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AIRCRAFT AND ROCKET ENGINE THEORY

Realization of Dual-Mode Combustion by Changing the Geometry of the Model Combustion Chamber Flow Part of a Ramjet Engine

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Abstract—This paper presents the results of experiments on the methane-hydrogen mixture combustion in a test bench model of a dual-mode wide-range ramjet combustion chamber with a variable geometry flow path, obtained as part of a work under the LEA program.

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The possibility of developing a wide-range ramjet propulsion system (PS) capable of operating at both subsonic and supersonic air flow rates in the combustion chamber flow path is considered for use as part of combined power plants of promising reusable two-stage vehicles of aerospace systems or single-stage vehicles of aerospace systems [1, 2].

The results of the calculated estimates show [1, 2] that for the effective operation of such a PS in a wide range of flight speeds, it is necessary to regulate the geometry of the working path (including the combustion chamber). Similar studies of the effect of the flow part geometry changes on the combustion were carried out at Moscow Aviation Institute (MAI) [3]. In the LEA program [4], the concept of a power plant with mechanical control of the flow part using a movable wedge (the lower wall of the engine) is considered (Fig. 1).

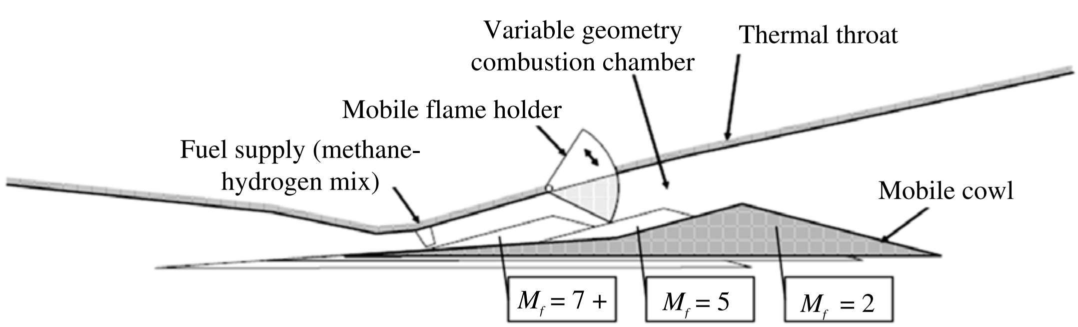

Fig. 1.

This paper presents some test results of the LEA concept model combustion chamber for power plant performed at Moscow Aviation Institute under a contract between MBDA (France) and Rosoboronexport (Russia). Simultaneously with the tests at MAI, a series of fire tests were conducted in France at the following test facilities: ATD5 (ONERA) and METHYLE (MBDA) (a connected pipe scheme) and S4 Modanein (ONERA) (in free jet conditions) [5, 6].

The concept of the power plant (see Fig. 1) of the LEA program was chosen based on the results obtained during numerous studies of ramjet engines [2, 7].

Unlike the “classical” scheme of the ramjet engine flow path, there is no mechanical throttling of the flow (critical section) in the exhaust part of the combustion chamber. In subsonic modes, the critical flow in the flow path is provided by thermal throttling (heat throat). With an increase in the flight speed, the lower wall is moved forward against the flow, while the cross section and the length of the flow path of the combustion chamber decrease.

For the LEA program, MBDA selected a mixture of gaseous components as fuel, namely, chemically pure methane (99.99%) and hydrogen [1, 2, 7, 8–10]. The use of methane makes it possible to provide a sufficiently prolonged flight experiment, although the physicochemical characteristics of methane significantly complicate the organization of the working process [11].

When designing a LEA concept model engine, MBDA and ONERA (France) carried out the preliminary calculations of the power plant using the CEDRE software package (with the kinetic model [12]). The main geometric dimensions of the combustion chamber and the range of ground test parameters were determined for modeling of flight Mach numbers from 2 to 7+. In accordance with the data, received from French colleagues, a full-size test model of the combustion chamber with mechanically movable elements of the flow path was prepared for experiments at MAI. The design of the model provided a discrete longitudinal change in the position of the combustion chamber lower wall and, accordingly, a required change in the length and area of the combustion chamber flow path. During the preparation of the tests, depending on the parameters of the experiment (simulated values of speed and altitude), the lower wall of the model was installed in the positions predicted for flight conditions.

Fuel was supplied from wing-shaped pylons located in the entrance part of the combustion chamber. The pylons were placed on the upper and lower walls. There were four fuel injection holes in each of them. Cooling of the pylons was provided by fuel. In addition, a number of holes on the upper wall were made for additional fuel supply.

Two systems are provided in the design of the model combustion chamber for igniting the mixture, namely, pneumatic throttling (blowing air jets) [13] and torch flame (hydrogen-air small-sized starting combustion chamber). The walls of the model chamber were cooled by water.

Fire tests were carried out at the test bench with connected pipe with fire heating of the model flow [14, 15].

The pressure and temperature of the flow at the entrance to the combustion chamber were provided by the corresponding mass flow of the components supplied to the fire heater (air, oxygen, kerosene). The required flow velocity at the entrance to the model had the discrete values (Mach number of the model flow M_{inlet} = 1.4; 1.5; 2.2; 2.5; 2.7; 3.5), which were provided using a supersonic nozzle of modular design. Other parameters (operation range of model flow stagnation temperatures 400–2100 (2300) K; operation range of mass flow at the heater exit 0.8–8.0 kg/s; operation range of stagnation pressures of the model flow 0.13–4.8 MPa; molar fraction of oxygen at the heater exit 7–29 %) were provided by the heater design. All parts of the heater hot path and nozzle were cooled by water.

The fuel supply system to the combustion chamber made it possible to change both the total fuel mixture consumption and the ratio of fuel consumptions injected from the pylons of the upper and lower walls. In addition, it was possible to vary the concentration of hydrogen in the mixture. It allows both a reliable ignition and change in the intensity of heat generation along the combustion chamber.

Forty two static pressure sensors were installed on the upper, side and lower walls of the combustion chamber flow path to monitor the working process.

The complete test series included simulation of flight Mach numbers M_f from 2 to 7+. For example, when modeling M_f = 4, the model flow at the combustion chamber inlet had a total temperature of T_0 = 760 K and the Mach number M_{inlet} = 1.5.

Figure 2 shows the distribution of static pressure along the combustion chamber obtained in one of the experiments in this mode (x/L_{model} = 0 corresponds to the outlet section of the heater nozzle, x/L_{model} = 1 corresponds to the outlet section of the expanding part).

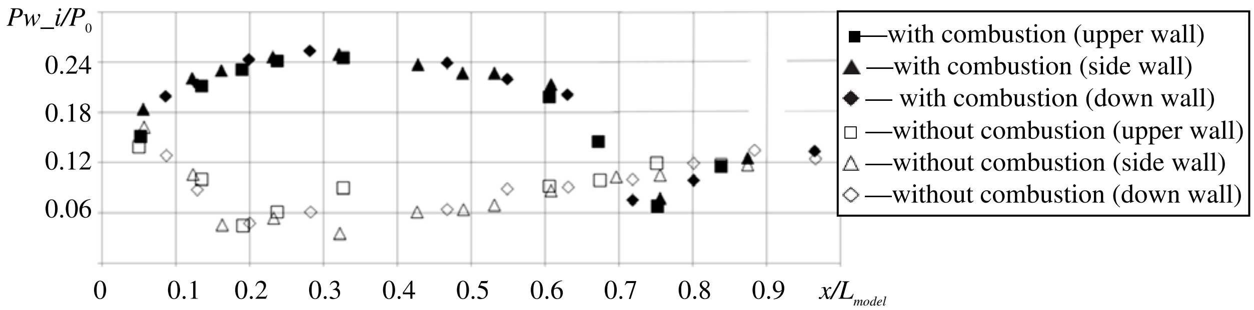

Fig. 2.

When modeling a flight with a Mach number of M_f = 6 (T_0 = 1650 K, M_{inlet} = 2.2), the wedge was installed upstream compared to the M_f = 4 mode.

Figure 3 shows the distribution of static pressure along the combustion chamber for this mode.

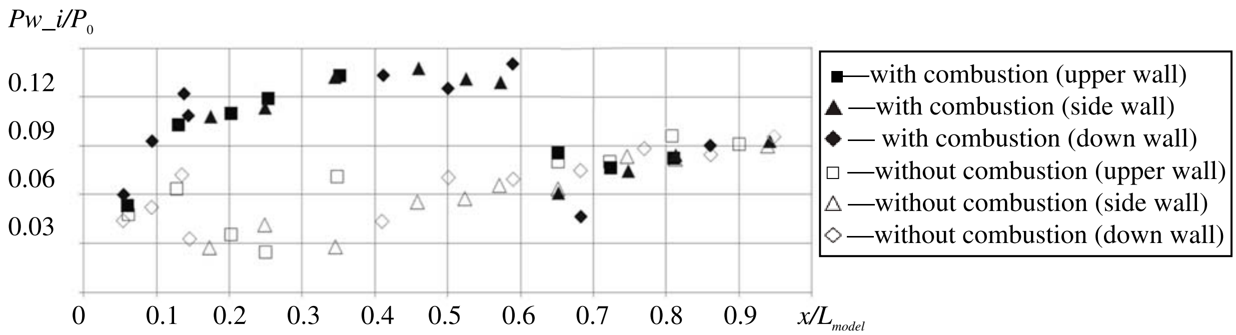

Fig. 3.

The experimental results presented (Figs. 2 and 3) led to state that the geometrical regulation of the flow part made it possible to obtain subsonic combustion in the M_f = 4 mode, and combustion in the supersonic flow in the M_f = 6 mode [16]. The results also show the occurrence of flow separation (after x/L_{model} > 0.4) due to the influence of atmospheric back pressure in the tail section of both combustion chambers in the tests without combustion.

At the same time, the separation of the flow leads to the appearance of a recirculation zone and a shock wave system, which could contribute to the occurrence of self ignition of the fuel mixture. Therefore, for further experiments, a two-stage supersonic ejector was designed and manufactured at MAI (Fig. 4).

The ejector was installed at the exit of the model (behind the expanding part of the channel). The ejecting air consumption was approximately 50% of the air flow through the combustion chamber. The use of an ejector made it possible to prevent the occurrence of a separation zone in the output part of the combustion chamber channel and to reduce the pressure in the expanding part of the channel (the nozzle part of the model). The lack of the flow separation led to the fact that in all test modes it became necessary to use the forced start of the combustion process.

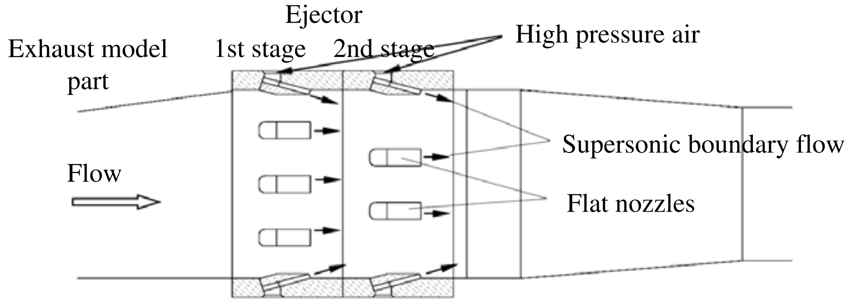

Fig. 4.

Figures 5 show a comparison of the measured distributions of static pressure along the upper wall (Fig. 5a) and the side wall (Fig. 5b) related to the total inlet pressure P_{w_i}/P_0 along the model channel in the case without and with the use of an ejector in the non-combustion mode (inlet conditions T_0 = 1650 K, M_{inlet} = 3.0). Here and further x/L_{model} = 0 corresponds to the exit section of the heater nozzle, x/L_{model} = 0.56—to the beginning of the expanding part, x/L_{model} = 1—to the exit section of the expanding part (the beginning of the ejector).

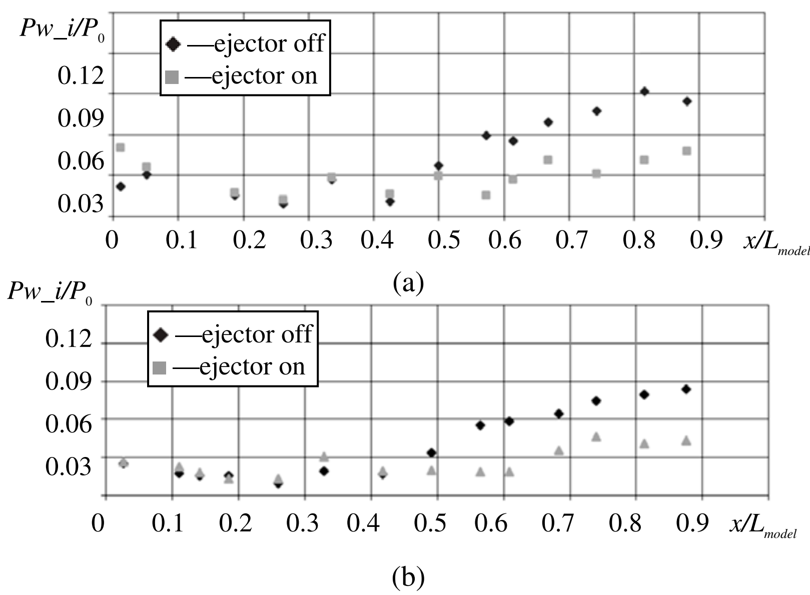

Fig. 5.

It is clearly seen (Fig. 5) that the pressure at the exit of the combustion chamber and the nozzle part of the model channel is significantly lower in the case of using the ejector.

One-dimensional calculation of the workflow and analysis of the results were carried out in MBDA (using the thermodynamic program PUMA), taking into account chemical kinetics. 3D calculations were performed both before (predictive) and after the combustion chamber tests in MBDA and ONERA using the CEDRE program.

Various turbulence and combustion (kinetics) models were used for 3D calculations, including turbulence models, namely, k–ε or k–ω models; Eddy Break Up combustion models with five elements and two reactions [12] or model with 16 elements and 79 reactions [17].

In MBDA, calculations of the flow in the combustion chamber channel were carried out for test bench conditions and conditions corresponding to flight (forecast).

Figure 6 shows a comparison of the results of the MBDA calculation with the results of pressure measurements at MAI for conditions at the inlet T_0 = 800 K, M_{inlet} = 2.2 with and without an ejector.

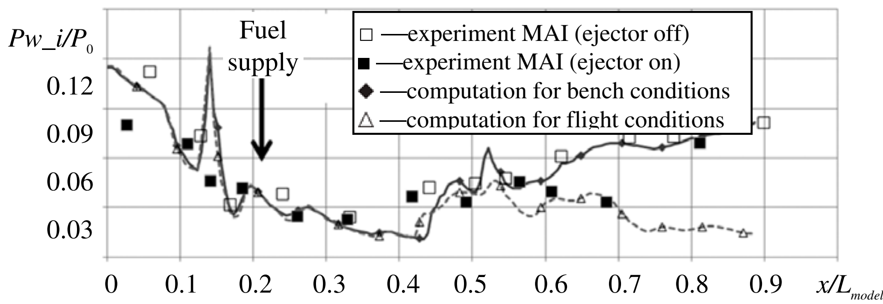

Fig. 6.

The results of the test conducted at MAI using an ejector exhaust system showed good agreement with the results of calculations up to a cross section of x/L_{model} = 0.7. Therefore, it can be argued that the use of an ejector exhaust system at the MAI test bench made it possible to eliminate the influence of atmospheric back pressure on the working processes in the combustion chamber and allows tests to be made in conditions close enough to flight conditions.

As an example, the experimental results obtained at MAI are compared with the results of LEA calculations in MBDA using different turbulence and combustion (kinetics) models. In all modes, the fuel supply systems were the same, the movable wedge was installed in the position obtained from the forecast calculations for flight conditions.

Figures 7–9 present the calculated and measured distributions of the static pressure P_{w_i} along the upper, lower and side walls of the combustion chamber model, referred to the total inlet pressure P_0.

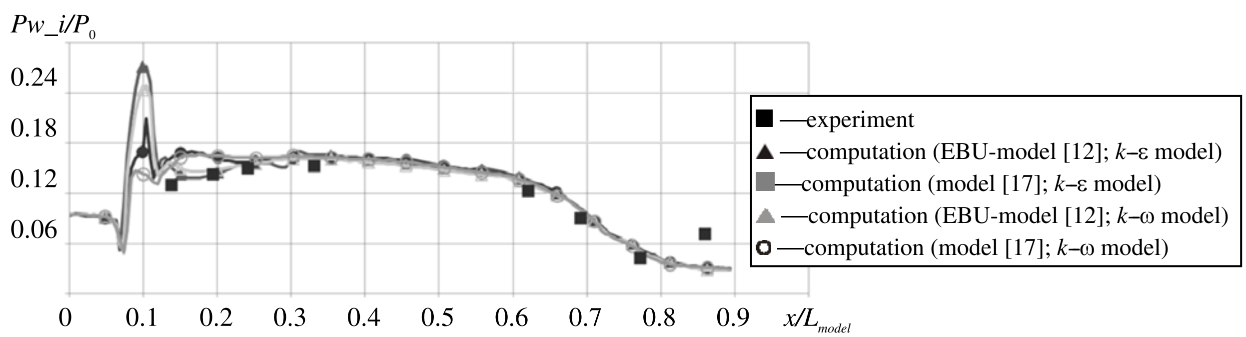

Fig. 7.

The calculated static pressure distributions for the mode M_f = 4, T_0 = 760 K with combustion are practically the same for both models and coincide well with the experimental results.

The difference between the calculated and experimental distributions of static pressure in the front of the combustion chamber shows the complexity of describing the local interaction of the fuel supply system, the shock wave system generated by it, the local combustion zones, and the boundary layer. In addition, it should be noted that the design features of this section of the combustion chamber do not allow for a sufficient number of pressure measurement points (for the desired flow structure detail).

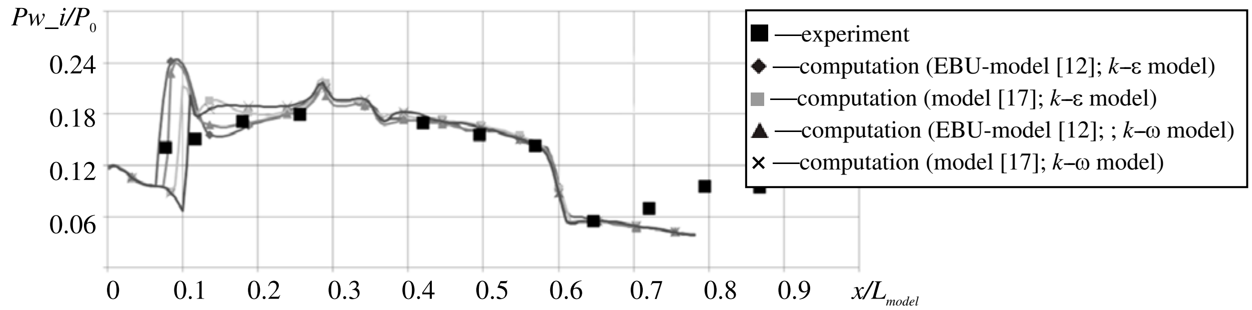

Fig. 8.

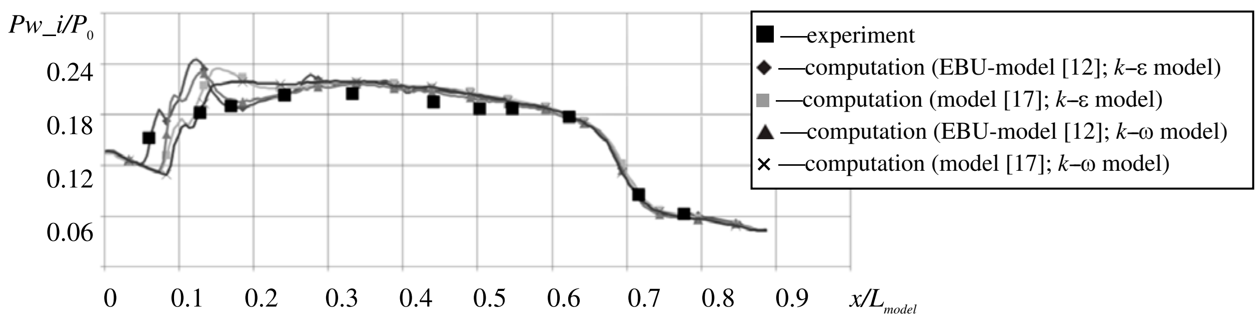

Fig. 9.

Thus, a cycle of fire tests was carried out at the MAI test bench, simulating parameters at the entrance to the model combustion chamber corresponding to flight conditions in the range of M_f numbers from 2 to 7 + (according to the scheme with an attached air duct).

The design of the model combustion chamber provided all the necessary range of geometric parameters in accordance with the LEA concept.

The use of control of the geometry of the flow part confirmed the possibility of obtaining stable combustion modes of the methane-hydrogen fuel mixture in both pre- and supersonic flow.

Experimental data on combustion modes depending on the concentration of hydrogen and the positions of the lower wall (shape) of the combustion chamber were obtained.

The use of an ejector exhaust system at the MAI test bench made it possible to remove the influence of atmospheric back pressure on the processes in the combustion chamber and carry out work in conditions close enough to flight conditions.

All three-dimensional calculations carried out by MBDA, using various programs and mathematical models, showed a good coincidence of the test results and calculations.

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