

CONTROLLING THE LEVEL OF THE SONIC BOOM GENERATED BY A FLYING VEHICLE BY MEANS OF CRYOGENIC FORCING.

2. DISTRIBUTED INJECTION OF A SUPERCOOLED GAS FROM THE VEHICLE SURFACE

V. M. Fomin, V. F. Chirkashenko,
V. F. Volkov, and A. M. Kharitonov

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The possibility of improving the efficiency of cryogenic forcing on the parameters of the hanging shock determining the length of the region of minimization of the sonic boom (middle zone) generated by a modified power-law body is studied. The effect of distributed injection of the coolant from the body surface on the formation of a perturbed flow near the body and at large distances from the body is considered. The scheme of distributed injection and the regime of coolant exhaustion are demonstrated to exert a significant effect on the length of the middle zone of the sonic boom. A scheme of cryogenic forcing is determined, which ensures reduction of bow shock wave intensity by more than 40% at distances corresponding to 7000 body diameters. The mechanism of cryogenic forcing on the flow structure near the body is discussed.

Key words: *supersonic transport, sonic boom, bow shock wave, cryogenic forcing, coolant, flow structure.*

Introduction. The present activities continue the study of controlling the parameters of the sonic boom (SB) by means of cryogenic forcing applied to the flow around a flying vehicle [1]. A modified (by means of forebody bluntness) power-law body, which ensures the minimum drag at moderate supersonic velocities [2], allows the intensity of the bow shock wave (SW) in the middle zone of the sonic boom to be reduced by virtue of the bluntness effect [3]. The region of SB minimization (middle zone) is limited to a distance at which the bow SW interacts with a hanging SW formed near the body surface and propagating with a high velocity. Contradictions in requirements to the geometric parameters of the modified power-law body (aspect ratio and bluntness radius) for reduction of SB intensity and drag necessitates limitation of the height of the SB minimization region. Fomin et al. [1] studied the possibility of increasing the middle zone owing to reduction of intensity of the hanging SW, provided by reduction of flow temperature in the zone of its formation by means of cooling the body surface. Reduction of flow temperature by 50°C, reached by coolant pumping in the model cavity made it possible to reduce the hanging SW intensity almost by a factor of 2 and, thus, to shift the point of its interaction with the bow SW to a distance equal to 1500 body diameters (calibers). This value is substantially smaller than the supersonic transport cruising flight altitude equal to 6000–7000 calibers. Difficulties arising in further reduction of flow temperature by this method and the necessity of further reduction of temperature under real flight conditions [1] show that this method of controlling the hanging SW intensity is insufficiently effective and stimulate the search for more effective methods.

Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; fomin@itam.nsc.ru; chirkash@itam.nsc.ru; volkov@itam.nsc.ru; khar@itam.nsc.ru. Translated from *Prikladnaya Mekhanika i Tekhnicheskaya Fizika*, Vol. 50, No. 2, pp. 136–144, March–April, 2009. Original article submitted March 21, 2008.

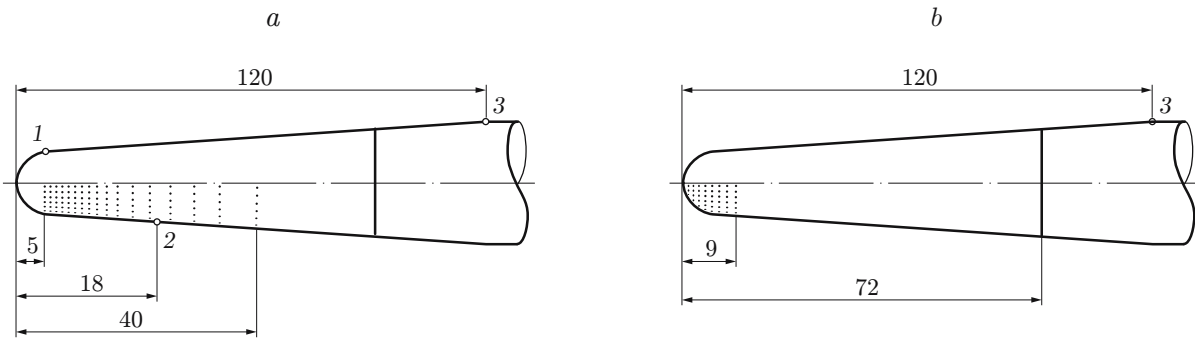


Fig. 1. Forebodies of the modified power-law body of revolution: model Nos. 1 and 2 (a) and model No. 3 (b); 1) thermocouple T1; 2) thermocouple T2; 3) thermocouple T3.

To obtain the middle zone length of interest for practice, active controlling of hanging SW parameters was additionally studied to increase the efficiency of reduction of flow temperature in the region where this SW appears [4]. Hanging SW formation was affected by means of distributed injection of the coolant from the model surface to the zone of hanging SW generation, which allowed a significant decrease in flow temperature in the region of hanging SW formation and, as a consequence, in the velocity of propagation of perturbations owing to convective heat exchange between the injected coolant and the free stream. To avoid possible generation of additional shock waves by the coolant jets, it is necessary to ensure an appropriate distribution of injection intensity over the body surface.

Test Conditions. The study was performed in a T-313 supersonic wind tunnel based at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences. The free-stream parameters were $M_\infty = 2.03$, $Re_1 = 25 \cdot 10^6 \text{ m}^{-1}$, and $T_0 = 258\text{--}263 \text{ K}$. The overall field of the flow perturbed by the body was obtained by a combined experimental and numerical method [5, 6] based on measuring the profiles of perturbed static pressure near the model mounted in the wind-tunnel test section and subsequent extrapolation of these profiles to large distances with the use of the quasi-linear theory [7]. The arrangement of the experiment and the methods of measurement and recalculation of the measured pressure profiles to large distances are similar to those used in [1]. The root-mean-square error of pressure sensors was within 65 Pa.

The model was a modified power-law body of revolution (aspect ratio $\lambda = 6$, power index $n = 0.75$, and relative bluntness radius $\bar{r}_{bl} = 0.2$) with a mid-section diameter $d_{mid} = 50 \text{ mm}$. It was made of 12Kh18N10T steel and was mounted on a cylinder. Model variants with different schemes of perforation for injection of a supercooled gas from the model surface into the flow were created with the use of replaceable forebodies 72 mm long (Fig. 1), which were attached to the original model. The forebodies were made of the LS-59 brass alloy whose coefficient of temperature deformation is close to the coefficient of the material of the original model. The lower surface (sector with a 180° angle from the side of the measurement plate) of the forebody of model No. 1 was perforated (the orifice diameter was 0.3 mm). The perforation began in the cross section close to the line of junction between the sphere and the power-law surface and ended at a distance of 40 mm from the model tip. The degree of perforation determined by the ratio of the area of orifices to the total area of the perforated surface S_{or}/S_{perf} was reduced with distance from the model tip from 8.0 to 1.3%, because the distance between the cross sections was changed and the number of orifices over the perimeter of each cross section was identical. The diameter of the orifice whose area was equivalent to the total area of perforation was 4.63 mm. The configuration of perforation of model No. 2 differed from that of model No. 1 only by the increased diameter of some orifices to 0.35 mm. The perforation zone on model No. 3 with orifices 0.5 mm in diameter started at the model tip and ended at a distance of 9 mm from the model tip. The mean degree of perforation was 40%. The diameter of the orifice whose area was equivalent to the total area of perforation orifices was substantially greater than that of model No. 2 and reached 6.6 mm.

The temperature on the forebody surfaces was measured by thermoelectric converters (thermocouples) of the T type (copper–Constantan) with a $100\text{-}\mu\text{m}$ diameter of electrode wires. The hot junction was located at the level of the outer surface of the model and was insulated from the model by a layer of the VS-9T temperature-resistant glue 0.3–0.4 mm thick. The cold junctions were withdrawn from the pressure chamber of the wind tunnel

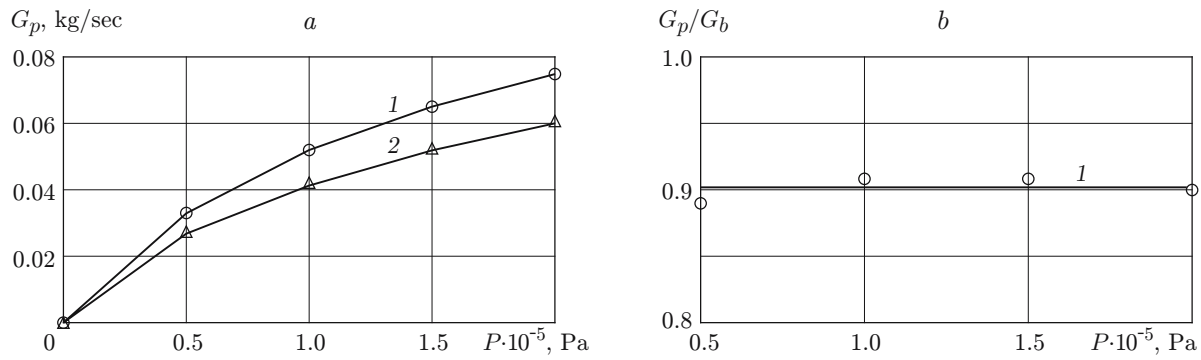


Fig. 2. Absolute (a) and relative (b) flow rates of the coolant through the perforation versus the reservoir pressure for water (1) and liquid nitrogen (2).

into the ambient atmosphere through electrode and compensation wires. The signals from the thermal converters were recorded by an NR34970A multichannel integrating voltmeter, which ensured temperature registration with an error smaller than 1.5° . For certain reasons, the number of thermocouples on the examined models was different (see Fig. 1).

The process of model cooling by means of coolant pumping in the inner cavity of the model was complicated by the fact that the cross-sectional area of the pipeline supplying liquid nitrogen into the model cavity was substantially smaller than the total area of the orifices of perforation and slots through which the coolant in the base part of the model was injected into the free stream. Therefore, a particular cooling technology was developed for each variant of the model [4]. The flow rate characteristics of the system of coolant supply onto the model were obtained by pumping technical water supplied from a pressurized reservoir. Figure 2 shows the flow rate (G_p) of the coolant passing through perforation of model No. 2 as a function of the reservoir pressure P and the ratio of the flow rates of the coolant injected through perforation and the coolant entering the base region of the model (G_b).

Results of the Study. The perforation schemes of model Nos. 1 and 2 were chosen to ensure coolant injection directly into the region of formation of the hanging SW. There are grounds to believe that the hanging SW, which arises owing to interaction of the flow accelerating in its motion around the spherical bluntness with the model surface, starts to form in the flow around a modified power-law body without coolant injection in the vicinity of the junction between the spherical and power-law surfaces. The hanging shock emerging in an immediate vicinity of the model surface, which is an envelope of the family of converging compression waves, transforms to a hanging SW with distance from the body. As the regime of coolant injection had to ensure effective cooling of the flow between the hanging shock and the model surface and the layer of the supercooled gas formed owing to evaporation of the coolant entering the flow should not generate additional shock waves, the degree of perforation was reduced in the downstream direction.

The perturbed pressure profiles measured in the flow near the surface of model No. 1 ($K = 3.7$) with injection of liquid nitrogen with an initial pressure of 0.135 MPa show that coolant injection exerts a noticeable effect on the process of formation of the hanging SW. Under such cryogenic forcing, the bow SW intensity remains almost constant, but the intensity of the rarefaction wave following behind the bow SW is reduced in the entire flow region, except for the region of formation of the hanging SW on the non-cooled model. In this region of the flow, which arises under the action of the injected coolant, the flow continues to expand with intensity higher than the intensity of the rarefaction wave generated by the non-cooled model. The expansion zone is closed by the hanging SW whose intensity is approximately equal to the intensity of the intermediate SW near the non-cooled model. The downstream displacement of the hanging SW obtained in this case corresponds to half of the model diameter, which indicates that the length of the middle zone can be increased. According to recalculation results, the length of the middle zone ensured by this model is 1500 calibers, which is comparable with the value obtained in [1] and is not of interest for practice.

Figure 3 shows the pressure profiles measured near the surface of model No. 2 ($K = 3.7$) under conditions without coolant injection and with injection of liquid nitrogen with an initial pressure of 0.15 MPa (Fig. 3a) and the results of their recalculation to large distances (Figs. 3b–3d). The pressure profiles are presented as the dependences

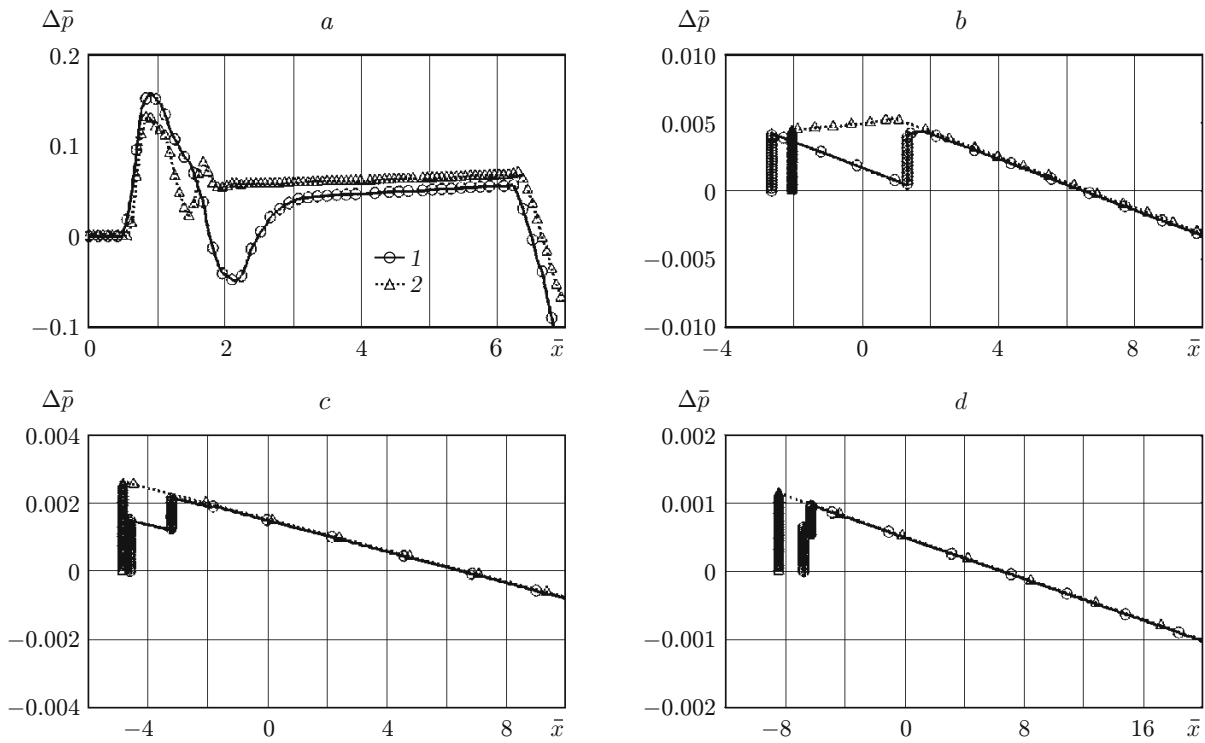


Fig. 3. Perturbed pressure profiles in the flow around model No. 2 at different distances from the model: $K = 3.7$ (a), 500 (b), 2000 (c), and 6000 (d); results of tests with and without coolant injection are indicated by points 1 and 2, respectively.

of the relative excess static pressure $\Delta\bar{p} = (P - P_\infty)/P_\infty$ on the relative distance $\bar{x} = X/d_{\text{mid}}$ (P and P_∞ are the static pressures in the perturbed and non-perturbed flow, respectively; the direction of the X axis coincides with the free-stream direction). In contrast to model No. 1, this modification of perforation ensures a significant increase in the length of the region and the degree of flow overexpansion behind the bow SW, which leads to a significant downstream displacement of the compression wave acting as a precursor for hanging SW formation. A small increase in bow SW intensity leads to a significant decrease in the impulse of the positive phase of the SB wave. An increase in coolant pressure leads to enhancement of flow rarefaction and to a greater downstream length of the expansion region with an insignificant increase in bow SW intensity.

In the course of evolution of the pressure profile deformed by cryogenic forcing, the downstream-shifted compression wave, owing to nonlinear effects, becomes transformed already at moderate distances from the model into a pressure shock (see Fig. 3b) located at a substantially greater distance from the bow SW than that in the case with model No. 1. In the course of its propagation, the bow SW induced by the bluntness intensely decays under the action of the following rarefaction wave before it can start interacting with the hanging SW. The process of decaying of the bow SW generated by the model without coolant injection is rather long owing to interaction of the compression wave propagating behind the bow SW and formed owing to interaction between the bow SW and the hanging SW. The process of intense decaying of the bow SW generated by the model with coolant injection persists up to large distances from the body (see Fig. 3d). According to recalculation results, the total length of the middle zone of this model can be increased to values equal almost to 7000 calibers, while the SB intensity is reduced by more than 40%.

Figure 4 shows the flow temperatures measured in the experiment near the surface of model No. 2 without coolant injection and with injection of the coolant with $P = 0.15$ MPa. The vertical bars on the abscissa axis indicate the beginning and end of the design supersonic flow regime. Before the beginning of the supersonic flow, the thermocouples mounted on the cooled model register the temperature almost corresponding to the liquid nitrogen temperature. After the beginning of the supersonic flow, stationary heat transfer is rather rapidly established near

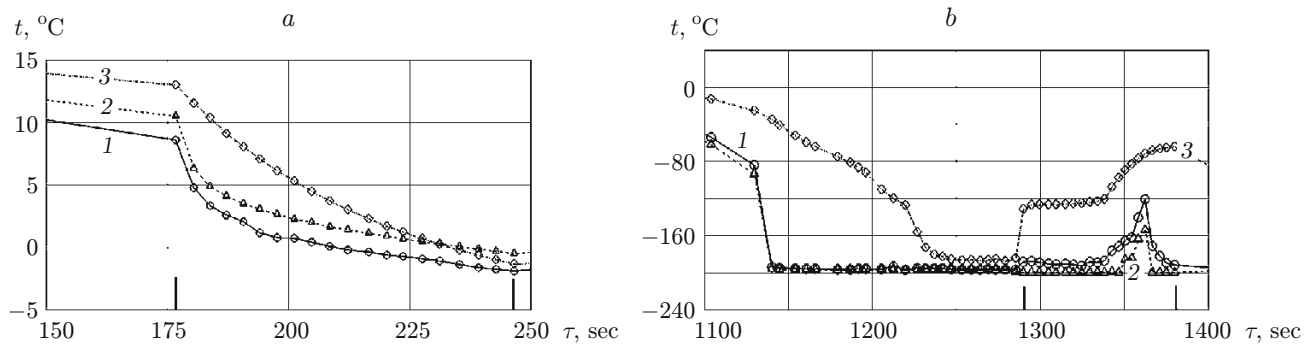


Fig. 4. Changes in flow temperature near the surface of model No. 2: (a) without coolant injection; (b) with coolant injection; 1) thermocouple T1; 2) thermocouple T2; 3) thermocouple T3.

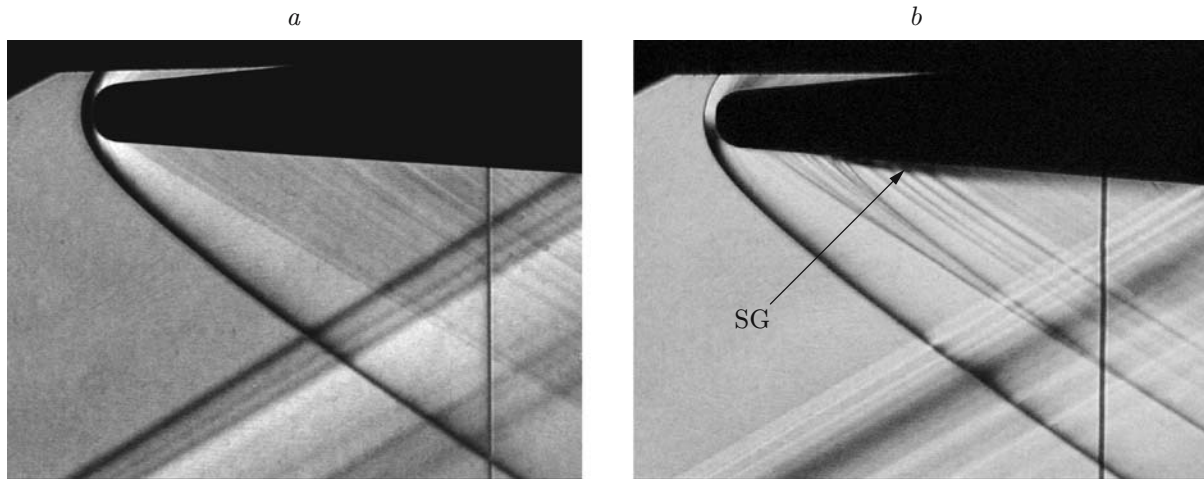


Fig. 5. Visualization of the flow near model No. 2: (a) without coolant injection; (b) with coolant injection ($P = 0.15$ MPa); the supercooled gas layer is indicated by SG.

the model surface. The thermocouple T3 located at the greatest distance from the model tip registers the maximum temperature, while the thermocouple T2 located on the lower surface in the perforated region registers an additional decrease in temperature to $t \approx -200^{\circ}\text{C}$. The temperature in the region of the junction of the spherical bluntness and the power-law surface, registered by the thermocouple T2, is substantially lower than the temperature on the cooled model in the absence of coolant injection [1]. Apparently, the entire amount of liquid nitrogen injected into the flow does not evaporate, and there is a liquid phase in the supercooled gas layer formed near the model surface. This fact is indirectly confirmed by the values of temperature registered by the thermocouple T2 (see Fig. 4b) located directly in the zone where the coolant enters the model surface (see Fig. 1). Under the test conditions, the temperature $t \approx -200^{\circ}\text{C}$ corresponds to the temperature of liquid nitrogen. An increase in flow temperature near the model surface at the end of the flow regime ($\tau > 1340$ sec) (see Fig. 4b) is caused by the formation of the gas phase in the model cavity owing to an increase in the coolant flow rate by means of increasing its pressure in the course of the experiment.

Figure 5 shows the schlieren pictures of the supersonic flow around model No. 2 under conditions without coolant injection and with injection of liquid nitrogen into the flow in the zone of hanging SW formation.

Injection of liquid nitrogen from the surface of the cooled model leads to formation of density gradients in the flow, which propagate over the characteristic surfaces with distance from the body and become fairly equalized. The formation of a supercooled gas layer near the perforated surface of the model (see Fig. 5b) is observed.

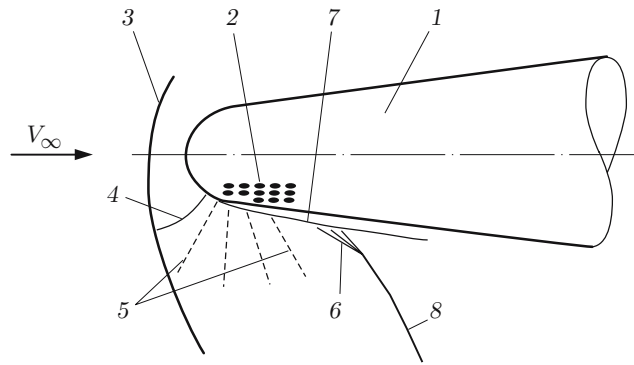


Fig. 6. Flow near a modified power-law body with coolant injection into the region of hanging SW formation (model No. 2): 1) modified power-law body; 2) perforation; 3) bow SW; 4) sonic line; 5) rarefaction waves; 6) compression waves; 7) supercooled gas layer; 8) hanging SW.

The results obtained allow us to gain new knowledge about the flow structure arising under cryogenic forcing of the flow around a modified power-law body.

Figure 6 shows the scheme of the flow formed in the case of injection of liquid nitrogen into the flow. Distributed injection of liquid nitrogen through perforation into the region of hanging SW formation on the model without cryogenic forcing leads to formation of a supercooled gas layer near the model surface with the presence of the liquid phase of the non-evaporated coolant. This layer is gradually entrained downstream by the incoming flow. The remaining liquid nitrogen rapidly evaporates, which is confirmed by improvement of optical transparency of the supercooled gas layer with distance from the perforation region (see Fig. 5b). Interaction of the flow accelerated owing to its motion around the spherical bluntness with the supercooled gas layer forming an effective solid leads to additional expansion of this flow (see Fig. 6). Interacting with the supercooled gas layer, the flow accelerated owing to its expansion induces a family of converging compression waves near the model surface. This interaction forms a hanging shock, which transforms to a hanging SW with distance from the model. Apparently, this process is determined by the increase in the effective radius of curvature of the surface experiencing the action of the supercooled gas layer and also by the reduction of the velocity of sound and, correspondingly, velocity of propagation of perturbations in the region located inside this layer. The specific feature of such a scheme of coolant injection is the specific shape of the supercooled gas layer, with the flow past this layer providing effective overexpansion of the flow almost without any increase in bow SW intensity.

A comparison of experimental results on controlling the hanging SW parameters reached on model No. 2 with results for model No. 1 shows that the perforation configuration is extremely important in organizing cryogenic forcing. As the flow temperature behind the SW affects the intensity of this wave [1], a significant contribution to pressure redistribution is made by intense convective cooling of the flow in the region between the hanging SW and the body surface, which is ensured by means of coolant injection. The results obtained, however, do not allow us to estimate the dependence of the flow formation process on the temperature and mass of the injected coolant. Additional studies are necessary to obtain this information.

As in the case with model No. 2, coolant injection from the surface of the spherical bluntness on model No. 3 increases the length of the flow expansion region behind the bow SW and, hence, leads to a significant downstream displacement of the zone of generation of the hanging SW. In contrast to model No. 2, the intensity of the bow SW near model No. 3 is substantially higher, owing to a greater effective bluntness radius ensured by the formation of the supercooled gas layer on the surface. Because of the downstream displacement of the hanging SW and an increase in velocity of the bow SW caused by its higher intensity, the length of the middle zone formed in the case with model No. 3 is greater than 7000 calibers. Despite an increase in bow SW intensity near the body, this intensity is reduced with respect to the original model by the minimizing effect of the bluntness, beginning from the distance equal to 2000 calibers; this reduction reaches more than 40% at large distances.

The main drawback of the cryogenic forcing scheme considered here is the increase in energy that should be spent on overcoming the increased drag force of the body and the negative thrust of the coolant jets.

The scheme of coolant injection from the model surface behind the spherical bluntness in the region of hanging SW formation (model No. 2) allows the energy needed to overcome the negative thrust generated by the

coolant jets to be reduced, because the coolant is injected from the surface aligned at smaller (as compared with the spherical bluntness surface) angles to the incoming flow. In this case, an effective temperature action on the hanging shock intensity is provided, because the temperature of the incoming flow impinging on the hanging shock is not reduced, in contrast to the case with coolant injection from the spherical surface on model No. 3. The decrease in the impulse of the positive phase of the SB wave obtained on model No. 2 with an insignificant increase in bow SW intensity testifies to a possible decrease in the drag of the body. In practical implementation of cryogenic forcing, the flying vehicle should carry a certain amount of the coolant onboard, which reduces the payload. These expenses can be partially compensated by decreasing the drag of the vehicle owing to the use of a modified forebody and reduction of the drag due to coolant injection.

To estimate the energy expenses needed to ensure effective reduction of SB intensity, we studied the effect of the coolant flow rate on the length of the SB middle zone. With an increase in the coolant pressure to 0.06 MPa, the middle zone length substantially increases and reaches more than 4000 calibers. With a further increase in pressure, the growth of the middle zone length becomes slower, and the middle zone length is approximately 7000 calibers for $P = 0.15$ MPa. Model No. 2 ensures the middle zone length of 6000 to 7000 calibers for an initial pressure of liquid nitrogen equal to 0.14–0.15 MPa. Under the test conditions used, the ratio of the flow rates of the injected coolant and air impinging onto the body mid-section was 7–8%. This ratio could be reduced to 1.5–2.0% with retaining the middle zone length by means of reducing the sector of coolant injection and the longitudinal size of the perforation region.

Conclusions. The study performed revealed a significant effect of distributed injection of a supercooled gas from the body surface on the structure of the perturbed flow in the region of hanging SW formation. The cryogenic forcing considered continues to be effective at large distances from the body and depends to a large extent on the perforation configuration and on the coolant injection regime. Thus, the possibility of controlling the parameters of the sonic boom generated by the flying vehicle and the aerodynamic characteristics of the flying vehicle was demonstrated.

A method was proposed to increase the SB middle zone to 7000 calibers. In this case, the bow SW intensity is reduced by more than 40%, as compared with the original model, which is of significant interest for practice.

Apparently, the main mechanisms of cryogenic forcing on the flow structure are the formation of a contact surface by the supercooled gas produced by evaporation of liquid nitrogen and convective cooling of the flow behind the hanging SW, responsible for a lower velocity of perturbations.

The method of cryogenic forcing considered here can be used independently or can be combined with available active methods of controlling the SB parameters and the aerodynamic characteristics of flying vehicles (injection of a discrete gas jet or low-temperature plasma, energy supply by laser or microwave radiation, etc.).

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