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Features of start-up processes of a vacuum supersonic tube

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Abstract. At present experimental gas-dynamic studies of supersonic flows mainly use complex experimental facilities, such as aerodynamic wind tunnels and shock tubes. However, in order to study supersonic flows with Mach numbers M < 4, a vacuum wind tunnel (which is much simpler) can also be used. This paper is concerned with starting processes occurring in a vacuum wind tunnel.

1. Introduction

Despite the active development of computational experiment and numerical methods for numerical simulation of aerodynamic flows, experimental verification of simulation results is an important stage in aerophysical modeling [1-2]. Nowadays, large complex experimental facilities, such as wind tunnels with receivers [3] and shock tubes [4], are used for such a simulation. In general, the use of these facilities allows one to cover the entire range of flow parameters for aerophysical research, but at the same time the use of such facilities is expensive and time consuming. To carry out aerophysical studies at relatively low Mach number of the flow, another class of setups can be used - aerodynamic vacuum tubes (vacuum wind tunnels). Such a setup is easy to operate, and at the same time all necessary research works can be carried out. The principle of operation of such an setup is simple — a vacuum is created in a large-capacity vacuum tank (the pressure is maintained at the level below 100 Pa), and the nozzle installed in the input part of the vacuum chamber opens to the atmosphere to start the airflow in the setup. At the exit of the nozzle, a supersonic jet is formed in which modeling can be carried out. To use such a setup, it is important to know the time parameters of its operation and the variations in the parameters and structure of the supersonic jet during operation. This paper is devoted to this study.

2. Experimental setup

In the Mozhaisky Military Space Academy a new ST-4 vacuum tube equipped with a set of interchangeable nozzles for the Mach number from 1.5 to 4 was built [5]. The parameters of the nozzles are given in Table 1. The length of the working part was 58 mm and the diameter of the output section was 40 mm for all nozzles.
Table 1. Parameters of supersonic nozzles used in the ST-4 vacuum wind tunnel

| Mach number M | Relative area of critical cross-section, $A_{exit}/A_{ref}$ | Diameter of critical cross-section, mm |
|---------------|----------------------------------------------------------|---------------------------------------|
| 1.5           | 1.17                                                     | 36.9                                  |
| 2             | 1.69                                                     | 30.8                                  |
| 2.5           | 2.63                                                     | 24.6                                  |
| 3             | 4.23                                                     | 19.4                                  |
| 3.5           | 6.78                                                     | 15.4                                  |
| 4             | 10.71                                                    | 12.2                                  |

To study the dynamic processes occurring in a supersonic jet during the operation of the setup, a special comb was made (see photo in Figure 1). Pressure sensors were connected to the every pin of this comb.

Figure 1. Photograph of the comb used to study pressure characteristics in a supersonic jet of the ST-4 wind tunnel.

Experimental schlieren pictures were taken at a 40 fps rate, and the time distributions of the pressure in the jet at different distances from the nozzle exit were obtained for each of the nozzle types listed in Table 1.

3. Experimental results

Let us consider the operation of the setup with nozzles for different Mach numbers. Figure 2 shows the schlieren pictures of the flow during jet evolution for a nozzle with Mach number $M = 2$, and figure 3 shows the readings obtained from pressure sensors attached to the comb.
Figure 2. Schlieren pictures of the supersonic flow emanating from a nozzle with Mach number $M = 2$ at different time moments: a) 0 s, b) 1 s, c) 2 s, d) 3 s

Figure 3. Readings of pressure sensors attached to the comb located at 40 mm from the nozzle exit.
It can be seen from Figures 2 and 3 that for quite a long time (a few seconds) there is a stationary flow in the region where the comb is located, that is, 40 mm from the nozzle exit. This time is long enough to carry out aerophysical studies with moderate Mach numbers. The picture remains the same for nozzles with higher Mach numbers. For example, figure 4 shows the readings obtained from the pressure sensors attached to the comb in the jet emanating from the nozzle with the Mach number $M = 3.5$.

![Figure 4. Readings of pressure sensors attached to the comb in the jet emanating from the nozzle with the Mach number $M = 3.5$. Pressure 1 is the pressure in the working chamber.](image)

It can be seen from figure 4 that the flow is stationary during a long time period, which is confirmed by schlieren pictures of the flow.

Thus, it can be concluded that if small-scale models are used for aerophysical modeling in the range of moderate Mach numbers ($M = 1.5 - 4$) of the flow, an experimental setup based on a supersonic atmospheric-vacuum tube can successfully replace more complex supersonic aerodynamic wind tunnels and shock tubes.

4. Conclusions
Studies aimed at exploring the possibility of using a ST-4 vacuum wind tunnel built in Mozhaisky Military Space Academy for the aerophysical experiment. Special attention was given to the start-up processes in the setup and temporal characteristics of the supersonic jet.

The experimental results confirmed the applicability of the ST-4 setup for carrying out experimental modeling for all designed Mach numbers (from 1.5 to 4). It is experimentally shown that there is a stationary flow regime in the supersonic jet emanating from a nozzle. The duration of this regime is long enough to perform an aerophysical experiment for all designed nozzles.

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