Gas dynamic process formation in reflected shock tunnels and its validation purposes by hypersonic aerodynamic shock tube example

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Abstract. The work for ensure the possibility of validation results for numerical simulation of gas-dynamic processes in a wide range with the use of modern techniques and certified measuring instruments are continued at the hypersonic aerodynamic shock tube facility. The method of precise experimental determination of the dynamic pressure at the critical section of the nozzle was tested. The results of calculations of the pressure field behind the section of the regular and elongated nozzles are validated. Measurements of the stagnation pressure before the nozzle were obtained experimentally.

1. Introduction
Experimental investigations in the Hypersonic Aerodynamic Shock Tube (HAST in IPMech RAS Research Resource Center) are continued for shock waves structure configuration study over high speed aircraft models [1−4] and validation of the results of numerical simulation of gas-dynamic processes [5, 6].

There are known works in which an acceptable coincidence of the calculated and experimental data of the pressures behind the nozzle section is obtained [7]. However, when calculating the nozzle functioning, it is necessary to know the values of pressures, velocity and other parameters before entering the nozzle (at the critical section). Taking into account the validation of the calculated flow fields near the models it is necessary to compare flow in quasi-stationary modes. In a short-acting impulse tube, which is HAST, quasi-stationary time is due to quasi-stationary processes in front of the nozzle. Quasi-stationary processes before entering the nozzle are considered.

Impulse shock tubes in which the ratios of the area of the critical section of the nozzle are less than the cross-sectional area of the shock tube are discusses. For example, in HAST, the diameter of the low pressure chamber is 80mm and the diameter of the critical section is 8mm. The ratio of the cross-section areas is 100. Such designs take place since the performance of the nozzle is determined by the degree of expansion, i.e. the ratio of the squares of the radius of the output and input sections of the nozzle. The larger it is, the better the flow parameters [7]. To obtain accurate parameters of the processes the method of direct measurements was used.

2. Scheme of experimental pressure measurement
For experiments, the shock part of the HAST facility [3] was used. Certified dynamic pressure sensors were placed in all tube tracts. For accurate and unambiguous setting of flow parameters, a
high-speed valve HSV80÷50 [8] with a response time of $2\times10^{-3}$ s was used. The leakage of the vacuum system was $10^{-4}$ mbar/s. Total view of HAST is shown in figure 1.

![Figure 1. HAST photo.](image)

The scheme of HAST shock part in the experiment is shown in figure 2.

![Figure 2. Scheme of the shock part of the HAST.](image)

Here are the blocks of high (Hb) and low (Lb) pressures, high-speed valve (HSV80 – 50), N–nozzle and PCB [9] certified dynamic pressure sensors (P1, P2, P3, P4). Here P1 sensor is located at the distance of 40 calibers from HSV 80 ÷ 50, sensors P3 and P2 – at distances of 0.01 and 0.02 m from the end of the shock part of the pipe, which includes the nozzle, respectively. These sensors are permanently mounted in the HAST. P4 sensor is temporarily installed in the critical diameter of the nozzle. Sensors P1, P2 and P3 are equal in modification and range and the certification transmission coefficients differ in the third sign. Typically, sensors located at some distance (for example, 100÷200 mm) from the critical minimum nozzle diameter (nozzle inlet).

Variant experiments were made with dynamic pressure sensor which was installed in shock part wall (figure 3a) or the dynamic pressure sensor was placed in the critical opening of the nozzle (figure 3b). Experiments were carried out at different distances between P3 and P4 sensors.
3. The results of the experiments

Result was obtained at this installation in shock part. These are the time periods of the incident and reflected waves, when the gas-dynamic parameters are constant, straight line - "shelves".

The value of the braking pressure (P4) of the reflected shock wave and the set of the pressure amplitude of the approaching contact surface coincides with the readings of the sensors P2, P3 under the standard modes of HAST. This will allow to conduct further experiments on the entire installation of HAST with the exception of a temporary sensor P4, to record the pressure before entering the nozzle by sensors P3 and even P2. The readings from the sensors were recorded using analog-to-digital converter with a frequency of 10 MHz on a computer with no rationing when the pressure in the high pressure chamber is 36 ATM, in the low pressure chamber is 500 mbar.

Time periods of reflected waves when the gas-dynamic parameters are constant on the sensors P2 - P4 are attended. They indicate a "plug" at a distance of 200 mm from the end of the shock tube (from the critical section of the nozzle). Curves 1, 2, 3 and 4 are in mV correspond to absolute readings of P1, P2, P3, P4 sensors, respectively. They can be seen in figure 4, where parameter in mV values are in left windows. The same graphs in figure 4 are reduced to one axis, for clarity the coincidence of indications is in figure 5.

The regions with constant pressure for some time are seen, the first is with an incident wave, the second is with a reflected shock wave. It can be seen that the cursor on the vertical line crossing all sensors (certified, single range) shows the same pressure in mV on the sensors P2, P3, P4. The pressure is the same in all directions: on the walls and on the end of the tube. If the P4 sensor is not present in the critical section of the nozzle, the brake pressure is determined when the readings of two certified sensors of the same range near the end of the pipe, for example, P2 and P3. These conclusions apply to impulse shock tubes in which the ratio of the critical area of the nozzle is significantly less than the cross-sectional area of the shock tube, for example, as in HAST.

At HAST facility comparison of sensor readings in the experiments showed that the flow stagnation pressure at the critical nozzle orifice can be taken from the sensor (sensors) constantly located in the pipe across the flow at distances of 0.01 (0.02) m from the nozzle entrance. At the same time, the period for which these readings are adequate is determined by the time of the straight line - "shelf" of reflected shock wave. The lower the speed of the shock wave and (or) the higher the pressure in the low pressure chamber, the longer the coincidence of the P2 and P3 sensors readings.

The time range $t = 3$ ms, as well as sensor readings at a distance of up to 0.02 m are guaranteed for the experimental installation of HAST. The method of direct measurement of the stagnation pressure reflects the structure of the gas flow and the configuration of the shock tube. Experimental and
calculated pressures at the inlet and outlet of the nozzles: standard, short and elongated; are presented in figure 6.

**Figure 4.** Curves: 1, 2, 3 and 4 in mV correspond to absolute readings of P1, P2, P3, P4 sensors.

**Figure 5.** Curves: 1, 2, 3 and 4 in mV are reduced to one axis.
Figure 6. Experimental and calculated dependencies at the inlet and outlet of the nozzles pressures (short and long).

These dependence pressures are almost linear, as it can be seen. When calculating the pressure behind the exit from the nozzle, the pressure measured in front of the nozzle is taken using a sensor located 100 mm away from the nozzle inlet (pressure “shelf”). These data are obtained for modes where the shock wave Mach number in front of the nozzle was \( M = 2 \). Conical short and elongated nozzles accelerate the air flow at the outlet to Mach \( M = 7 \text{÷} 8 \) [7].

The experimental measurement in the HAST of the flow velocity before the critical section of the nozzle required for the calculation of flows behind the nozzle is not difficult. The velocity of the flow in front of the nozzle was measured by the time of the shock wave between the sensors P2 and P3 and the stationary distance between them.

Graphs of the initial pressure in the high-pressure chamber and in the low-pressure chamber were obtained for predetermined pressure in front of the nozzle. They are shown in figure 7.

Thus, for the purposes of validation of numerical simulation of gas-dynamic processes behind the nozzle the "inverse problem" is experimentally solved. First, the pressure at the nozzle outlet is determined, then at the nozzle inlet corresponding to the pressure on the "shelf", then the modes of setting the high and low pressure chambers are determined, according to figure 7.

Conclusion
In the experiments the shock wave stagnation pressure was observed in the shock part in front of the nozzle, which is necessary for the calculations of gas dynamic processes in the nozzle. This is the coinciding pressure of the sensors readings in the stagnation straight line -"shelves". The method consists in combining the zeros of graphs of at least two dynamic pressure sensors close to the critical section of the nozzle and measuring the amplitude of the coinciding pressures.

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![Experimental dependencies at the long nozzle inlet pressure from high and low pressure camber initial pressures.](image)

**Figure 7.** Experimental dependencies at the long nozzle inlet pressure from high and low pressure camber initial pressures.

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