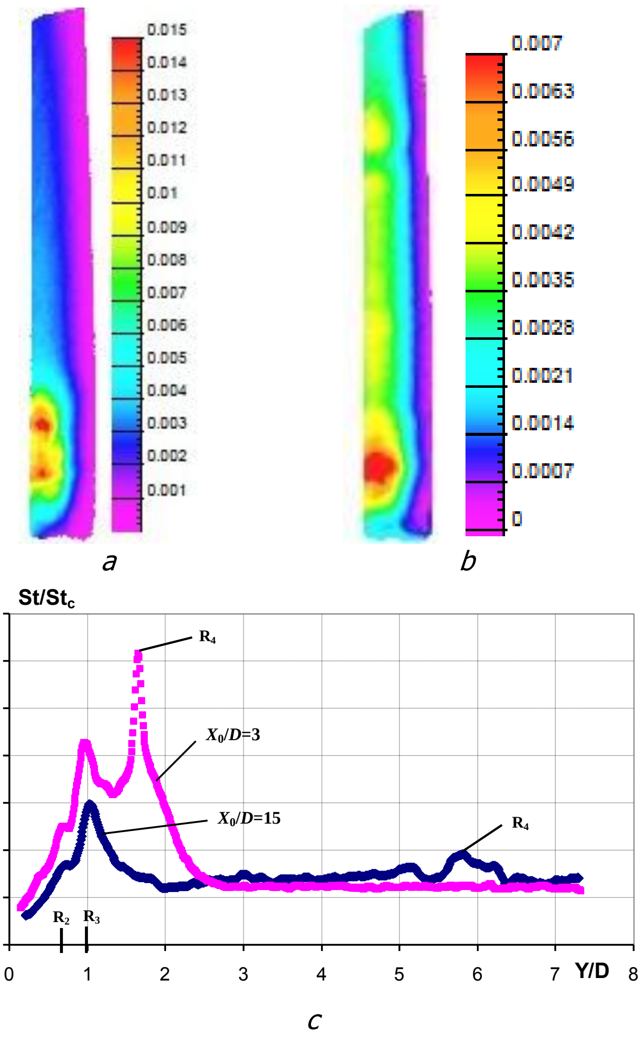


Fig 6. Heat flux on the cylinder front surface at its different distances from plate leading edge at the bluntness r/D=0.1 and Re_D=5.1·10^5 (St_c=5.15·10^{-3}): *a* – X_0/D=3, *b* – X_0/D=15, *c* – St number distribution at X_0/D=3 and 15

4. Heat transfer on the cylinder

Figure 6 shows the heat transfer features on the cylinder front surface at small and large cylinder distances from the leading edge of blunted plate (r=1 mm). At small distance of the cylinder (X_0/D=3, Fig. 6, a), three areas of peak heat transfer are formed on its front surface: at the reattachment point (R_2), at the point of separation shock incidence (R_3) and at the point of plate bow shock incidence (R_4). The position of points R_2, R_3 and R_4 on X-axis in Fig. 6, b was determined from Schlieren images and from the calculation of bow shock wave. At X_0/D=3, the most significant increase of heat transfer occurs at the point of bow shock incidence (R_4): here the Stanton number is more than 6 times greater than the calculated value St_c. Stanton number also sharply increases in the zone R_3 (more than 4 times) and in the zone R_2 (2.5 times).

At large distance of cylinder position (X_0/D=15, Fig. 6, b, c), the maximum value of the Stanton number in the R_4 zone is significantly lower than in the previous case (St_{max}/St_c=2) due to the weakening of the shock wave. Two peaks of heat flux are formed in R_4 zone in this case. The formation of an additional peak of the heat flux can be caused by the expansion of the high-pressure jet and the formation of high-pressure region at the end of the "barrel". Similar effect was observed at M_∞=8 in [2]. In the R_2 and R_3 zones, the relative values of Stanton number at X_0/D=15 are less than at X_0/D=3 due to some pressure drop on the plate surface with the distance from leading edge, and also due to thickening of the boundary layer on the plate. The position of the R_2 and R_3 zones, as noted above, weakly depends on the distance of cylinder position despite the laminar-turbulent transition of the boundary layer on the plate (in this case, it begins at $X_0/D\approx$10).

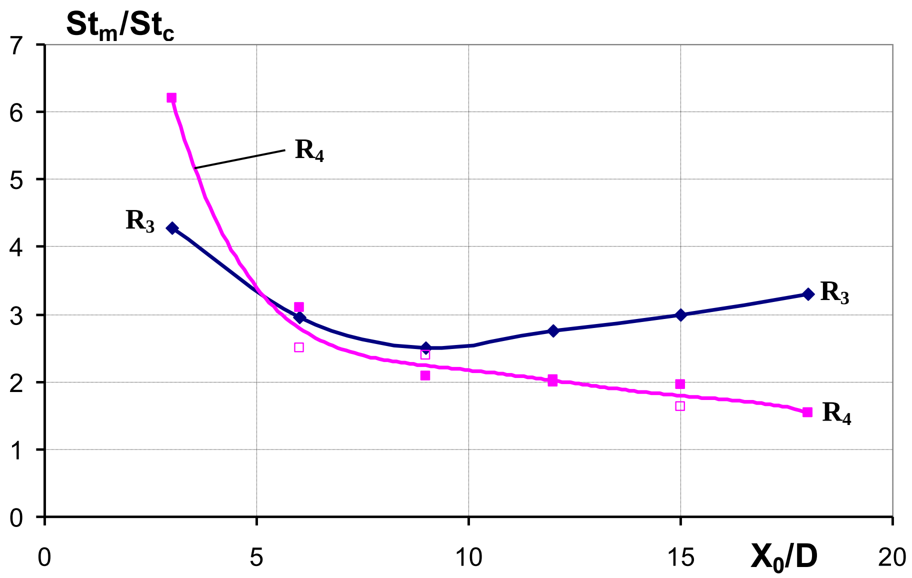
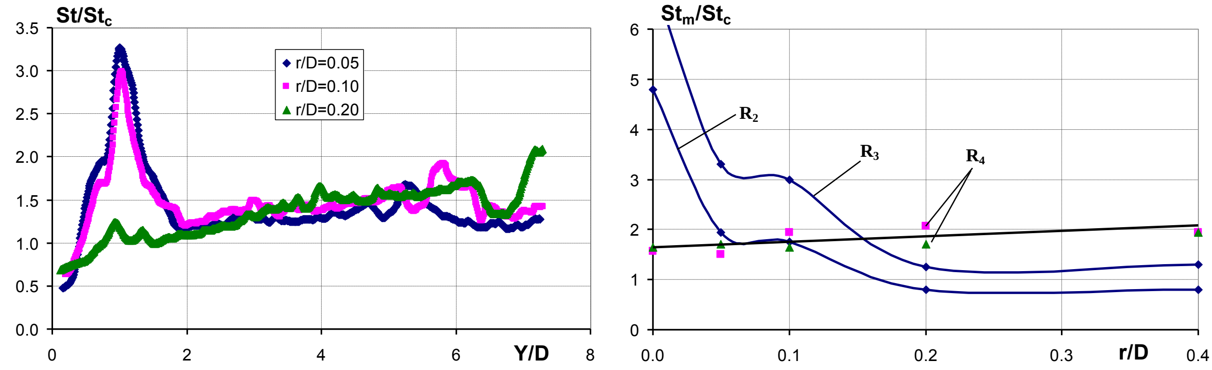


Fig 7. An influence of cylinder position distance from plate leading edge on maximum heat flux values at Re_D=5.1·10^5 and r/D=0.1

An influence of cylinder position distance from the plate leading edge on the heat transfer is also shown in Fig. 7. In the zone of bow shock incidence (in the zone R_4), the displacement of the cylinder back leads to significant decrease of maximum Stanton number. This is caused, first of all, by the weakening of bow shock of the plate: at X_0/D=3 and r/D=0.1 (X_0/r=30) the pressure change (P/P_∞) in the shock wave is more than 3, and at X_0/D=15 (X_0/r=150) it is less than 2. In addition, at bow shock weakening, the high-pressure jet is elongated. As a result, it can deviate upwards (from the plate) under the action of pressure difference in zones 4 and 5, which also leads to a weakening of heat transfer. In zone of separation shock incidence on the cylinder (R_3), the peak value of Stanton number changes non-monotonically depending on X_0/D: at X_0/D=10 the decrease of Stanton number is replaced by its increase due to laminar-turbulent transition of the boundary layer on the plate, which leads to an increase in the slope angle and the intensity of separation shock.

Next, we consider the effect of plate bluntness on heat transfer, Fig. 8. At large distance of cylinder position from plate leading edge, for all investigated plate bluntness, the flow in R_4 zone interacts weakly with the flow in R_2 and R_3 zones, and these flows can be considered independently: in R_4 zone the flow depends mainly on the local intensity of plate bow shock and, consequently, from X_0/r ratio, while in R_2 and R_3 zones - from the local parameters of plate boundary layer.

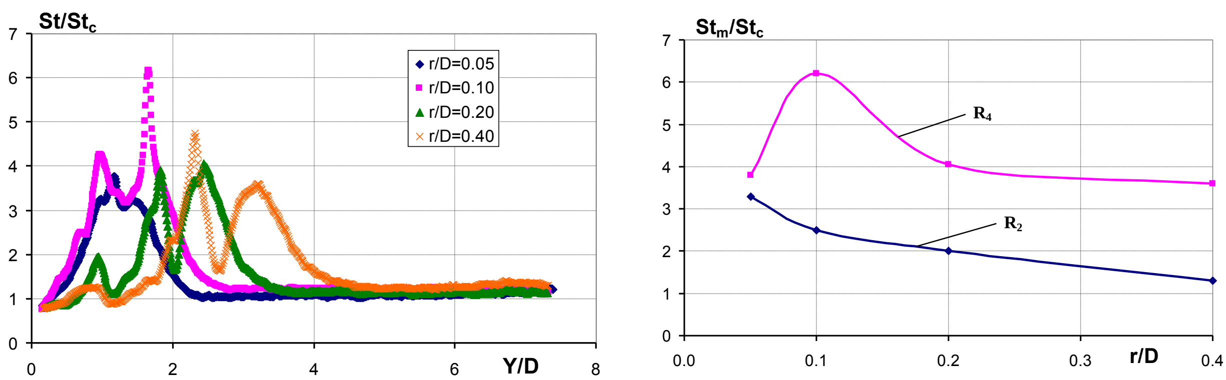


a *b*

Fig 8. An influence of plate bluntness radius on heat transfer at X_0/D=15 (Re_D=5.1·10^5): *a* – St number distribution along the cylinder, *b* – dependence of maximum St value on plate bluntness radius in R_2, R_3 и R_4 zones

In the zone of bow shock incidence on the cylinder (R_4), as noted above, two peaks of heat transfer are formed. As the blunting radius increases and the corresponding X_0/r ratio decreases, the maximum Stanton numbers in these peaks increase monotonously (Fig. 8, b) due to an increase of local intensity of bow shock: according to the calculation of inviscid gas flow, the pressure drop P/P_∞ in the bow shock increases from P/P_∞≈1.9 at r/D=0.1 to P/P_∞≈2.9 at r/D=0.4.

In R_2 and R_3 zones located near the plate, a slight plate blunting (to r/D≈0.1) reduces the heat transfer coefficient sharply. This effect is caused by the formation of high-entropy layer during gas flowing through the plate bow shock and by corresponding decrease of gas density in front of the interference zone. An influence of HEL on heat transfer increases with an increase of bluntness radius. However, at significantly large bluntness radius (at r/D=0.2 in the case of X_0/D=15), the unabsorbed HEL reaches the separation point, and a further bluntness increase almost does not affect the flow characteristics before the separation point and in the separation zone itself, and, therefore, the heat transfer. A similar effect was observed in studies of heat transfer on blunted plate in the zone of external shock incidence [4].



a *b*

Fig 9. An influence of plate bluntness radius on heat transfer at X_0/D=3 (Re_D=5.1·10^5): *a* – St number distribution along the cylinder, *b* – dependence of maximum St value on plate bluntness radius in R_2 и R_4 zones

At small distance of the cylinder from plate leading edge X_0/D=3 (Fig. 9), the flow is more complex than at large distance. On a sharp plate, the entire flow zone in front of the cylinder near the plate surface is separated. Heat transfer on the cylinder increases sharply at the end of separation zone (in R_2 zone) and in the zone of separation shock incidence (in R_3 zone). However, it was not possible to measure the value of the heat transfer coefficient in these zones at r=0 because the surface temperature went beyond the operating range of Temperature Sensitive Paint. At the increase of bluntness radius, the Stanton number at the end of separation zone (in R_2 zone) initially (up to $r/D\approx0.1$) decreases due to the loss of total pressure in the bow shock wave, and then an influence of bluntness radius on heat transfer decreases (Fig. 9, b) in the same way as it happens at large distance of the cylinder from the leading edge (Fig. 8, b).

In the zone of bow shock incidence R_4, the heat transfer increases with an increase of bluntness radius due to an increase of bow shock intensity (Fig. 9, b). However, this happens only to some small bluntness value $r/D\approx0.1$. Further bluntness increase leads to a decrease of heat transfer coefficient in R_4 zone.

5. Conclusions

An experimental study of the structure of the flow and of heat transfer on the plate near the cylindrical obstacle and in its absence at M=5 and Re_L numbers from $0.6\cdot10^7$ to $4\cdot10^7$ at laminar, transitional and turbulent states of undisturbed boundary layer is carried out. An influence of plate bluntness radius and of cylinder position distance from plate leading edge on the gas flow is studied.

The formation of a narrow semicircular zone of enhanced heat transfer on the plate in front of the cylinder in the vicinity of reattachment line is confirmed. It is shown that maximum St_m value in this zone not only exceeds many times the St value on the plate in undisturbed region, but also exceeds the St_c value on front surface of isolated cylinder calculated for laminar flow.

It is shown that an increase of plate bluntness radius to a certain value decreases significantly the maximum St_m value on the plate in front of the cylinder.

The maximal Stanton number values on the cylinder in the zones of separation and bow shocks incidence are up to 6 times higher than the Stanton number value St_c calculated for isolated cylinder in undisturbed flow. This sharp increase of heat transfer occurs because of the formation of thin high-pressure jet in the zone of intersection of shock waves with the cylinder bow shock.

In the zone of separation shock incidence on the cylinder, a small plate blunting (up to $r/D\approx0.1$) drastically reduces heat transfer due to formation of high-entropy layer near the plate surface, while further blunting increase has weak effect on heat transfer. The backward displacement of the cylinder leads to a non-monotonic change of heat transfer due to the laminar-turbulent transition of boundary layer and the corresponding increase of the angle of separation shock inclination.

In the zone of plate bow shock incidence on a cylinder, an increase of plate leading edge bluntness leads to some increase of Stanton number maximum if the cylinder is located far from plate leading edge. This effect is caused by an increase of bow shock intensity in the zone of its incidence on the cylinder. If the cylinder is located close to plate leading edge ($X_0/D\approx3$), the heat transfer on the cylinder changes non-monotonically with an increase of plate bluntness (first increases and then weakens) because of the flow structure change.

Acknowledgment

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