GROUND FACILITY TESTS OF HIGH SPEED RAMJET DEMONSTRATORS

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Abstract

The article deals with the problematic issues of providing complex ground tests of high-speed ramjet engines demonstrators. Approbated schemes of experimental installations for investigation of combustion in subsonic and supersonic flows are presented. Schemes allows most adequately estimate the coefficient of fuel combustion efficiency in the connected-pipe tests of model combustion chambers. For the purpose of more correct interpretation of the obtained experimental data during altitude tests of high-speed ramjet demonstrators in free jet, both object and test cell diagnostics of the flow interacting with the test object are considered. Some results of complex tests of the high-speed ramjet demonstrator are presented.

1 Introduction

Any program for the development of flying vehicle (FV) and engines necessarily completed by flight tests. However, flight tests should be preceded by a stage of complex ground tests:
- model elements and assemblies of demonstrators of FV and air-breathing engines (ABE) separately on the scheme of the connected-pipe (CP) or on the scheme with airflow (free jet, semi-free jet);
- materials separately and materials in composed of demonstrators;
- fuels;
- models and element modules of combustion chamber (CC) demonstrator on CP scheme;
- integrated large-scaled and full-size models, demonstrators and prototypes on the scheme with airflow.

This stage of ground tests of demonstrators is necessary for:
- quick and relatively cheap verification and adjustment of technical decisions;
- obtain the best possible experimental information;
- accumulation of the summary experimental samples development, evaluation of their service life and reliability;
- after experimental diagnostics of objects;
- validation of mathematical models (zero-dimensional, one-dimensional, three-dimensional high level, etc.).

A unified methodological approach to ground tests of high-speed FV and ABE demonstrators should indicate the sequence of research and key measured parameters, the main of which is the engine thrust, which allows to determine the integral combustion efficiency [1, 2].

2 Ground tests on CP scheme

The main tasks to be solved in the creation of high-speed ramjet [3] - is to ensure the efficient combustion of fuel, including at supersonic flow rates, and ensuring the cooling of the combustion chamber construction, the operating

temperature of working gas in which can reach 3000 C and above.
At Mach flight numbers $M_\infty>5$, the total temperature of the air entering the engine exceeds 1000°C, which does not allow the use of air for cooling the CC as in other types of ABE. At «medium» ($7...8<M_\infty<10…12$) and «large» ($M_\infty>10…12$) hypersonic Mach numbers cooling of the CC is possible only with the use of fuel coolant. Fuel after cooling of heat-stressed structures should be supplied in specified proportions to the flow path of the CC. It is obvious that the cooling system must be corresponded to the geometric dimensions (exposed surface) of the CC. To obtain the required level of thrust in flight the working process must be sufficiently effective. This should be provided by high characteristics of mixing and combustion processes, high fuel efficiency, reliable stabilization of combustion in high-speed flows in conditions that have not been encountered until now. Also to ensure the efficiency of heat-stressed elements of the engine and, first of all, the combustion chamber, it is necessary to use new high-temperature materials and coatings. Experimental studies of the structure of high-speed flows in channels with chemical reactions, contributing to the understanding of the fundamental aspects of aerothermochemistry (mixing, ignition, combustion, equilibrium, dissociation, icing), as a rule, are carried out on small installations on CP scheme [4-6]. By the conducting these studies different ways of feeding fuel practiced, technical solutions are approbated, theoretical assumptions are tested, computing programs are verified. Schemes of experimental facilities for the study of combustion processes in subsonic and supersonic quasi-air flows [7] are shown in figure 1.
The design of model CC (MCC) can be made in both non-cooled and cooled versions. Non-cooled structures made of metals do not allow long-term testing and the use of known composite materials limits the thermocyclic life of the experimental setup. In addition, in the case of uncooled design it is difficult to determine the experimental amount of heat leakage to the walls of the MCC. The use of a cooled version of the design allows not only to provide a long service life of the MCC but also makes it possible to increase the accuracy of determining the amount of heat leakage from the combustion products into the channel walls. To do this it is necessary to measure the mass flow rate of the cooler as well as its temperatures in the inlet and outlet sections of the cooling path.

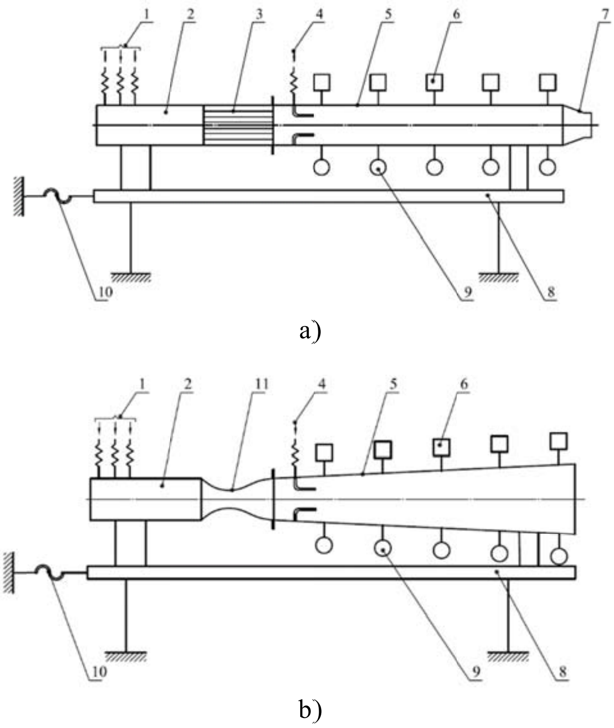


Figure 1. Schemes of experimental facilities for the study of combustion processes in subsonic (a) and supersonic (b) quasi-air flows:
1 – high-enthalpy quasi-air flow components; 2 – high-enthalpy quasi-air flow generator; 3 - adapter (straightener); 4 - fuel; 5 – model CC; 6 – temperature sensor; 7 – outlet nozzle; 8 – dynamometric platform; 9 - static pressure sensor; 10 – force sensor; 11 - nozzle

In accordance with the above schemes of experimental facilities for the study of combustion processes in subsonic and supersonic quasi-air flows (figure 1) in CIAM experimental setup were created using 3D-prototyping technology of heat-resistant alloys such as Inconel (figures 2 and 3) allowing to simultaneously measure the pressure and temperature in the MCC and its cooling system and at the same time to record the indications of the force sensor. Comparison of the fuel combustion efficiency coefficients η_{TR} and η_p obtained by the method of processing the force sensor indications [1] and processing the pressure sensor indications showed a coincidence within the limits of not exceeding 5...10 %.

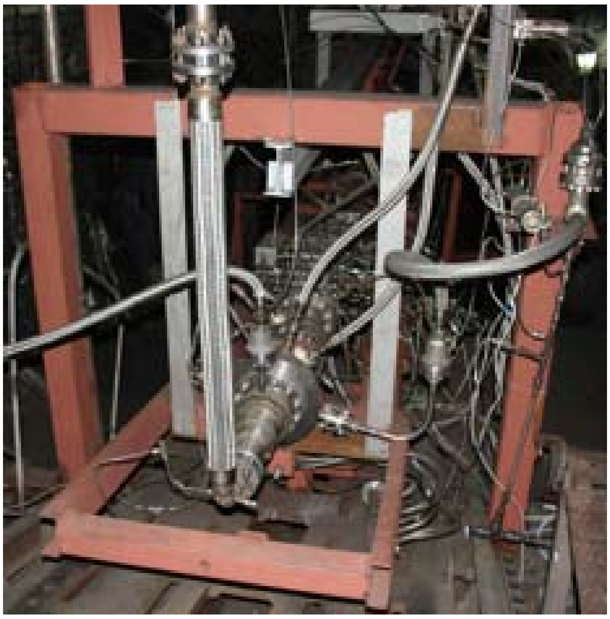


Figure 2. Experimental installation for the study of combustion processes in subsonic and supersonic quasi-air flows on a dynamometric platform. Components in the generator of high-enthalpy quasi-air flow are fed through flexible hoses perpendicular to the axis of the model combustion chamber.

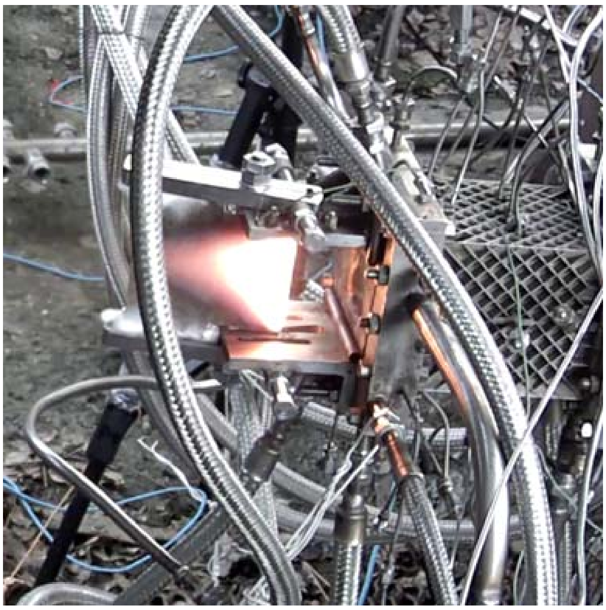


Figure 3. Performance tests in a high-enthalpy oxidizing flow of a sharp leading edge using a cooled model combustion chamber made by 3D prototyping of a heat-resistant alloy of the Inconel type

The accuracy of the indirect calculation of the combustion efficiency coefficient according to the indications of the pressure sensors η_p for uncooled MCC increases with decreasing size of the flow path and increasing the exposed surface of MCC.

It should also be noted that in the experimental studies the geometric dimensions of the MCC structures change due to thermal loading which also causes additional errors in the calculation of the combustion efficiency on the registered experimental data. However, in comparative studies of different ways of fuel supply influence on the efficiency of the working process in the MCC both methodological approaches can be used for comparative evaluation of the combustion efficiency.

Stationary operation mode of cooled MCC allows to investigate various materials, elements and assemblies of high-speed ramjet demonstrators for performance in high-enthalpy oxidative flow. These can be either structural elements with sharp leading edges [8] (figure 3) or structural elements and assemblies of CC demonstrators.

Also elements and components of technological test cell equipment, for example, screens of thermocouple combs and pressure are tested for efficiency in a stationary high-enthalpy oxidizing flow. After carrying out the necessary preliminary cycle of experimental studies on CP scheme it seems appropriate to further develop gas-dynamic and technological solutions in free jet tests.

3 Altitude tests of high-speed ramjet demonstrators in free jet

Development of elements and units of high-speed ramjets and FV as well as their integration should be based on further testing both on the ground test cells and in flight i.e. it is necessary to carry out preliminary calculations for two working fluids: atmospheric air and quasi-air test cell flow to account for the possible differences in the thermophysical, thermodynamic and chemical properties of the working fluids. It should these differences be identified especially for the tests at M≥5.

At ground tests it is necessary to consider differences of properties of quasi-air flow from atmospheric air [9].

The main differences between the test cell flow and atmospheric air:

- the presence of impurities of combustion products(fire heating), products of erosion of electrodes and ionized and dissociated products of high-temperature electric arc (plasmotron), sublimation products and dust flow (Cowper heaters);
- non-equilibrium (chemical, energetic and thermodynamic) of the working fluid;
- chemical and thermodynamic differences affect the wave structure of the flow, the combustion efficiency and thrust characteristics;
- non-uniformity (spatial and temporal) of the test cell flow in the transverse and longitudinal directions.

The problem of transfer of ground test results of high-speed ramjet integrated with FV to the full-scale real operating conditions for Mach numbers M≥5 is currently unsolved and requires careful research. The methodology of ground tests should take into account the possibility of research of the same model of the demonstrator on different test rigs and further interpretation of the generalized experimental results.

For experimental studies of gas-dynamic and physical-chemical processes implemented in the ducts of high-speed ramjets various models of high-speed ramjet demonstrators integrated with the fuselages of experimental FV were developed and manufactured.

The developed integrated «engine + FV» models were repeatedly exhibited at international exhibitions (figure 4).

Depending on the tasks to be solved the developed experimental objects are tested on various installations, wind tunnels and test rigs.

Aerodynamic models of GLL-AP (figure 5) are investigated for «small» hypersonic Mach numbers ($5<M_\infty<7\ldots8$) in aerodynamic tubes of ITAM SB RAS [3, 10]. So in the process of experimental studies [10] were identified regimes in which the air intake in integration with the nose of FV fuselage did not provide the necessary parameters at the entrance to the internal flow duct (figure 5b).

a)

b)

Figure 4. Integrated «engine+FV» models: a) – X2000; b) – GLL-AP

a)

b)

Figure 5. a) Aerodynamic model GLL-AP;
b) Oil-black visualization flow around model GLL-AP at «small» hypersonic Mach number.

This circumstance led to additional design studies aimed at forming the nose of the fuselage to ensure the operation of the air intake in a wide range of operating parameters. The found solutions were experimentally re-investigated in the ITAM SB RAS [10] and subsequently confirmed by GLL-AP tests at the CIAM test rig (Figures 6 and 7).

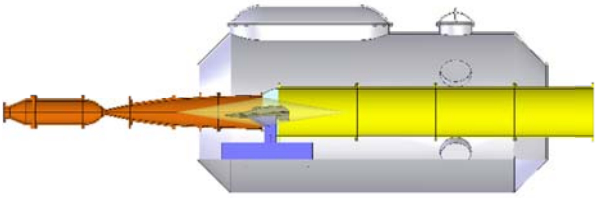
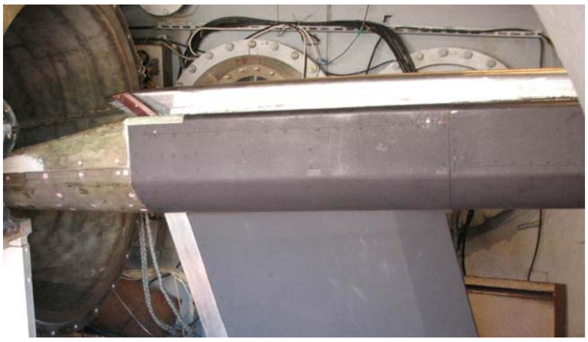


Figure 6. Scheme of large-scale model GLL-AP location on the CIAM test rig.



a)

b)

Figure 7. a) Large-scale model GLL-AP at CIAM test rig; b) Specialized measurement system of large-scale model GLL-AP

To determine the flow pattern at the external air intake and determine the thickness of the boundary layer at the inlet to the internal air intake of a large-scale model (LSM) of GLL-AP CIAM and LII together had developed specialized measurement system (figure 7): surface pressure sensor (PS); Γ-shaped pressure sensor (ΓPS); scanning pressure sensor (SPS); rake of pressure sensors (RPS); thermo-anemometers (TA); thermocouple (TC); thermal resistance (TR).

It is known that the increase of boundary layer thickness adversely affects the characteristics of the air intake and accordingly the engine thrust. In the experiment on LSM the degree of this effect was estimated by determining the thickness of the boundary layer at the intake inlet by measuring the distribution of total pressure in the height and width of the inlet as well as the static pressure on the surface in the width of the inlet. Measurements were performed using SPS, RPS, and PS. In this case, two SPS are placed directly in front of the entrance to the inner part of the air intake: one - in the center of the entrance, the other - at the edge to assess the thickness of the boundary layer in the width of the entrance. To eliminate the influence of SPS on the engine the scanning was performed before and after the engine run. In addition at the side walls on the outside of the module two RPS were installed so that the lines of their receiving holes are parallel to the side edges of the intake inlet. Knowledge of the temperature (heat flux) on the outer surface of the thermal protection of the LSM allows to determine the nature of the flow in the boundary layer that is the position of the laminar-turbulent transition zone which is especially important when assessing the force effect on the LSM due to friction. These temperatures (heat fluxes) are determined by the indications of the thermocouple system installed in the thermal protection material at a certain distance from the outer surface from the solution of the boundary inverse problem of thermal conductivity.

Mass flowrate through the experimental object (EO) is determined both by the pressure sensors before entering the inner part of the air intake, and by a specially designed mass flow meter device (MFD) attached to the nozzle of the EO (figure 8). According to the measurement data obtained during the ground tests of the LSM GLL-AP, the Mach number M of the flow and the ram corresponding to the conditions of the flow around the nose of the LSM, the temperatures of the outer surface of the fuselage of the LSM, heat fluxes and the temperature distribution over the thickness of the thermal protection in the heat-loaded points of the LSM, the air temperature in the LSM compartments, the flow parameters and the thickness of the boundary layer at the intake inlet of the LSM and the mass flow of air through the engine were estimated.

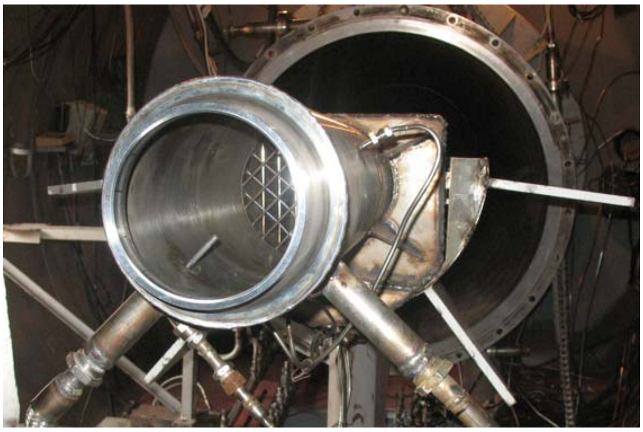


Figure 8. Mass flowmeter device (MFD) fixed to the nozzle of experimental object.

The state of the LSM elements (including thermal protection) and the performance of the measuring system elements were also assessed. The character of the flow on the external air intake of the engine (laminar with transition to turbulent at the first wedge) and directly before the entrance to the engine (turbulent) was determined. The thickness of the boundary layer before entering the engine was ~25 mm.

Panels of thermal protection of LSM GLL-AP showed their performance and durability under the conditions of tests and prospects for further research to be used as thermal protection in flight tests. Significant destruction of the surface of the panels of the thermal protection, changes in the shape of the panels resulting in a perceptible change in the operation conditions or the aerodynamic characteristics of the LSM were not detected.

In the range of «small» hypersonic Mach numbers during ground tests in conditions closed to full-scale when the fuel is supplied to the CC of the LSM GL-AP positive effective thrust was registered created by the model engine in integration with the experimental flight vehicle (figure 9). During the test the longitudinal force sensors (figure 9) firstly showed the resistance of the experimental object. After the fuel supply and the combustion process began the excess of the force generated by the demonstration engine in integration with the experimental flight vehicle over the resistance of the experimental object was registered (figure 9).

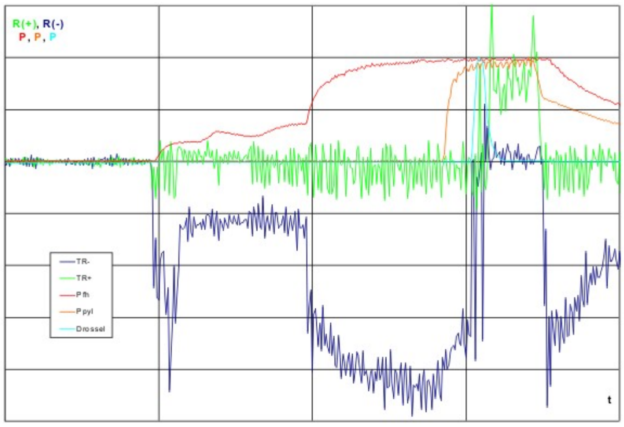


Figure 9. Indication of longitudinal force sensors during altitude tests of the experimental object

The tests confirm thrust effectiveness of ramjet integrated with the aircraft on «small» hypersonic Mach numbers.

It should be noted that during the test with a long (more than ten seconds) warm-up of test objects their resistance can be reduced by 10% or more. It was also fixed that for intakes with narrow regime diapason the heating of walls can lead to either non-start or failure of intake run.

Conducting altitude tests at hypersonic Mach numbers is a complex task in itself. The vacuum in the working part of test rig is provided by the work of the exhauster machines of altitude compressor station. The generator of high-enthalpy air flow creates the necessary total parameters of the working gas corresponding to hypersonic flight speeds. The duration of the tests on the test rig depends on the simulated operating parameters, the air supply in the balloon battery and the thermal condition of the experimental object [3]. Before the testing of certain experimental objects at the large test rig in CIAM it is possible to conduct experimental studies of test rig characteristics on scale model of test rig (figure 10) in the laboratory of hypersonic and plasma technologies of MIPT.

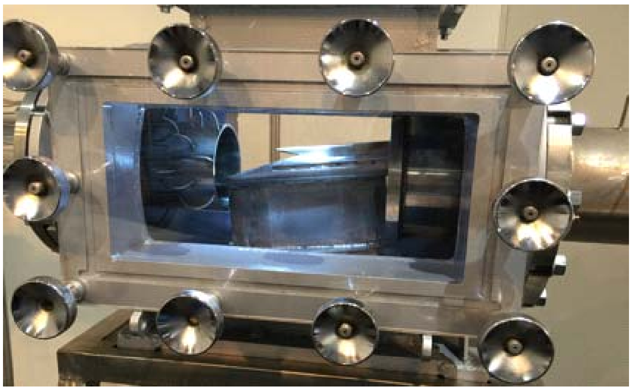


Figure 10. Photo of scale model of test rig.

On scale model of test rig the questions of start-up and working capacity of the working part of test rig at different modes with various experimental object loadings are investigated.

Preliminarily the flow path of test rig is selected by means of computational studies using high-level computing programs (CFD).

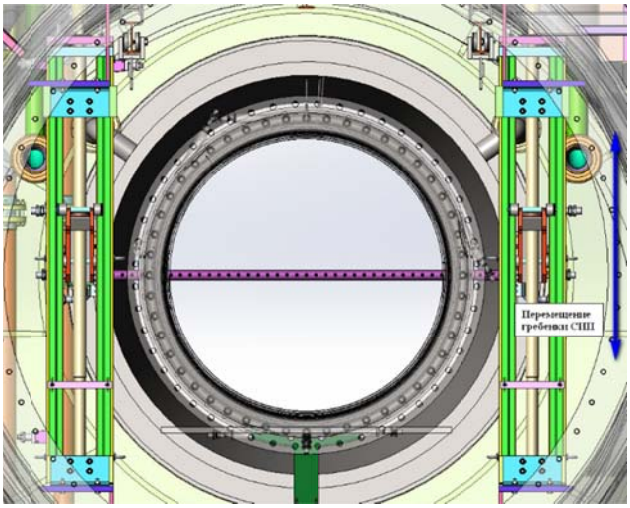
Before the cycle of tests of the experimental object gas-dynamic parameters at the outlet of the aerodynamic nozzle (ADN) are measured with the help of temperature and pressure field measurement system (FMS) to validate the parameters of the test rig.

The mechanism of FMS movement provides the movement of measuring comb across the AND exit section. For one test stream is scanned in increments of at least 100 mm. The duration time spent comb stationary is about 5 s. The scheme of FMS installation in the test chamber is shown in figure 11.

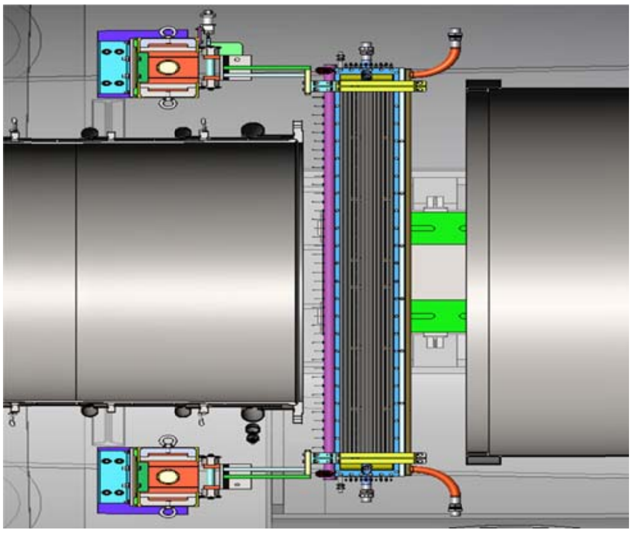
The movement of FMS is provided together with information cables, flexible water metal hoses, flexible nitrogen metal hoses necessary for cooling of FMS.

FMS comb is structurally made in the form of a welded rail-body. Pressure and temperature stagnation chambers are screwed into the FMS body on the side of incoming flow. The inner cavity of the body is designed to accommodate the terminals of the pressure and temperature sensors.

The presence of a powerful experimental base in Russia taking into account the complex methodology of testing allows for long-time testing of elements and components of high-speed ramjets with modeling conditions as close as possible to the operational.



a) front view



b) view from the top

Figure 11. Scheme of FMS installation in test chamber

4 Conclusions

At conducting ground tests on CP scheme a comparison of combustion efficiency coefficient of fuel η_{TR} and η_p obtained by processing the indications of force sensor and pressure sensors showed a coincidence within 5...10 %.

In experimental studies the geometric dimensions of MCC change as a result of thermal loading which also causes additional errors in the calculation of the combustion efficiency coefficient according to the registered experimental data.

For the purpose of a more correct interpretation of the experimental data obtained during the ground tests of high-speed ramjet demonstrators in free jet it is advisable to use of scanning pressure combs and special mass flowmeter device attached to the nozzle of the test object as diagnostic matter of flow interacting with the test object. Prior to the testing of high-speed ramjet demonstrators, it is desirable to diagnose the flow at the outlet of the ADN with the help of a scanning system for measuring pressure and temperature fields.

The flow path of the test rig is preliminary selected by means of computational studies using high-level computing programs (CFD) and then experimentally is investigated on a scale model of test rig to confirm start-up and performance of test rig duct at different modes when loading the working part by the experimental objects.

In the range of «small» hypersonic Mach numbers ($5<M_\infty<7…8$) during ground tests under conditions as close to real as possible when fuel was supplied to the CC of the demonstrator a positive effective thrust was registered and created by the model engine in integration with the experimental FV.

It is registered that in the process of tests at long time (more than ten seconds) warming-up of test object its aerodynamic drag can decrease by 10% and more. It is fixed that for air intakes with narrow regime diapason the heating of walls can lead to either non-start or failure of intake run.

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