Effect of vacuuming on gas-dynamic parameters

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Abstract. The peculiarity of end-to-end temperature registration on models at the beginning of the experiment, then during high-speed pumping of the test unit into a vacuum and when a high-speed flow is applied to the model is experimentally revealed. The dependence of temperature registration on the vacuum depth and the independence of heat flow registration is shown.

1 Introduction

Computer modeling of aerothermodynamic parameters of high-speed aircraft [1–4] is associated with physical modeling on models. The necessary conditions for the implementation of validation of calculations were created at the laboratory installation "Hypersonic aerodynamic shock tube" (HAST) [5].

(a) (b)

Figure 1. The laboratory hypersonic aerodynamic shock tube (HAST) and a display view "0.1 mbar" in high-speed pumping station

The test tasks for the HAST behind the nozzle section are given in [6]. The flow outflow from hypersonic nozzles at Mach numbers M = 5–9 on the model is initiated by a shock wave within a wide range of experimental parameters. Setting the pressure in the high (HPC) and

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low (LPC) pressure chambers allows you to create a flow braking pressure at the nozzle inlet up in a wide range [7]. The arguments given below relate to the rapid vacuuming of a HAST test block by high-speed pumping stations to a high vacuum short-term. It is revealed the temperature on the models changes in the process from rapid vacuuming. The HAST and high-speed pumping stations are shown in figure 1.

The readings of the heat flow sensors located on the models change during vacuuming. In fast experiments involving vacuuming and starting the nozzle, it is necessary to take into account the temperature change during vacuuming.

2 Research techniques

In [8], the measurement of heat fluxes in high-speed flows was carried out using sensors on anisotropic thermoelements and thin-film resistance sensors and was calculated from the change in the temperature of the working surface in time.

There are known studies [9] in which, to determine the initial temperature, calorimetric heat flow sensors were first heated to 294–302 K. Then the heated model with sensors is inserted into the flow using a lateral movement device. This method of registering the initial temperature cannot be applied in HAST.

The gas-dynamic parameters measured in the flow by sensors located on the models behind the nozzle depend on the initial conditions in the vacuum unit. When the aerodynamic block is evacuated, for example, to 1 Pa, the temperature drops significantly. The test unit is pumped to a vacuum of 10^2–10^{-2} Pa by high-performance pumping stations. Then the flow flows out to the model with Mach numbers M = 5–9. Heat flow sensors of the thermocouple and calorimetric type are installed on the model “blunted edge” flush with its surface. Photos of the model with heat flow sensors on the blunted edge are shown in figure 2.

Figure 2. Photo models

The calorimetric heat flow sensor CT1 and the coaxial thermocouple certified MCT sensor are installed on the model in the same plane and at the same distance from the nozzle cut. The calorimetric sensor CT2 is at a distance of 20 mm from the sensor CT1.

A feature of the measurement of the heat flow in the flow in HAST is the limited time of the quasi-stationary initial flow outflow from the nozzle. These times are 0.5–7 mc for different HAST regimes.

Then the specific heat flow is determined by expression:

$$q = \rho \cdot c \cdot h \frac{\Delta T}{\Delta \tau},$$

where ρ, c, h—density, heat capacity and its thickness, respectively; ΔT—is the change in sensor temperature during the exposure time interval $\Delta\tau$. In this case, there $\Delta\tau$ should be less time for quasi-stationary: $\Delta\tau \leq t_{gf}$, the parameter $\rho \cdot c \cdot h$ is a constant-valued quantity that characterizes properties of the heat flow sensor.

The temperature was recorded as follows. At first, before vacuuming, the zero signal was driven in accordance with the room temperature by applying a transfer coefficient. So, for the MST sensor, it is equal to 60 μV/K. When the sensor signal passes through an amplifier with a coefficient of $K_{amp} = 100$ and a low-pass filter, the transfer coefficient in the experiments became $K_{mst} = 6$ mV/K.

The sensors registered: first, the room temperature, the temperature after 2–3 minutes of switching on the pre-vacuum pump, then turning on the turbomolecular pump of the pumping station, then during the operation of the pumping station, after it is turned off and when the flow affects the model.

3 Results and discussion

It was experimentally revealed that vacuuming an aerodynamic block with a volume of 800 liters (4 meters long, 0.5 m in diameter) to a high vacuum takes 20–40 minutes. Procedures for switching off vacuum pumps, monitoring the pressures in the HPC and LPC, pressing the "Start" buttons of the computer and the high-speed valve [10], were taken 5–7 minutes.

The short time of through-vacuuming and starting the nozzle led to the following features of the temperature sensors readings by installed in the model in front of the nozzle. In the first 3–5 minutes of vacuuming, the readings of the certified MCT sensor and the sensors of laboratory manufacture CT1 and CT2-in all modes increase, and then decrease until the end of vacuuming from 10^5 Pa to 1 Pa (figure 3).

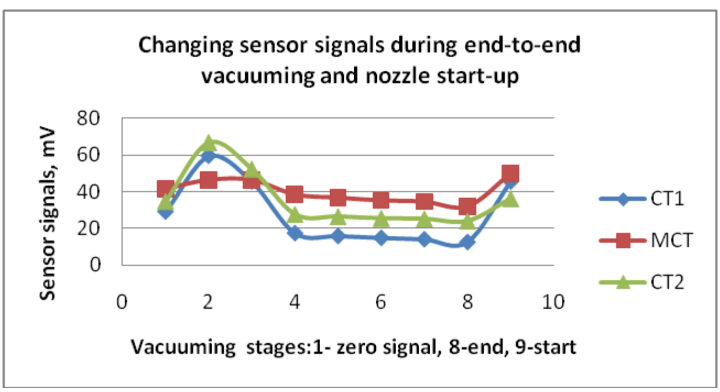

Figure 3. Graphs of the MCT, CT1 and CT2 sensors during end-to-end vacuuming of the HAST and starting the nozzle

The first sensor readings in mV correspond to room temperature. At the beginning of rapid vacuuming from 10^5 Pa, when the free path of gas particles is small, an air flow sweeps over the surface of the model. In this flow, the gas molecules collide, the temperature rises. In the future, when the turbomolecular pump is turned on after the action of the forevacuum pump, the pumping goes faster, the free path of the molecules increases, the density, temperature and pressure drop. At the same time, the temperature is lower at a higher vacuum. Then the vacuum pumps are stopped and after 3–5 minutes the discharge from the nozzle is carried out. The temperature measured by the sensors is rising.

 https://doi.org/10.1051/matecconf/202236201025

For the fast processes described above, the heat exchange of the gas cooled by vacuuming inside the aerodynamic block with the external environment through the receiver wall does not have time to happen in one experiment. When the HAST test block is standing under vacuum for a long time, the temperature on the sensors is equalized relative to room temperature. The temperature before starting the nozzle is not equal to room temperature; it must be recalculated to the temperature corresponding to the degree of vacuum. Temperature measurements during vacuuming showed that first it is necessary to correlate the room temperature and the sensor readings before the experiment. Then recalculate it at the end of vacuuming and compare it with the temperature when it flows out of the nozzle.

The data on the thermal response of a certified MCT sensor in different starts and under different initial conditions are shown in figure 4.

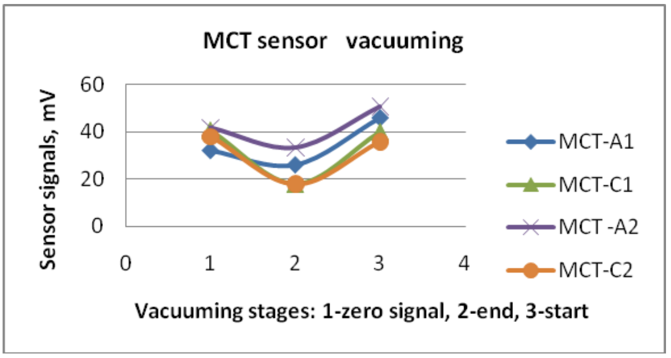

Figure 4. The MCT vacuuming graph for various initial conditions

The temperatures in the test mode $P_{test} = 1$ Pa are close (figure 4, point 1, MCT-C). When the test mode is $P_{test} = 10^2$ Pa, the temperature is higher (figure 4, point 1, MCT-A).

The heat flows measured by a certified MCT sensor at $P_{HPC} = 36 \cdot 10^5$ Pa, test regimes in the LPC and test block are shown in figure 5.

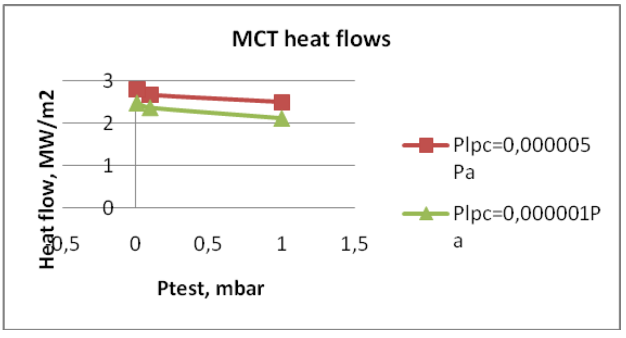

Figure 5. Heat flow to the MCT sensors

The advantage of a more accurate determination of the heating temperature of the model in a high-speed gas flow, taking into account the vacuuming in figure 4 will show. Heat flow is measured traditionally by temperature increment between stage 2 and stage 3 and a known transmission coefficient. The determination of the temperature of the surface heated by the flow in a high vacuum environment has changed.

Previously, there was no graph part from stage 1 to stage 2. Two sensor signals were measured before (stage 2) and after (stage 3) starting the nozzle. At the same time, the signal at point 2 was adjusted to the room temperature, for example, 293 K. Then, at $k = 6$ mV/K, when starting the nozzle, the temperature for MCT-A2 ($P_{test} = 10^2$ Pa) and MCT-C2 ($P_{test} = 1$ Pa) increased by 3 K and 3.3 K, respectively, and was determined as 296 K and 296.3 K, respectively. But linking stage 2 to room temperature to determine the nominal temperature is incorrect in fast processes and deep vacuuming of the model location environment.

Now the signal in stage 1 (before vacuuming) is adjusted according to room temperature, then the temperature is calculated before (stage 2) and after (stage 3) starting the nozzle. For example, at $k = 6$ mV/K after vacuuming for MCT-A2 ($P_{test} = 10^2$ Pa) and MCT-C2 ($P_{test} = 1$ Pa), the temperature decreased in stage 2 by 2 K and 2.83 K, respectively. Temperature increase when starting the nozzle between stage 2 and stage 3 increased by 3 K and 3.3 K, respectively. However, in stage 3, the measured nominal temperatures were 294 K and 293.47 K, respectively.

If vacuuming and starting the nozzle is not fast, it takes a lot of time, during which heat exchange with the external environment occurs, the difference in the sensor readings in stage 2 and stage 1 figure 4 is leveled. This is also typical for low vacuum or without vacuuming of the model placement environment.

For fast experiments with high vacuum, the effect of the difference in sensor readings in stage 2 and stage 1 figure 4 is to 3 K.

The error of measuring the MCT temperature in different phases from the sensor nozzle was up to 1.2 percent.

The physical causes of temperature changes during vacuuming are as follows. At the beginning of rapid vacuuming from 1 atm, when the free path of the gas particles is small, an air stream sweeps over the surface of the model. In this flow, the gas molecules collide, the temperature rises. In the future, when the turbomolecular pump turns on after the action of the forevacuum pump, pumping goes faster, the free path of molecules increases, density, temperature and pressure drop. At the same time, the temperature is lower at a higher vacuum. Then the vacuum pumps stop and the nozzle is start after 3–5 minutes. The temperature measured by the sensors is rising.

For the fast processes described above, the heat exchange of the gas cooled by vacuuming inside the aerodynamic block with the external environment through the receiver wall does not have time to happen in one experiment.

4 Conclusion

During the experiments, a temperature change was detected by quickly checking the temperature on the models at the beginning, at the end of vacuuming before exposure to a high-flow model, and then directly into the flow. At the same time, the temperature on the model after vacuuming was not equal to room temperature, which corresponds to zero signals.

The presented study was supported by Government program of basic research of Russian academy of science (contract # AAAAA 20-120011690135-5).

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