Experimental study of the control agent flow parameters in the channel, simulating the ramjet air flow duct

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Abstract. This article presents the results of the experimental study of heat transfer when the supersonic air flow interact with the surface of the ramjet model air flow duct in the range of Mach numbers $M = 5 - 7$. Experimentally obtained temperature distribution along air flow duct of a ramjet shown. The temperature along the axisymmetric model of the air flow duct was measured using the designed hot probe. Distribution of the Mach number along the symmetry axis of the model air flow duct is obtained numerically. A comparison of the numerical and experimentally obtained values of the Mach number showed their satisfactory agreement.

1. Introduction

Nowadays, in the practice of rocket production, work on the development of aircraft-shaped missile with hypersonic flight speeds is intensively developed [1 – 3]. One of the most perspective directions of solving the problem of increasing flight speed of the aircraft in the atmosphere is usage of ramjet engines on solid fuel [2, 3]. In open circuit ramjet engines [3], the combustion of a solid-fuel occurs in a high-speed gas flow. The structure and thermogasdynamic parameters of the streaming flow affect the combustion regularities of fuel. Due to the burning of the fuel cell, the geometric characteristics of air flow duct change. Changes in the geometric characteristics of air flow duct, the structure and parameters of streaming flow are interrelated processes. Interaction between these processes must be taken into account in the designing of a specific open circuit ramjet engines. In this regard, the development of calculating methods for the intraballistic characteristics of ramjet engines (thrust, specific impulse, propellant burning velocity, intrachamber pressure, etc.) is one of the main steps in predicting the structure and parameters of the gas flow in air flow duct of the engine. Due to change over time of the air flow duct geometric characteristics during engine operation under trans– and supersonic gas flow velocities, mathematical models under development require verification by comparison with experimental data. Since testing full-scale engines associated with large material costs, it is advisable to carry out preliminary studies on model installations to obtain objective experimental information.

2. A technique of conducting experimental studies

This paper presents the results of an experimental study of the distribution of temperature and specific heat flux along the surface of a model air flow jet engine duct in the range of Mach numbers $M = 5 - 7$.

An experimental study was conducted on a pulsed wind tunnel [4 – 6]. To create a supersonic flow in the range of Mach numbers $M = 5 - 7$, steel axisymmetric profiled nozzles were used in an air
injection system of wind tunnel [5]. In the tests, the pressure and temperature of the flow in chamber and in the airflow duct of the model ramjet were recorded.

One of the calorimetric methods for measuring the temperature and heat flux was used to measure the gas temperature in the air duct of the model. These methods are well studied and widely used [7 – 9]. To measure the temperature along the wall of the air duct of a model ramjet, a hot probe was designed and manufactured. The type of model ramjet with the installed hot probe is schematically shown in Figure 1.

Figure 1. Model ramjet: photograph (a); scheme of installation of hot probe into the model (b); scheme of hot probe (c).

The hot probe (see Fig. 1c) is a set of fluoroplastic and copper rings. Chromel – copel thermocouples are installed on the outer surface of each copper ring.

In the conducted studies, several temperature sensors were used [8, 9]. They had a difference in geometric shape and mass. Diameter of the tablet 3·10⁻³ m, thickness of one’s 3·10⁻⁴ m. To fabricate temperature sensors in the form of a ring and a tablet, the requirement to deviate mass characteristics was no more than 2·10⁻⁶ kg and 1·10⁻⁷ kg, respectively. Various thermocouples were used to measure thermoelectric voltage. The diameter of the thermocouple wire was varied (0.1 ÷ 0.3)·10⁻³ m, various materials were used: chromel – alumel, chromel – copel, copper – constantan [10]. The characteristics of the temperature sensors used above have affected, first, their response time.

In the range M = 5 – 7, for each value of the Mach number, a series of 8 thermogasdynamical tests were carried out. The temperature values along the surface of the airflow duct in eight sections were recorded. The operating time of the wind tunnel was t = 4 c.

Figure 2 shows the results of a series of experiments using two different hot probe with the same geometric and thermal characteristics, but equipped with different sensors: in the form of a ring with a chromel – copel thermocouple and a tablet type with a copper – constantan thermocouple. A thermocouple diameter was 0.3 mm. The distribution of temperature values was recorded on the surface of the airflow duct with air flow around it at a speed M = 5.

At the same time, the difference in temperature values recorded by two types of sensors at the corresponding geometric points was no more than 10 %. According to the results of conducted research, it is advantageous to use a thermal probe with a ring-type temperature sensor (Fig. 1c). The use of such a sensor has several advantages: it has a wall thickness of 10⁻³ m, therefore, it can be used for quite a long time in experiments when recording temperature values as a result of exposure to high-temperature heat fluxes; reliable fixation when installed in a thermal probe provides a stable resistance to the gas-dynamic loads of the incident air flow; reception of the signal increases noise immunity even when interacting with an oblique shock wave sensor. These advantages make it possible to use such hot probe in experiments with real fuels.
3. Analysis of the results of the experimental studies

The distribution of heat flux values over time in each cross section of the thermal probe was determined numerically by integrating the non-stationary heat-transfer equation [7 – 9] over the entire volume of the copper ring:

\[ q_i(t_i) = \frac{m \cdot C_p}{S_i} \cdot \frac{(T_i - T_0)}{t_i}, \]

where \( q \) the heat transfer rate \([W/m^2]\); \( t \) time \([s]\); \( m \) the mass \([kg]\); \( C_p \) the specific value of the heat capacity at constant pressure \([J/(kg\cdot K)]\); \( S \) the area of the inner surface of the ring \([m^2]\); \( T \) temperature \([K]\); \( i \) the current index of registration of values, with a known frequency in time.

Conditions for conducting one of the series of experiments: \( M = 5 \), heater inlet temperature for preignition chamber of wind tunnel 700 K, running time of wind tunnel 4 s. Figure 3a shows the experimental averaged maximum temperature values along the wall of the airflow duct (averaged over a series of 8 experiments), calculated and experimental value of the Mach number on the axis of symmetry, where \( x \) is the distance from the initial section of the model along the airflow duct to the current section of the working junction thermocouples. Fig. 3, b presents the values of the heat flow rate obtained using formula (1).

Figure 3. Values of the recorded temperature (●), Mach number (■), calculated distribution of the Mach number along the axis of symmetry (---) (a) and the distribution of heat flux over time (b).
Experimental and theoretical studies of gas dynamics, heat transfer, and gas flow patterns in an airflow duct of a ramjet engine in the range of Mach numbers $M = 5–7$ with developed technical means of measurement showed the adequacy of the results on the physics of the process under study. A comparative analysis of the calculated (---) and experimental data (■) presented in Figure 3a showed that the difference in the Mach number on the axis of symmetry in the profiled airflow duct does not exceed 9% under the considered flow conditions.

Conclusions
Experimental data obtained in this work for an inert model with a supersonic airflow duct are new and obtained on the newest specially developed unique experimental installation, which allows the study of the gas flow structure and heat transfer in an airflow duct of air-jet engine in the range of Mach numbers $M = (5 ÷ 7)$. Technical equipment with high spatial-temporal resolution was developed and used.

The obtained results of measurements of the temperature of the airflow channel surface and its distribution along the length are adequate physical representations of the process under study; they demonstrate satisfactory agreement with theoretical calculations.

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