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Measurements and modelling of wall heat fluxes in rocket combustion chamber with porous injector head

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ABSTRACT

A rocket combustion chamber with a porous injector head, which is a new concept for injecting propellants, is tested. The hot-fire tests are carried out using cryogenic oxygen and hydrogen at the mass ratio of oxidizer to fuel of 6 and at pressure of 80 bar. Pressures, wall temperatures, and wall heat fluxes are measured along the axis of the chamber. The wall heat fluxes are determined by the calorimetric method. The wall heat flux has a maximum at a distance of 50–100 mm from the injector plate. To interpret the experimental results, numerical simulations are performed using the commercial CFD code ANSYS CFX. The turbulent flow is modelled by the Favre-averaged Navier–Stokes equations and the shear-stress transport model. The turbulent combustion is modelled using two different models: the extended eddy-dissipation model and the extended coherent flame model. Results obtained with the different models are compared both with experimental data and with each other. The numerical results agree with the experimental data. The extended eddy-dissipation model gives the very good agreement which is achieved by applying additional parameters ('Flame Temperature' and 'Extinction Temperature') dependent on the mixture fraction.

1. Introduction

The application of porous materials can improve the performance of rocket combustion chambers used at present. A porous injector head can provide effective mixing of fuel and oxidizer at low pressure drop in the injector head. This new injection concept is being under development at the German Aerospace Center (DLR-Lampoldshausen) [1–3]. Nowadays, the transpiration-cooled injector plates are used in some rocket engines (for example: SSME and J-2) where the small fraction of the fuel flow is fed through tiny holes in the injector plate for cooling and the main part of the fuel is still injected through coaxial injectors [4]. Coaxial injectors proved their efficiency, but they require a very precise manufacture and keep their efficiency in the narrow range of mass flows which is bounded from above and below. These problems can be easily solved by the application of a porous injector head where a fuel is fed into combustion chamber through a porous plate, and an oxidizer is fed through many distributed simple injectors. According to the hot-tests at the Institute of Space Propulsion of the German Aerospace Center (DLR-Lampoldshausen) [2] the porous injector head (Fig. 1) allows to maintain the high combustion efficiency over the wide throttling range from 37.5% to 125%. Besides the manufacture costs and the throttling capability porous injector head has two additional advantages over conventional coaxial injectors. Porous injector head operates at a smaller pressure drop than injector heads with coaxial injectors. The small diameter of the injectors in a porous head results in a small jet break-up distance which allows reducing chamber length. Such features improve the performance of rocket engines.

Rocket combustion chambers are exposed to severe thermal loads during the burn. The components of a thrust chamber assembly (injector head, side walls, and nozzle) require the adequate cooling. The proper design of a rocket combustion chamber needs the knowledge of the heat fluxes inside the chamber. The accumulated experience (experimental tests and simulations) with the conventional impinging and co-axial injectors is sufficient for combustion chamber design; however, the existed knowledge on porous injector heads is not enough.

Zhukov and Haidn [5] considered the heat transfer in a porous injector plate at the conditions of the present work. They found an analytical expression connecting the incident heat flux and the temperature of the hot side wall of a porous injector head. It was shown that the heat loads are not problematic at least for an injector head made from sintered bronze (i.e., for the injector head which is used in the present work). However, the thermal loads are still an issue for other parts of thrust chamber assembly: side

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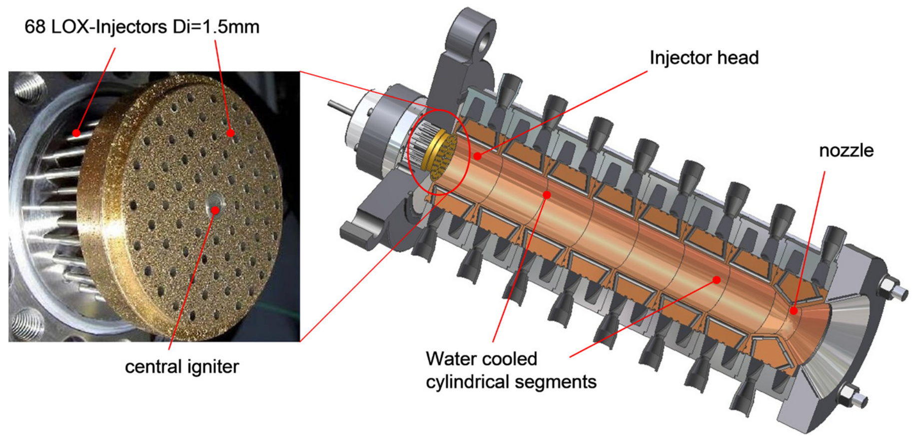

Fig. 1. The photo of porous injector head API-68 and the cross-section of sub-scale combustion chamber model 'B'.

walls and nozzle. The aim of the present work is to study experimentally and theoretically the wall heat fluxes in a combustion chamber with a porous injector plate.

While the wall heat flux reaches a maximum in the throat of the combustion chamber, the peculiarities of the injector head should be negligible there and further downstream in the divergent nozzle. (The flow in a "good" combustion chamber should be already uniform upstream the throat.) The particularities of the porous injector head should come out at the first 100 mm from the injector plate. At this location the parameters of the flow depend strongly on the injection conditions. The flow and the heat fluxes in a combustion chamber with coaxial injectors were studied by many other researchers, e.g., in the extensive series of works from ASTRIUM (now Airbus D&S) [6–8]. However, the flame of porous injector head requires the numerical analysis.

In the present work the incident heat fluxes to the side walls of the combustion chamber with a porous injector head are studied both experimentally and theoretically. In our previous work [3] we already simulated the flow in the combustion chamber with the porous injector head. These preliminary results gave us a very important conclusion and showed the direction of the further steps. Study [3] showed that the modelling in two-dimensional (2D) domain does not give accurate results for the chamber with porous injector head, and that the use of the coarse three-dimensional (3D) numerical mesh gives better results than the use of the very fine 2D mesh. The heat flux to the wall is very sensitive to the arrangement of the injectors nearest to the wall. (This is also supported by the longstanding experimental experience at our institute.) The disagreement between the simulation results and experimental data were reduced from 30% to 15% by the switch to 3D geometry from 2D geometry. The agreement with the experimental data was improved because the semi-rectangular pattern of injectors of the tested injector head API-68 (Fig. 1) can be represented adequately only in a 3D geometry.

2. Experimental methods

Segmented, water cooled combustion chamber model 'B' and porous injector head API-68 (Fig. 1) were designed, manufactured and tested at DLR-Lampoldshausen. The combustion chamber operates with LOx/H_2 or LOx/CH_4 propellant combination in the wide pressure range up to 12 MPa. The hot tests have been done at the European Research and Technology Test Facility P8. This test facility operates in a controlled blow-down mode and enables investigations with liquid and gaseous hydrogen at typical rocket engine operating conditions.

The segmented design enables the implementation of various test equipment without additional expenditures. The combustion chamber has an inner diameter of 50 mm and consists of six cylindrical elements, each of 50 mm length, with a separate cooling supply. The heat exchange occurs in a row of cylindrical cooling channels. Two collectors in each section provide a uniform mass flow through all cooling channels. The changeable nozzle section allows changing the contraction ratio (the ratio of the cross-sectional area of the combustion chamber to the throat area) from 2 to 8.4. The nozzle segment with a 28 mm throat and the corresponding contraction ratio of 3.2 has been used in the present study.

Combustion chamber 'B' is used predominantly to study the heat transfer on the hot-side wall and the influence of different design solutions (for example, a new injector head design) on the thermal loads on the combustion chamber walls. The wall heat flux measurements were carried out using the calorimetric method in the present study. The wall heat fluxes have been determined using measurements of temperature and pressure at the inlet and the outlet of each section in accordance with the formula:

$$Q = \phi \cdot [H_{out}(T_{out}, P_{out}) - H_{in}(T_{in}, P_{in})], \quad (1)$$

where Q is a heat flux to the segment, ϕ is a coolant mass flow rate, $H_{out}(T_{out}, P_{out})$ is the specific enthalpy of water at the outlet of a cylindrical segment as the function of temperature and pressure, $H_{in}(T_{in}, P_{in})$ is the specific enthalpy of water at the inlet of a segment. In addition, the surface temperatures on the hot-gas side were measured.

The key feature of the tested combustion chamber is the porous injector head called API-68 (Advanced Porous Injector, 68 injectors), see Fig. 1. The injector plate is made from sintered bronze. Hydrogen is fed into the combustion chamber through the massive porous plate which consists of sintered bronze beads with a diameter of ~0.6 mm. Liquid oxygen is injected through 68 separate injectors distributed uniformly over the porous plate. Each single injector is a cylindrical tube with an inner diameter of 1.5 mm. The thickness of the injector tip amounts only 0.25 mm, and fuel and oxidizer get in direct contact immediately after the injection in contrast to classical showerhead injector heads, which looks similar at first sight. In the center of the injector plate, the outlet of an igniter torch is located. The combustion chamber with API-68 shows a stable behavior with the pressure drop between the fuel dome and the chamber below 5% of the mean chamber pressure. The simplicity of the used design offers a large potential for manufacturing cost savings.

The nozzle used in the experiments has a very simple geometry. Both the converging and diverging parts are conical. The converging part has an opening angle of 54°. The diverging part has an opening angle of 70°. The converging and diverging parts are jointed by a circular arc with a radius of 20 mm. The center