CONTROL OF SONIC BOOM LEVEL BY CRYOGENIC ACTION ON THE PROCESS OF FLOW AROUND THE AIRCRAFT

Chirkashenko V. F.*, Fomin V. M.*, Kharitonov A. M.*, Volkov V. F.
*** Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences**

Keywords: *sonic boom, bow shock wave, hanging shock wave, modified power-law body, cooling agent*

Abstract

Problems inherent in the development of a supersonic passenger plane of the second generation, which stimulate the use of unconventional methods of sonic boom reduction, are analyzed.

A method of reducing the intensity of the intermediate shock wave and excess pressure momentum owing to cryogenic interaction is justified. This method allows the length of the region with a low sonic boom level to be increased (by 50%) and the intensity of the bow shock wave in the far zone to be decreased (by 12%).

Introduction.

Sonic boom (SB) reduction is one of the urgent problems. Solving this problem will speed up the development of supersonic passenger aviation. For this purpose, various investigations have been performed in various aerodynamic centers since the second half of the last century (e.g., [1–7]). In 2011, Chernychev published a monograph entitled “Sonic boom” [8], where he summarized the results of theoretical and experimental SB studies performed in Russia and other countries. Principles of SB minimization and possible configurations constructed with allowance for requirements of the high aerodynamic perfection of the aircraft and structural constraints are also discussed in that book. These and other studies are mainly based on searching for an optimal distribution of the volume and lift force over the aircraft length. The results obtained in these studies show that it is impossible to ensure an acceptable pressure difference of 50 Pa on the bow shock wave (BSW) for a broad range of supersonic aircraft. This fact is evidences by the flights of Tu-144 and Concorde, which showed that the level of excess pressure on the Earth surface in the cruising flight mode is greater than 100 Pa even if the configuration is close to an optimal one from the viewpoint of the SB [9]. The results of supersonic passenger plane research performed at the Central Aerohydrodynamic Institute (TsAGI) [10÷12] also show that it impossible at the moment to provide an admissible SB level for aircraft with a large takeoff weight (more than 100 tons) without deteriorating its engineering performance and cost efficiency. The main reason is a significant increase in the lift force contribution to the SB intensity with increasing aircraft weight. As a result, the shock wave (SW) generated by the wing has a high velocity of propagation (because the SW velocity is proportional to its intensity); this SW catches up with the BSW generated by the fuselage already at moderate altitudes and enhances the intensity of the latter due to their interaction. Thus, it is impossible to maintain an admissible distance between the shock waves from the fuselage and from the wing down to the ground surface (the so-called effect of the middle zone of the SB).

Exotic configurations with an extended nose part of the fuselage, with V-shaped wings, and with joined wings were also considered for the purpose of realization of the middle zone effect. However, detailed studies [12 14] showed that these measures do not ensure the lift-to-drag ratio necessary for a supersonic aircraft to be cost-efficient either. There are reasons to believe that the admissible SB level will be reduced to 15 Pa in the future [15]. This fact stimulates investigations of unconventional active methods of controlling SB parameters. Results of these studies will probably provide a solution of the SB problem.

Active control of SB parameters has been studied for many years at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (ITAM SB RAS). These have been mainly unconventional methods based on mass addition in the form of expanding fan-type or axisymmetric air jets with various orientations with respect to the model and addition of thermal energy generated by combustion of a hydrogen-air mixture [16, 17], which demonstrated that such methods offer prospects for disturbed flow formation both near the aircraft and at large distances from it. Indirect confirmation of this fact is the results on drag reduction by adding thermal energy near the body; these results were described in detail in [18]. Tretyakov at all [19] obtained supersonic flow regimes with a powerful pulsed optical discharge induced by laser radiation in a supersonic flow of argon ahead of the body. A change in the flow structure with BSW dissipation and a significant decrease in the body drag with increasing pulse frequency were observed.

Methods of energy supply to a supersonic flow by means of laser and microwave radiation, electron guns, and electric arc discharge successfully applied for modeling flow control processes were also investigated. It is also of interest to study the SB control processes with the use of these active methods on the formation of the disturbed flow in the vicinity of the aircraft and its evolution at greater distances. The prospects of this approach are confirmed by publications [20 25].

At the same time, the effect of energy removal (flow cooling) on the formation of the disturbed flow near the aircraft for drag and SB reduction was also studied. This approach was investigated in much detail in the case of a cryogenic action on the flow by means of both cooling the aircraft surface [26] and distributed injection of a supercooled has from the aircraft surface [27].

In this work, the total field of the flow disturbed by the body was calculated by a combined experimental-calculation method [28, 29] based on measuring the disturbed static pressure profiles near the model mounted in the wind tunnel test section and subsequent recalculating these results to greater distances with the use of the quasi-linear theory [30].

1. Reduction of the SB level by a cryogenic action.

The experimental studies were performed in a T-313 supersonic wind tunnel based at ITAM SB RAS [31] in the regime with M_∞= 2.03, $Re_1 = 25 \cdot 10^6$ 1/m, and T_o=258-263 K. The experimental arrangement and the measurement techniques were described in detail in [26].

The model geometry was a modified power-law body of revolution ($\lambda = 6$, n = 0.75, and $\bar{r}_з = 0.2$) with a mid-section diameter d_{mid} = 50 mm, which was mounted on a cylinder. The choice of this geometry is based on the results of [32], where the effect of the body shape on the parameters of the SB generated by this body was studied. In that work, a class of power-law bodies modified by means of spherical bluntness of the nose part was determined; the effect of bluntness ensured a significant (by 50%) decrease in the BSW intensity in the middle zone, as compared with the initial body having the same aspect ratio with a relative bluntness radius $\bar{r}_з = 0$.

There are two copper-constantan thermocouples on the model surface; the hot junctions of these thermocouples are located at a distance of 5 mm (T_1) and 120 mm (T_2) from the model tip. The electrode wire diameter is 100 μm. The hot junction is mounted at the level of the external surface of the model and is insulated from the model by a layer (0.3÷0.4 mm) of the VS-9T high-temperature adhesive. The third thermocouple is mounted on the external surface of the model in the region of perforation through which the coolant was injected. The thermocouple signals are detected by an HP34970A multichannel integrating voltmeter, which provided temperature measurements within 1.5^{o}.

Figure 1 shows the flow structure around the chosen modified power-law body, the perforation zone through which the coolant was injected, and the supercooled gas layer formed in this case.

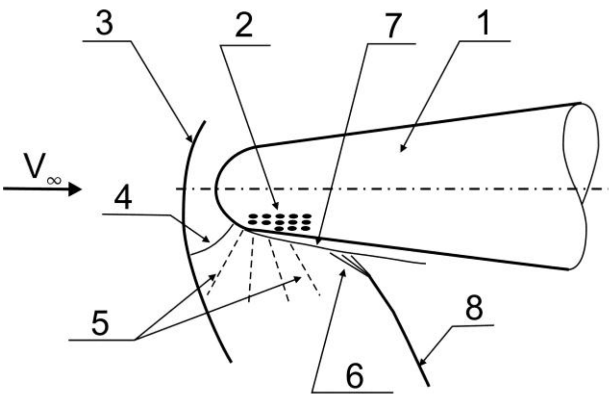


Fig. 1 Flow near the Modified Power-law Body with Coolant Injection into the Region Of Hanging SW formation:

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 length of the SB middle zone is determined by the distance where the BSW interacts with the intermediate SW formed further downstream, but propagating with a velocity greater than the BSW velocity. The intermediate SW is formed in the disturbed flow owing to the evolution of the hanging SW with increasing distance from the model. The intermediate SW formation results from interaction of the expanding flow around the spherical bluntness with the model surface. The intermediate SW intensity and its position on the disturbed pressure profile at a given flow Mach number M_∞ is determined by the geometric parameters: power index n, aspect ratio $\lambda = l/d_{mid}$, and relative bluntness radius $\bar{r}_з = 2r_з/d_{mid}$, where l and d_{mid} are the length and the maximum diameter of the body, respectively. Figure 2 shows the behavior of the asymptotic parameter of the BSW intensity as a function of the distance (height H) from the model, aspect ratio, and bluntness radius of the power-law body. Jumps of the asymptotic parameter of the SW intensity caused by BSW interaction with the intermediate SW occur at distances corresponding to the length of the middle zone of the SB. Here the SW intensity is calculated as $\Delta\bar{P}_{SW} = (P_{SW} - P_\infty)/P_\infty$, where P_{SW} and P_∞ are the static pressure ahead of and

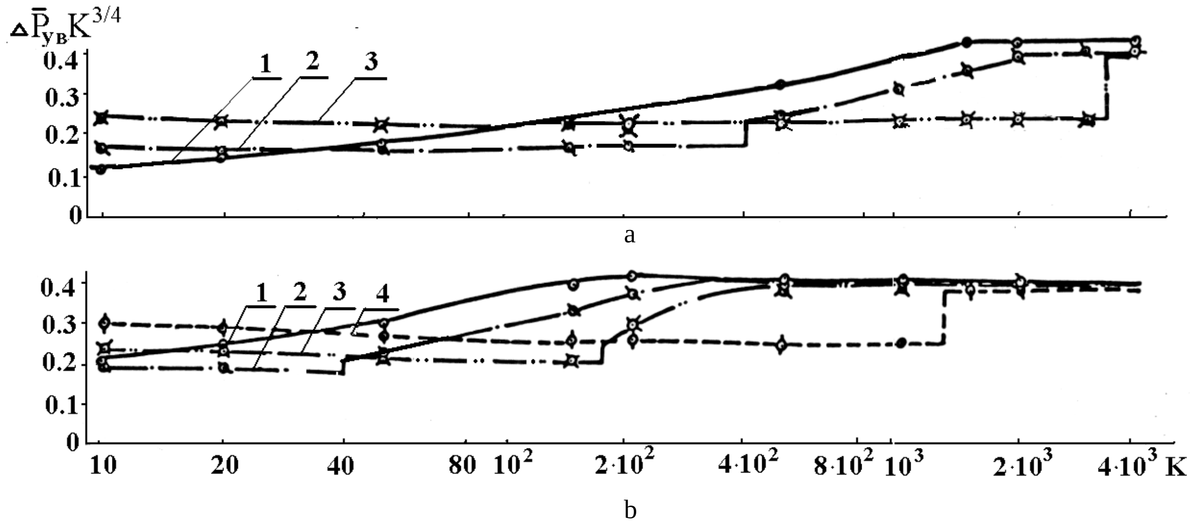


Fig. 2 Decay of the BSW Intensity with Distance from the Modified Power-law body versus the Aspect Ratio and Bluntness of the body At $M_\infty = 2.03$: (*a*) $\lambda = 4$, $\bar{r}_b$ = 0 (*1*), 0.1 (*2*), and 0.2 (*3*); (*b*) $\lambda = 6$, $\bar{r}_b$ =0 (*1*), 0.1 (*2*), 0.2 (*3*) and 0.3 (*4*).

behind the SW, respectively. $K = H / d_{mid}$ is the normalized distance from the body in calibers.

A typical feature of these bodies is a lower drag force at a given aspect ratio and power index of the body, depending on the bluntness radius, as compared to the initial power-law bodies $\bar{r}_з = 0$ with an identical aspect ratio, which are bodies proving the minimum drag force at moderate supersonic velocities [32]. Reduction of the drag and SB intensity confirms the prospects of using these bodies in practice. As the aspect ratio is increased, the efficiency of drag reduction becomes lower and almost vanishes at λ = 6. At the same time, the length of the SB middle zone increases with increasing aspect ratio and bluntness radius (Fig. 2). Thus, the requirements to the body geometry in terms of reduction of SB parameters and drag reduction are contradictory.

Correspondingly, to increase the length of the SB middle zone to distances corresponding to the cruising flight altitude (K = 6000 7000) with the minimum possible increase in the drag force, it is necessary to have a mechanism that would delay the instant of intermediate SW/BSW interaction. This can be ensured by shifting the region of intermediate SW formation in the downstream direction, by decreasing the intermediate SW intensity, or by preventing its formation altogether.

In [16, 33], injection of an air jet from the nose part of a slender body in the upstream direction with respect to a supersonic air flow made it possible to obtain flow regimes with M□ = 2 with both reduced drag of the body and reduced SB parameters. In this case, the middle zone length was limited by the formation of an intermediate SW on the disturbed pressure profile owing to interaction of the jet layer of injected air with the body surface. A similar pattern was observed in [34] in the case of injection of a low-temperature plasma jet upstream a supersonic flow.

The gas-dynamic relation on the oblique SW, which establishes the relationship between the SW intensity and the ratio of the static temperatures behind the SW and ahead of it, has the following form [35]:

$$\frac{T}{T_\infty} = (1+\Delta\bar{P})\frac{\gamma-1}{\gamma+1}\left(\frac{4\gamma}{(\gamma-1)(\gamma+1)\left(1+\Delta\bar{P}+\frac{\gamma-1}{\gamma+1}\right)}+1\right) \qquad (1)$$

The results calculated by this formula and plotted in Fig. 3 show that a decrease in temperature behind the SW leads to reduction of the SW intensity.

The temperature behind the intermediate SW can be reduced by organizing a coolant flow through the internal cavity of the model or by means of distributed injection of a supercooled gas from the body surface in the region of intermediate SW formation. In the first case, the decrease in the flow temperature behind the intermediate SW and, thus, in the velocity of sound determining the velocity of propagation of disturbances is provided by means of heat conduction in the thermal boundary layer. In the case of coolant injection into the flow, the heat conduction becomes more intense owing to forced temperatures on the oblique temperatures on the oblique convection.

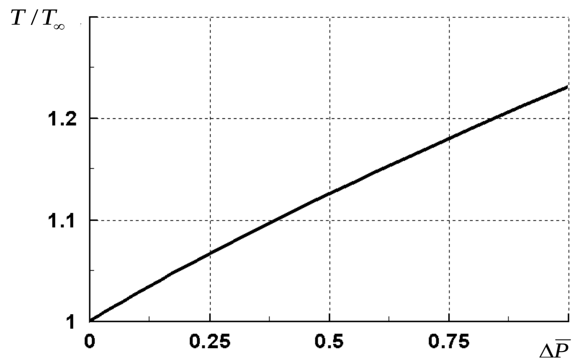


Fig. 3. Ratio of the Static Temperatures on the Oblique SW versus the SW Intensity.

The experimental arrangement is schematically shown in Fig. 4. The static pressure was measured by a plate with pressure taps 5; the measurement region was located at a distance of 185 mm from the model axis, which corresponds to 3.7 mid-section diameters of the model.

The root-mean-square error of recording of the pressures measured by TDM9-A-0.1 and KPY42-A pressure gauges in the interval of

$0 \div 0.1$ MPa did not exceed 60 Pa. The useful signal of the relative excess static pressure behind the reflected SW was determined under the assumption of linear interaction of the disturbed flow generated by the model with the background pressure distribution on the measurement plate (without the model). The pressure fluctuations on the measured profiles were smoothed by a special algorithm.

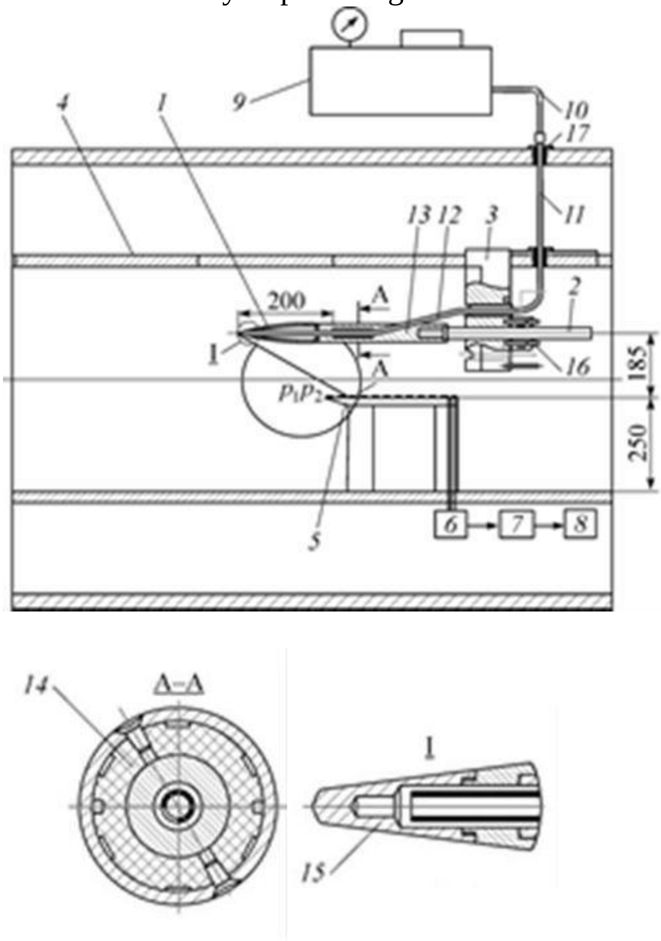


Fig. 4 Sketch of the Experiment:
1 – model, 2 – tail sting, 3 – bracket, 4 – wind-tunnel test section, 5 – perforated measurement plate, 6 – pressure sensor, 7 – registration system, 8 – PC, 9 – reservoir with liquid nitrogen, 10 – pipeline for liquid nitrogen feeding to the pressure chamber, 11 – pipeline d = 8 mm, 12 – pipeline d = 6 mm, 13 – intermediate sting, 14 – fluoroplastic insert, 15 – replaceable nose part, 16 – collet clamp, 17 – thermal insulator.

When experiments without coolant injection were performed, the model was cooled by organizing a coolant flow through its internal cavity. Liquid nitrogen used as a coolant was injected with an excess pressure from reservoir 9 through pipelines 11 and 12 into the cavity in the nose part of the model. From this cavity, the coolant passed over notches in the heat-insulating insert 14 to the bottom part of the model and then to the main flow. Before wind tunnel starting, the model placed in the test section was cooled with an operating injector, which provided coolant entrainment from the test section to the exhaust duct of the wind tunnel.

The measurement region of the measurement plate 346.5 mm long included 100 pressure taps 0.5 mm in diameter arranged with a step of 3.5 mm. The signals from the pressure gauges were detected by an automated data acquisition system and were fed to HP34970A 45-channel voltmeters 7, which ensured registration of 5.5 decimal digits with subsequent transfer of the digital information to a personal computer 8 for recording in the database and processing.

The pressure profiles were recalculated to large distances for the cases of a uniform atmosphere by the method [29] based on the quasi-linear theory [5]. The relations that describe the magnitude of the disturbed pressure on the characteristic and its position at an arbitrary distance from the initial profile have the following form in the second approximation with respect to the disturbance intensity:

$$\Delta\bar{p} = \Delta\bar{p}_0 \left(\frac{r_0}{r}\right)^{1/2},$$

$$x = \beta r - k_1 \Delta\bar{p} r_0^{1/2}\left(r^{1/2} - r_0^{1/2}\right) + k_2 \Delta\bar{p}^2 r_0 \ln\left(\frac{r}{r_0}\right) + x_0; \qquad (2)$$

where $\Delta\bar{p} = \dfrac{p - p_\infty}{p_\infty}$, $\beta = \sqrt{M_\infty^2 - 1}$, M_∞ is the Mach number, $k_1 = \dfrac{(\gamma+1)M_\infty^2}{\gamma\beta}$, $k_2 = \dfrac{(\gamma+1)^2 M_\infty^2}{2\gamma\beta^{1/2}}$, and γ is the ratio of specific heats.

Figure 5a shows the profiles of the relative excess static pressure behind the reflected BSW, which were measured near the model (K = 3.7). Figure 5b shows an enlarged fragment of the pressure distribution in the region of formation of the intermediate hanging SW.

There are no noticeable changes in the flow structure in the BSW vicinity (Fig. 5a). At the same time, in the region of formation of the intermediate hanging SW, the excess pressure on the cooled model is lower behind the SW and higher ahead of the SW than on the non-cooled model. As a result, the pressure difference on the intermediate SW near the cooled model surface is almost twice lower than the corresponding difference on the non-cooled model (Fig. 5b). The lower (as compared with the non-cooled model, Fig. 5a) level of pressure behind the intermediate SW persists in the downstream direction to the expansion wave, which leads to noticeable reduction of the momentum of the positive phase of the SB wave.

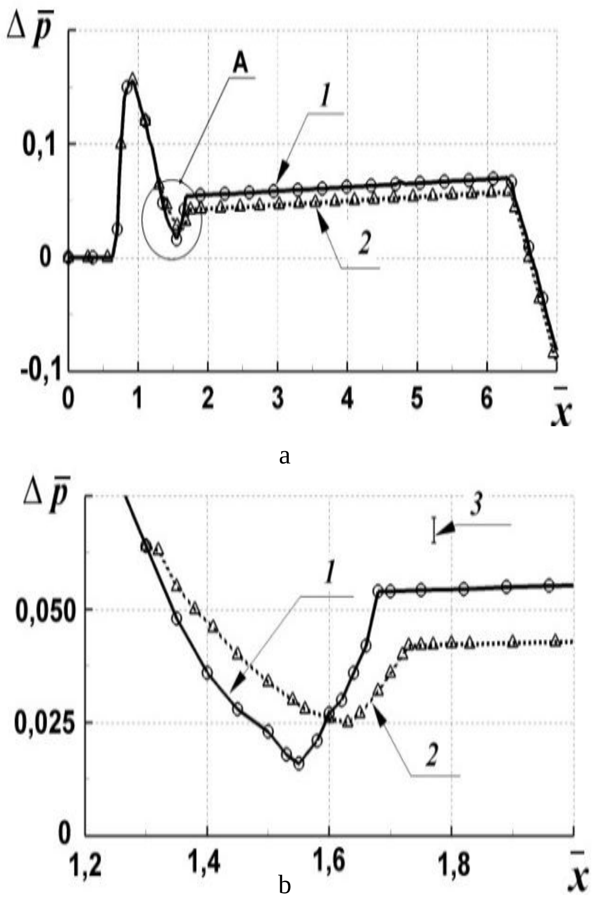


Fig. 5 Pressure profiles measured near the Model:
1 – non-cooled model, *2* – cooled model, 3- confidence interval of measurements.

Thus, the cryogenic action reduces the intermediate SW intensity and the momentum of the positive phase of the SB wave at an unchanged BSW intensity.

Figure 6 shows the typical temperatures of the model surface as functions of the current time of the experiment.

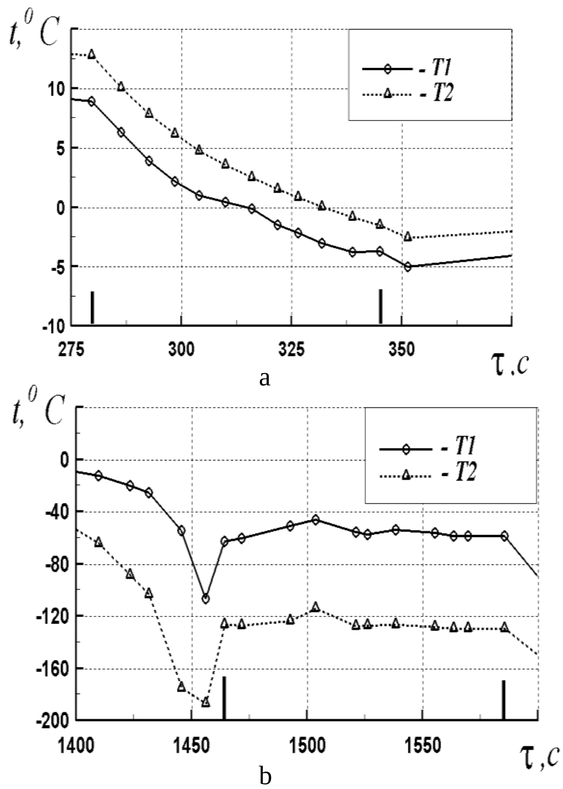


Fig. 6 Changes in temperature of the Model Surface; (*a*) non-cooled model; (*b*) cooled model.

The model surface is equipped with two thermocouples whose hot junctions are located at distances of 5 mm.

The model surface is equipped with two thermocouples whose hot junctions are located at distances of 5 mm (T1) and 120 mm (T2) from the model tip. The vertical bars on the abscissa axis show the beginning and end of the supersonic regime of wind tunnel operation. In one minute after the beginning of the test regime (Fig. 6a, T1), unsteady heat transfer on the non-cooled model surface leads to a continuous decrease in temperature, which reaches at the end of the test regime at the point where the thermocouple T1 is placed. On the cooled model surface (Fig. 6b, T2), steady heat exchange between the model and the incoming flow is rapidly established after the test regime of the wind tunnel is reached. The temperature in the region of hanging SW formation (Fig. 6b, T1) reaches the level, which is appreciably higher than the free-stream static temperature T_∞ = -130°C.

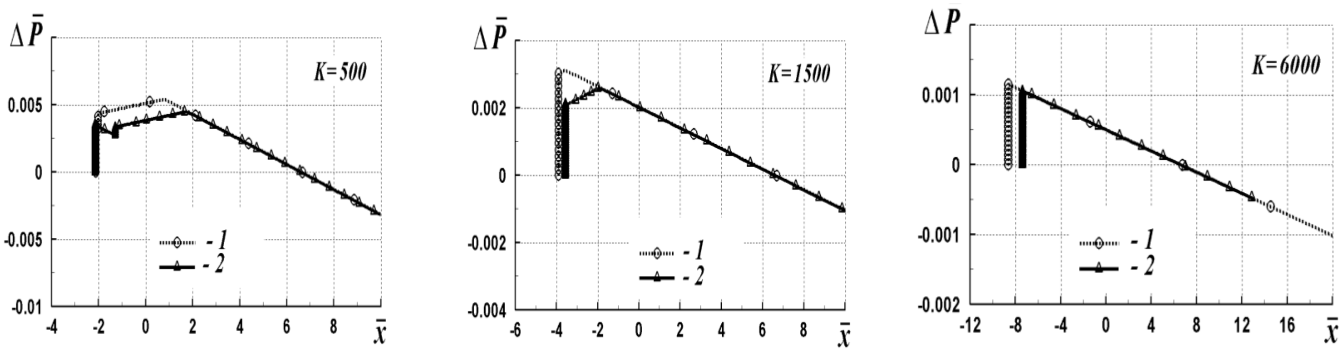
Thus, model cooling allowed us to reduce the model surface temperature in the region of hanging SW formation approximately by . Thus, the ratio of temperatures determining the hanging SW intensity changed from $T/T_\infty = 1{,}87$ to 1.52, i.e., by 18.5%. A comparison of the measured and calculated results shows that the decrease in the flow temperature agrees with the change in the intermediate SW intensity. These estimates give us grounds to believe that the decrease in the intermediate SW intensity is caused by the decrease in the velocity of propagation of disturbances in the region of their formation.

To reach the temperature ratio $T/T_\infty = 1$ preventing hanging SW formation under the test conditions used, it is necessary to reduce additionally the surface temperature by 61ºC, which can be ensured by increasing the coolant flow rate, reducing the model wall thickness, or replacing the model material by a more heat-conducting material.

Under natural conditions, the cruising flight of supersonic passenger planes occurs at altitudes of about 18000 m, at $T_\infty = 217\,\mathrm{K}$, which is greater than the static temperature of the flow under the experimental conditions by a factor of 1.52. For this reason, it is possible to reach the desired ratio of temperatures under natural conditions at a greater level of surface temperature reduction. Thus, it is necessary to model real temperature conditions to obtain reliable information on the influence of the velocity of propagation of disturbances on intermediate hanging SW formation.

Thus, the results obtained show that it is possible to control the process of formation of wave structures, such as a hanging SW, formed in an immediate vicinity of the surface inducing these shocks by means of surface cooling in the region of SW nucleation.

The evolution of the disturbed pressure profiles at large distances is shown in Fig. 7. At the distance K = 500 from the non-cooled model (Fig. 7a), the BSW is formed due to interaction of the intermediate SW with the SW from the blunted part of the model, resulting in enhancement of the intensity of the latter. The intermediate SW generated by the cooled model propagating with a lower velocity because of reduction of its intensity persists on the pressure profile. Its presence on the pressure profile is observed up to the distance K = 1400, which ensures BSW intensity reduction to 50%. The BSW at the distance K = 1500 from the cooled model (Fig. 7b) is formed due to interaction with the intermediate SW, resulting in enhancement of the intensity of the latter, but this intensity is still appreciably lower than the BSW intensity in the case with the non-cooled model. The process of its further decay under the action of a positive pressure gradient behind it is slower than the BSW decay in the case with the non-cooled model. As a result, the BSW intensity in the case with the cooled model at the distance K=6000 (Fig. 7c), which actually corresponds to the asymptotic decay law, remains approximately 12% lower than that in the case of the non-cooled model. The decrease



a b c

Fig. 7 Pressure profiles behind the Bow SW at different distances from the Model:
1 – non-cooled model, *2* – cooled model.

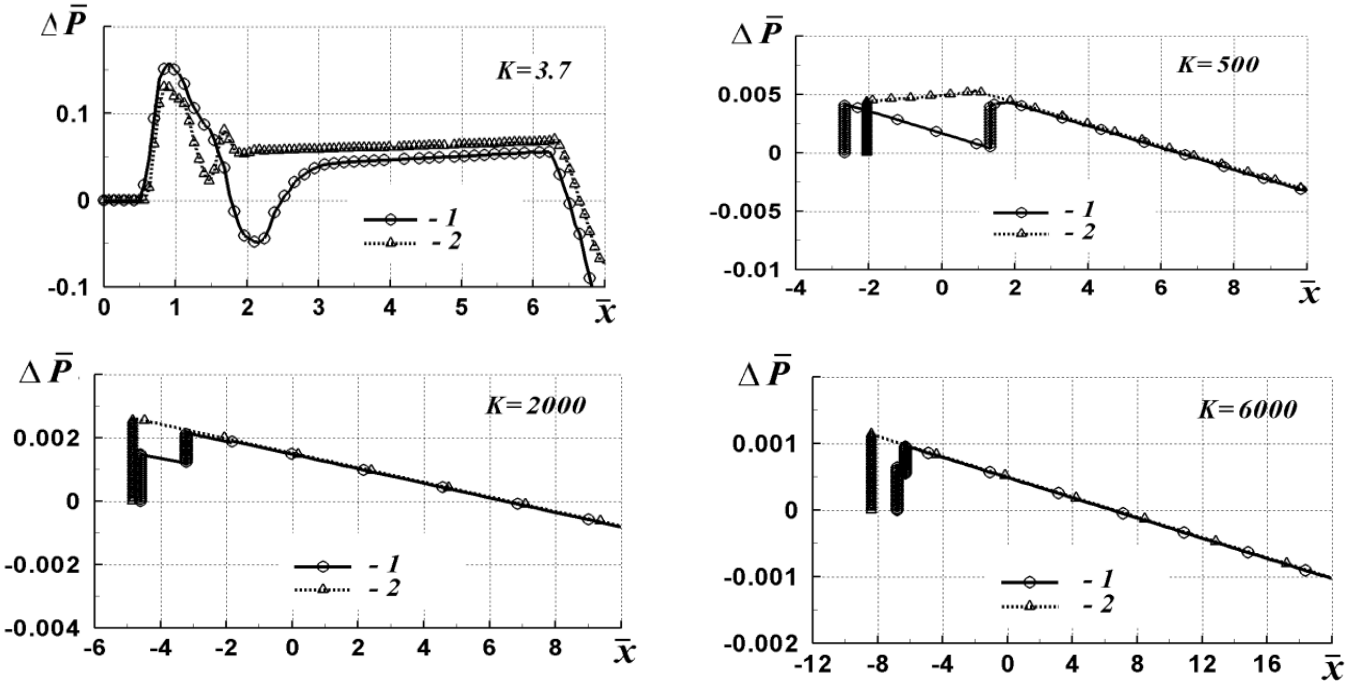


Fig. 8 Disturbed pressure profiles in the flow around the Model at different distances from the Model: (a) K =3.7; (b) K = 500; (c) K = 2000; (d) K = 6000; results of tests with and without coolant injection are indicated by 1 and 2, respectively.

in the flow temperature by 50 ^{o}C owing to coolant pumping through the model duct made it possible to decrease the hanging SW intensity approximately by a factor of 2, which ensured an increase in the middle zone length (region of minimization of the BSW intensity) up to 1400 calibers. However, this value is substantially, smaller than the distance corresponding to the altitude of the cruising flight of a supersonic aircraft (6000 - 7000 calibers).

Therefore, to reach the middle zone length of interest for practice, the possibility of active control of hanging SW parameters was studied [27]. The process of hanging SW formation was subjected to distributed injection of liquid nitrogen from the model surface to the region of hanging SW formation. This method allows the flow temperature in the hanging SW formation region and, hence, the velocity of propagation of disturbances to be substantially reduced owing to convective heat exchange between the injected coolant and the flow. The flow pattern around the model with coolant injection into the flow is shown in Fig. 1. To eliminate the waves from the injected coolant jets, the degree of perforation was decreased in the downstream direction from the region of hanging SW formation. Based on the results of studying various schemes of distributed injection with variations of the coolant flow rate, it was demonstrated that the efficiency of the cryogenic action on SB parameters and the drag force of the aircraft appreciably depends on the perforation scheme and on the coolant injection mode. As a result, the scheme of nitrogen injection from the model surface directly behind the spherical bluntness and the optimal regime of coolant injection were determined.

Figure 8 shows the measured disturbed pressure near the model with a promising scheme of injection and the evolution of disturbances after recalculation to large distances. Injection of liquid nitrogen into the region of hanging SW formation (Fig. 8a) near the model appreciably increases the length of the expansion region and the degree of flow overexpansion. This leads to a significant downstream shift of the compression wave, which is a precursor of formation of the intermediate hanging SW. A minor increase in the BSW intensity leads to a significant decrease in the momentum of the positive phase of the SB wave, which testifies to body drag reduction.

In the course of evolution of the pressure profile deformed by the cryogenic action, the downstream-shifted compression wave transforms to a pressure shock owing to nonlinear effects already at moderate distances

b

from the model (Fig. 8b); this pressure shock is located at a much greater distance from the BSW, as compared with the model. The BSW induced by the body bluntness is intensely attenuated by the expansion wave following the BSW until the BSW interacts with the hanging SW. The process of intense decay of the BSW generated by the model with coolant injection is observed up to large distances from the body (Fig. 8d). According to the recalculation results, the total length of the middle zone formed by this model can be increased up to values almost equal to 7000 calibers, and the SB intensity is reduced by more than 40% thereby.

Thus, it is possible to control the process of formation of wave structures of the hanging

This method allows the flow temperature in the hanging SW formation region and, hence, the velocity of propagation of disturbances to be substantially reduced owing to convective heat exchange between the injected coolant and the flow.

The main mechanisms of the action on SB parameters are (1) formation of an effective body by the supercooled gas (Fig. 1); the flow around this effective body induces an expansion wave shifting the region of hanging SW formation in the downstream direction and (2) reduction of the velocity of propagation of disturbances.

Conclusion

It is possible to control the process of formation of wave structures of the hanging SW type formed in an immediate vicinity of the surface inducing these structures by the following methods:

- cooling of the surface in the region of nucleation of these structures by means of heat conduction in the thermal boundary layer;
- cooling of the flow by coolant injection into the region of nucleation of these structure by means of forced convective heat transfer and formation of an expansion wave shifting the hanging SW in the downstream direction.

The intensities of the BSW and intermediate SW and their relative positions on the pressure profile in the middle zone, which were predicted numerically and recalculated from the experimental data, agree well, which confirms that the combined numerical method can be applied to study the SB parameters at the stage of SST design.

The results obtained by the comprehensive experimental and numerical method confirm the reliability of the SB middle zone length and tail SW parameters.

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