DOI: 10.13009/EUCASS2019-575

Investigation of laminar-turbulent transition of 2D supersonic boundary layer by scanning constant temperature hot-wire anemometer

Kocharin Vasilii, Kosinov Alexander, Yatskikh Alexey, Yermolaev Yuriy, and Semionov Nikolay*
** Khristianovich Institute of Theoretical and Applied Mechanics SB RAS*
Institutskaya str., 4/1, Novosibirsk, 630090, Russia, kocharin1208@gmail.com

Abstract
The work is devoted to the experimental study of the regularities of laminar-turbulent transition in supersonic boundary layers at Mach number $M = 2$ and 2.5 in the low-noise supersonic wind tunnel T-325 of ITAM SB RAS. The measurements were made by a constant-temperature hot-wire anemometer in the scanning mode. The procedure of decomposition of the fluctuations of the boundary layer into total temperature pulsations and mass flux disturbances was carried out. It was found that at the laminar-turbulent transition process the ratio of the mass flow and total temperature pulsations remains almost constant.

1. Introduction

The laminar-turbulent transition of supersonic boundary layer is one of the most important fundamental problem of fluid and gas mechanics. Experimental and numerical studies of turbulence in wall shear flows continue to be the subject of close attention of scientists from leading scientific centers of the world. To date, numerical methods for studying laminar-turbulent transition processes are actively developing. For the application of direct numerical simulation and model approaches, their careful verification is required. For a correct comparison of theoretical calculations and the results of experimental studies of the development of both natural and controlled disturbances, it is necessary to solve the problem of initial data. A detailed knowledge of the pulsation field of the boundary layer is required.
The most complete data can be obtained with a hot-wire anemometer. The hot-wire probe has the necessary high-frequency response and sufficient spatial resolution. It is known that the hot-wire anemometer is sensitive to pulsations of mass flow and the stagnation temperature [1-9]. The sensitivity to the variation of these values is different and depends on the relative temperature of the probe wire (temperature load). By changing the temperature load, it is possible to separate the pulsations and obtain data on the level of perturbations of each type. This approach to the study of high-speed flows has proved itself well in investigations of the field of free-stream pulsations in wind tunnel. With reference to experimental investigations of boundary layer pulsations, a similar measurement technique is also used, but these papers are mainly devoted to measurements in turbulent boundary layers [4-8]. To study the laminar-turbulent transition in high-speed boundary layers, studies of the development of pulsations of velocity, density, and temperature downstream in supersonic boundary layers are promising. Investigations of the influence of such parameters as the Mach number of the oncoming stream and the geometry of the model can provide a basis for the development of theoretical and computational methods for predicting the position of the laminar-turbulent transition.
This paper is devoted to the study of the growth of mass flux pulsations and disturbances of total temperature during the laminar-turbulent transition of a two-dimensional boundary layer with the Mach number of the oncoming flow $M_\infty = 2$ and 2.5.

2. Experimental setup

Experiments were performed in the T-325 long-duration blowdown low-noise supersonic wind tunnel, at the Khristianovich Institute of Theoretical and Applied Mechanics Siberian Branch of the Russian Academy of Sciences, at Mach number $M_\infty = 2$ and 2.5 at unit Reynolds number $Re_1 = 11.5\cdot10^6$ m^{-1}. The steel flat plate with sharp leading

DOI: 10.13009/EUCASS2019-575

edge was used as an experimental model. The width and length of the plate were respectively 200 and 440 mm. The experimental model was installed under zero angle of attack.
Flow pulsations were measured by constant temperature hot-wire anemometer (CTA) at scanning regime. In this hot-wire anemometer, the ratio of the resistances in the leg was 1:10, and the minimum scanning step for the probe resistance was 0.025 ohms. The hot-wire probe was made from tungsten wire diameter 10 microns. In Fig. 1 a response of the CTA to the test signal is shown. As can be seen the frequency response of the hot-wire anemometer is limited to 300 ÷ 400 kHz. The probe was moved with the help of traversing gears which the wind tunnel is equipped with. At each point 10 oscillograms of the pulsation signal of the CTA were measured at 10 different values of the temperature loading.

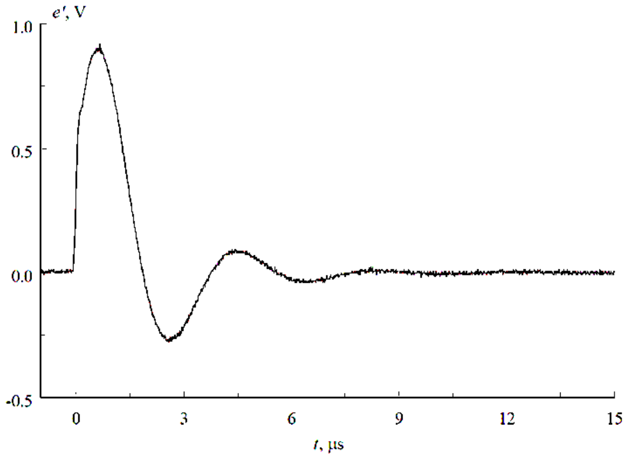

Figure 1: The response of the CTA to the test signal

In the experiments total and pulsating output signal of the hot-wire anemometer were synchronously recorded to the computer. The full signal was digitized using a 12-bit analog-to-digital converter with a sampling frequency of 46.875 kHz. The similar ADC with a sampling frequency of 750 kHz was used to record a pulsation signal. For each value of the wire temperature load, 4096 points of the total signal and 65536 points of the pulsating component were recorded. The measurements were carried out with 10 different values of overheat of the probe wire from 0.4 to 1.0. In Fig. 2a and 2b the oscillograms of total and pulsation signal at different overheat ratio measured in free flow of T-325 are shown.

a b

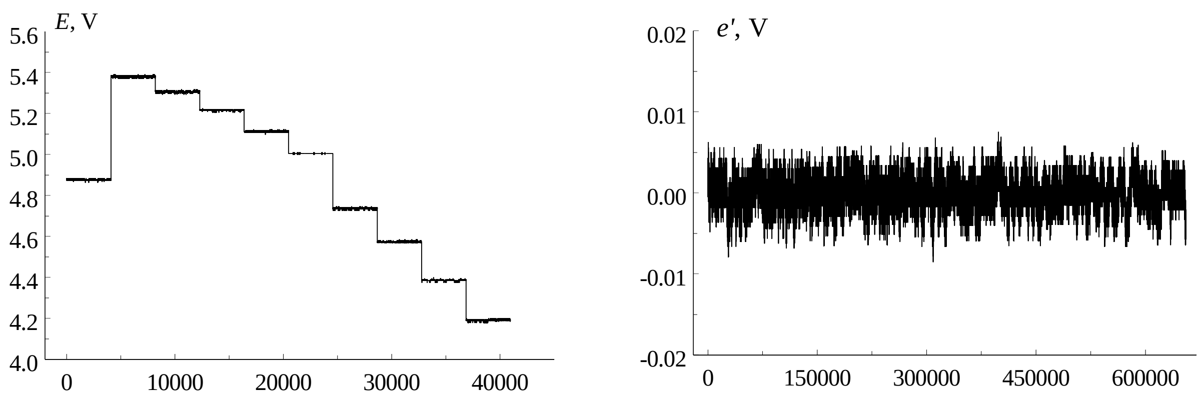

Figure 2: Examples of (a) total and (b) pulsation signals

The decomposition of the output signal of the hot-wire anemometer on the pulsation of the mass flux and the total temperature is provided according to the well-known algorithm [9]. The hot-wire probe is sensitive to pulsations of mass flow m' and total temperature T_0'. The normalized pulsating signal of the hot-wire anemometer can be represented in the following form:

DOI: 10.13009/EUCASS2019-575

$$\frac{e'}{E} = Q \cdot m' + G \cdot T_0' \quad \textbf{(1)}$$

where E is the mean voltage of the total signal of the CTA, Q – coefficient of sensitivity to pulsations of mass flow, and G – to the total temperature fluctuations. From the recorded data of total signal for each overheat ratio the mean voltage E of the output of the CTA is calculated. Assuming that the pulsations of total temperature and mass flow in the boundary layer are completely correlated, the RMS level of pulsations can be written in form:

$$\frac{<e'>}{E} = Q \cdot < m' > + G \cdot < T_0' > \quad \textbf{(2)}$$

Sensitivity to the total temperature pulsations depends on the wire temperature loading. Thus, by making measurements at several values of overheat of hot-wire probe, the pulsations can be separated.

3. Results

3.1 Calibration of the hot-wire anemometer

Calibrations of the hot-wire anemometer probe were carried out at two flow Mach numbers M_∞ = 2 and 2.5. The hot-wire anemometer probe was installed in a free stream of the test section of the T-325. The mass flux of the freestream was varied by the pressure variation in the chamber. For each value of mass flux, the mean voltage of the full signal of the hot-wire anemometer was measured at 10 different values of the probe wire temperature. During calibration, the total temperature changed by no more than 1.5%.
The results of the calibration of the hot-wire anemometer probe are shown in Fig. 3. In Fig. 3a shows results for the Mach number M_∞ = 2, in Fig. 3b results for M_∞ = 2.5.
From the results of the calibration of the constant-resistance hot-wire anemometer probe, it can be seen that the coefficients of sensitivity to perturbations of the mass flow and total temperature vary slightly from the value of the flow Mach number. The sensitivity to fluctuations of the mass flow practically independent on the value of the temperature load. In the same time, the sensitivity to total temperature pulsations varies significantly from the temperature load. Note, that at large values of temperature load ($\tau \approx 0.8$), the sensitivity of the hot-wire anemometer probe to temperature pulsations is small, and it can be considered that in this case the signal of the hot-wire anemometer is associated only with mass flow pulsations.

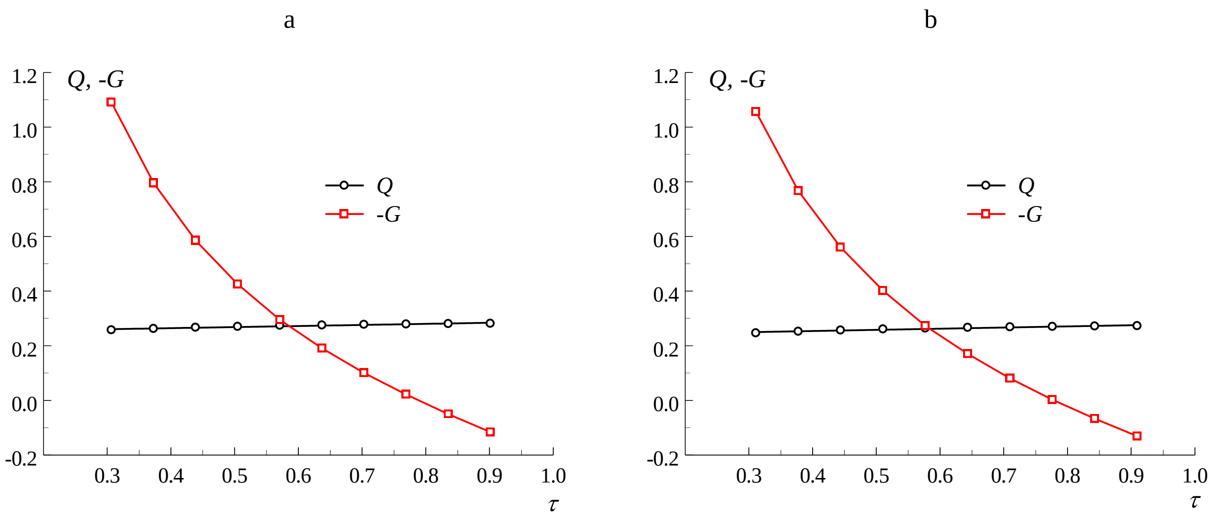

Figure 3: Sensitivity coefficients Q and G at Mach numbers M_∞ = 2 (a) and M_∞ = 2.5 (b)

DOI: 10.13009/EUCASS2019-575

3.2 The boundary layer of the flat plate at Mach 2 and 2.5

In experiments on a flat plate, we analyzed the development of natural pulsations downstream for both Mach numbers M_∞ = 2 and 2.5 with a unit Reynolds number $Re_1 \approx 11.4 \times 10^6$ m^{-1}. In this section, disturbances in the frequency range from 5 to 375 kHz are considered. The results of measurements of the boundary layer profiles along the normal to the surface coordinate (y-coordinate) and the growth of disturbances downstream (x-coordinate) are presented.

In Fig. 4 shows the obtained profiles of the mean voltage and the level of the pulsation signal of the hot-wire anemometer at the free-stream Mach number M_∞ = 2. At each position of the hot-wire probe relative to the plate, data were recorded at ten values of the temperature load of the hot-wire probe. In Fig. 4a shows the distribution of the mean voltage for different values of probe overheating, in Fig. 4b distribution of pulsation RMS levels. The experimental data obtained with the Mach number M_∞ = 2.5 are presented in Fig. 5.

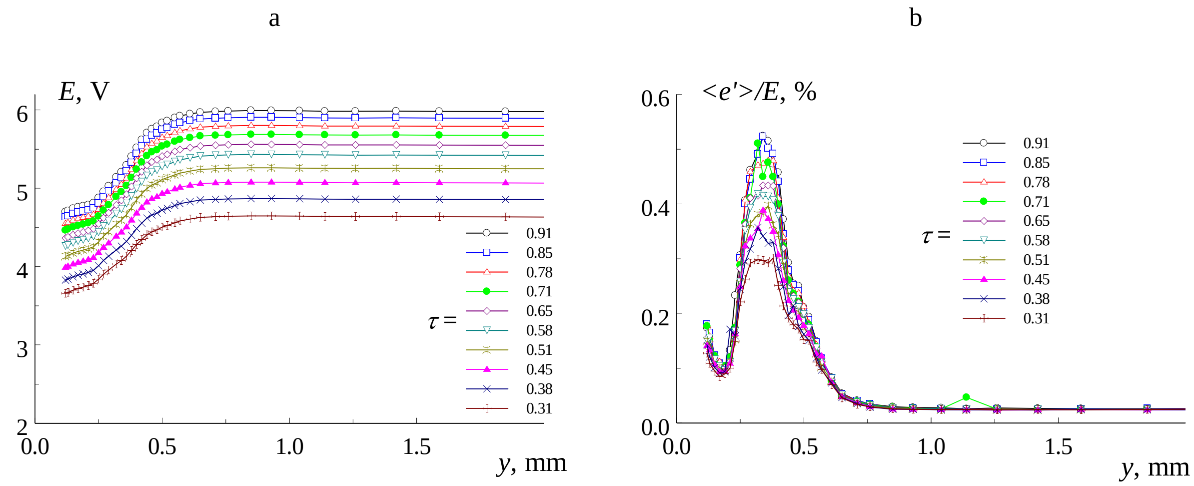

Figure 4: Profiles of mean voltage (a) and pulsating signal level (b) at various probe temperature load; x = 90 mm, M_∞ = 2, $Re_1 \approx 11.4\times10^6$ m^{-1}

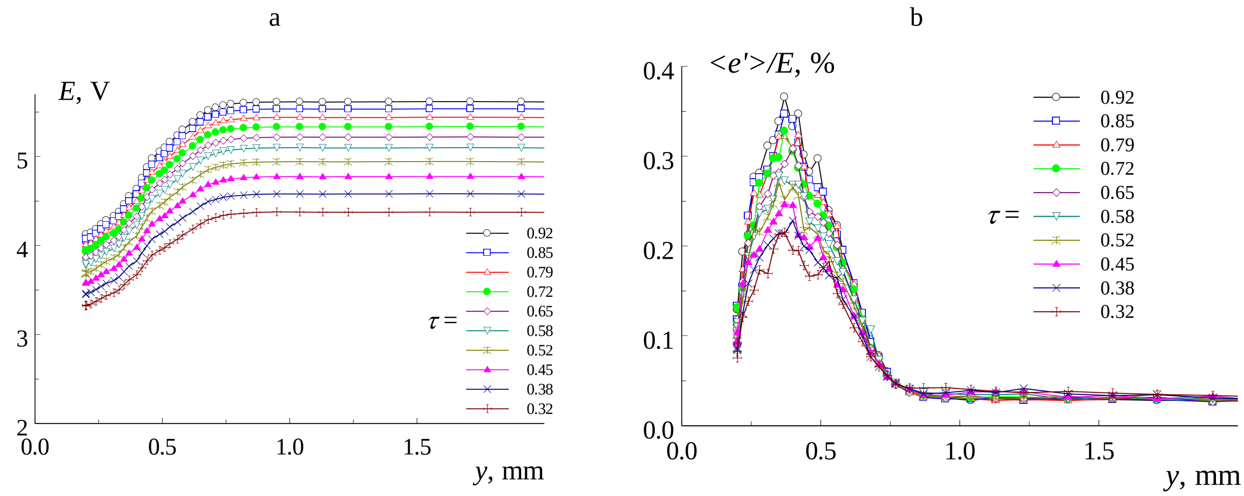

Figure 5: Profiles of mean voltage (a) and pulsating signal level (b) at various probe temperature load; x = 90 mm, M_∞ = 2.5, $Re_1 \approx 11.4\times10^6$ m^{-1}

At small values of the y coordinate normal to the model surface, a region with a constant value of the mean voltage is observed. In this area, a small level of pulsations is also observed. This behavior of the mean voltage and pulsations is explained by the fact that the hot-wire probe anemometer is located in the transonic region of the boundary layer. When the hot-wire anemometer probe is removed from the surface, a shear flow is observed with a significant gradient of mean voltage in the direction normal to the surface. At the same time, an increase in the level of

DOI: 10.13009/EUCASS2019-575

pulsations is observed. With a further increase in the y coordinate, the mean voltage ceases to depend on the normal coordinate, and the disturbance level decreases significantly, which indicates that the probe goes beyond the upper boundary of the boundary layer. The thickness of the boundary layer was 0.6 mm for Mach 2 and 0.75 mm for Mach 2.5.

The pulsation level of the hot-wire anemometer in the boundary layer differs for different values of probe temperature load, which is associated with a significant change in the sensitivity to disturbances of the total temperature. At the same time, the level of the pulsation signal of the hot-wire anemometer above the boundary layer is constant for all values of the probe overheat. This indicates the absence or small amplitude of perturbations of the total temperature of the flow outside the boundary layer.

Using the sensitivity coefficients determined during calibration and modified disturbance Kovasznay diagrams, the pulsations of the mass flow and the total temperature were determined. Because of the fact that measurements at different values of the temperature load cannot be made simultaneously, and the natural pulsations of the boundary layer have a random nature, it is possible to determine only the root-mean-square levels of pulsations of the mass flow rate $<m'>$ and the total temperature $<T_0'>$.

The results of the separation of temperature and mass flow pulsations are shown in Fig. 6. Note that the maximum amplitude of the pulsations in the profile x = 90 mm for Mach 2.5 is greater than the corresponding maximum for Mach 2, which is in accordance with the growth curve. Also, in Fig. 6 shows the ratio of the pulsations of the total temperature to the pulsations of the mass flow. For both Mach numbers inside the boundary layer, this relationship reaches the value of -0.15.

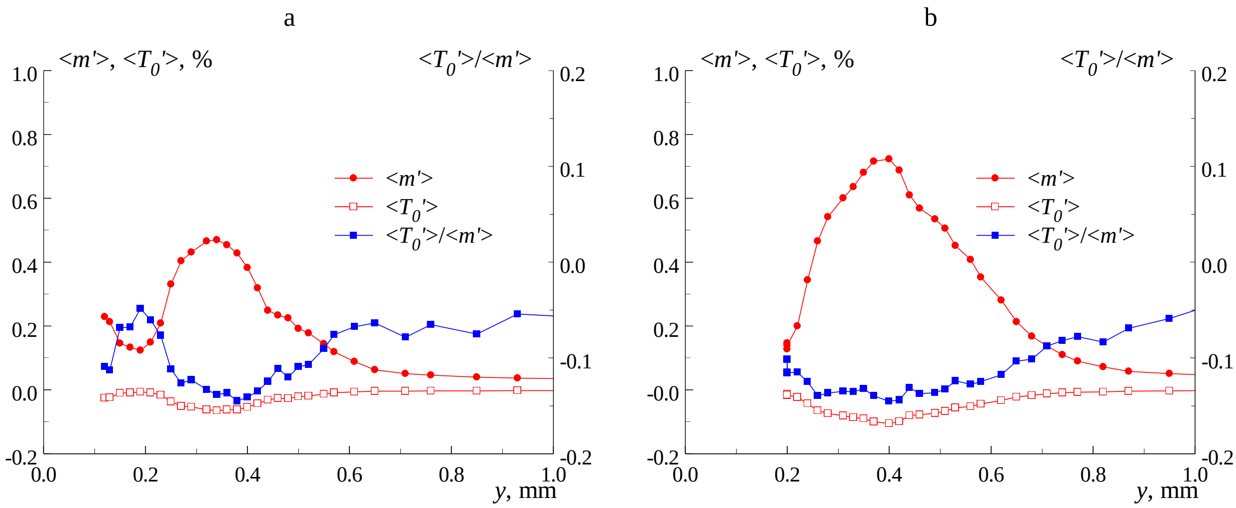

Figure 6: Profiles of Mass flow and total temperature pulsations at M_∞=2 (a) and M_∞=2.5(b), $Re_1 \approx 11.4\times10^6$ m^{-1}

The results of measurements of boundary layer disturbances growth downstream are presented in Fig. 7. The measurements were carried out in the supersonic part of the boundary layer in the region of the maximum level of disturbances. At the same time, the mean mass flow was constant ($\rho U_{loc}/\rho U_\infty \approx 0.7$).

The level of mass flow pulsations and total temperatures increase downstream. The transition to the turbulent flow regime in the boundary layer is accompanied by a decrease in the amplitude of the pulsations. It can be seen that in the case of a Mach number of 2.5, the laminar-turbulent transition occurs at a coordinate value of $x \approx 150$ mm, which corresponds to the Reynolds number $Re_x = Re_1 \cdot x = 1.71 \cdot 10^6$. With the Mach number $M_\infty = 2$, the turbulent regime could not be reached. Based on statistical and spectral analyzes, it was determined that the linear region of perturbation development is located up to $x \approx 130$ mm for Mach 2 and $x \approx 90$ mm for Mach 2.5.

The distributions along the longitudinal coordinate x of the ratio of the disturbance temperature perturbation levels to the mass flow disturbance levels are shown in Fig. 7b. It can be seen that this ratio remains constant at all stages of the laminar-turbulent transition of the supersonic boundary layer at Mach 2 and 2.5. This result can be useful in the formulation of studies of laminar-turbulent transition of boundary layers using direct numerical simulation.

DOI: 10.13009/EUCASS2019-575

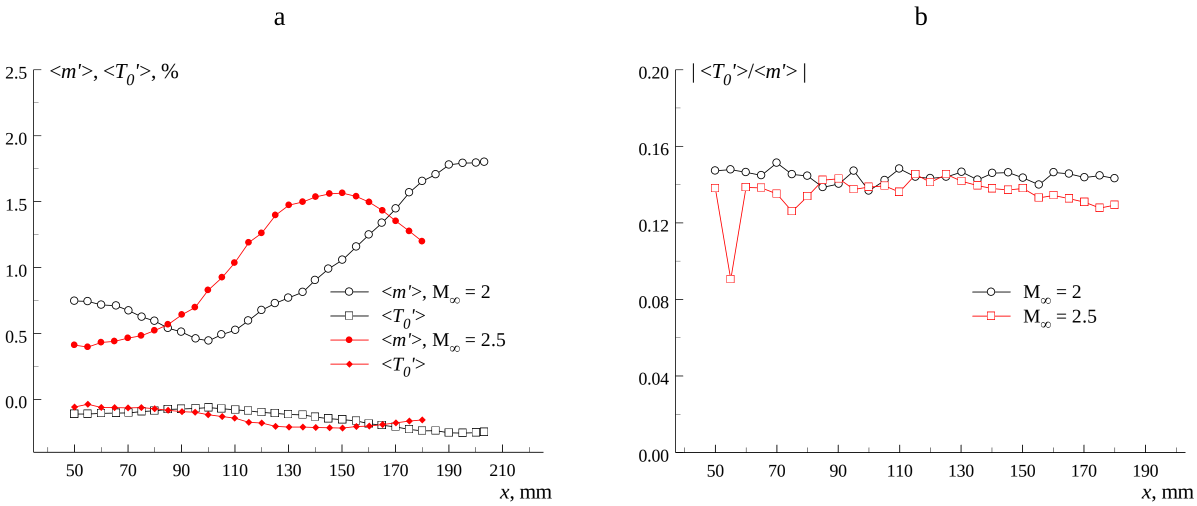

Figure 7: Development of boundary layer disturbances at Re_1 = 11.4×10^6 m^{-1} and Mach numbers M_∞ = 2 and M_∞ = 2.5

4. Conclusion

The procedure of calibration of the probe of the scanning hot-wire anemometer was carried out. According to the results of the calibration of the scanning hot-wire anemometer, it was shown that the sensitivity coefficients are practically similar for M_∞ = 2 and 2.5. It was found that the coefficient of sensitivity to mass flow pulsations is close to 0.25 for all values of hot-wire probe temperature load, while the coefficient of sensitivity to total temperature pulsations decreases with increasing of the probe overheat.

Also, the results of an experimental study of the laminar-turbulent transition in supersonic boundary layer of a flat plate at Mach numbers 2 and 2.5 were presented. The hot-wire measurements of the boundary layer pulsations were carried out in scanning regime. Using the sensitivity coefficients determined during calibration and modified disturbance Kovasznay diagrams, levels of pulsations of the mass flow and the total temperature were determined. It was obtained that in supersonic boundary layer the ratio of the disturbance temperature perturbation levels to the mass flow disturbance levels remains constant at all stages of the laminar-turbulent transition.

Acknowledgments

The work was financially supported by the Russian Science Foundation (Project No. 17-19-01289).
The study was conducted at the Joint Access Center «Mechanics» of ITAM SB RAS.

References

[1] Kovasznay L.S. 1950. The hot-wire anemometer in supersonic flow. *J. Aeronaut. Sci.* Vol. 17. No. 9. 565–584

[2] Lebiga V.A., Zinov'ev V.N., Pak A.Y. 2002. Using a hot- wire anemometer for measurement of characteristics of a random acoustic field in compressible flows. *Journal of applied mechanics and technical physics.* Vol. 43, No. 3. 488–492.

[3] Weiss J., Knauss H., Wagner S. 2003. Experimental determination of the free-stream disturbance field in a short-duration supersonic wind tunnel. *Experiments in fluids.* Vol. 35. No. 4. 291–302.

[4] Weiss J., Knauss H., Wagner S., Kosinov, A. D. 2001. Constant temperature hot-wire measurements in a short duration supersonic wind tunnel. *The Aeronautical Journal.* Vol. 105. No. 1050. 435–450.

[5] Kovasznay L.S. 1953. Turbulence in supersonic flow. *J. Aeronautical Sciences.* Vol. 20. No. 20. 657–674

[6] Kistler A.L. 1959. Fluctuation measurements in a supersonic turbulent boundary layer. *The Physics of Fluids.* Vol. 2. No. 3. 290–296.

[7] Smits A.J., Hayakava K., Muck K.C. 1983. Constant temperature hot-wire anemometer practice in supersonic flows. *Experiments in Fluids.* Vol. 1. No. 1. 83–92.

[8] Morkovin M.V. 1956. Fluctuations and hot-wire anemometry in compressible flows. *AGARD Rept* 24.

DOI: 10.13009/EUCASS2019-575

[9] Kosinov A.D., Semionov N.V., Yermolaev Yu.G. 1999. Disturbances in test section of T-325 supersonic wind tunnel. *Preprint Institute of Theoretical and Applied Mechanics*, No 6–99.
[10] Yermolaev Yu.G., Kosinov A.D., Semionov N.V., Tagaev S.N., Semisynov A.I. 2009. On the pulsation decomposition of supersonic flow for natural and controlled conditions of experiments. *Recent Advances in Fluid Mechanics and Aerodynamics, 7th IASME/WSEAS International Conference on Fluid Mechanics and Aerodynamics.* 89–93.
[11] Lenz B.2008. Experimental investigation of the spatial propagation of artificial disturbances in the separation region of a laminar boundary layer. *14th International Conference on Methods of Aerophysical Research: Proc. Novosibirsk.*
[12] J. Wu, P. Zamre, and R. Radespiel. 2015. *Exp. Fluids* 56: 20.
[13] H. Schlichting. 2017. Boundary-Layer Theory. *Springer.*
[14] S. A. Gaponov and A. A. Maslov. 1980. Development of Disturbances in Compressible Flows.