Experimental studies and multi-factor analysis of the fuel component distributions over the mixing head nozzles of the liquid rocket engine

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Abstract. A model device of the liquid rocket engine mixing head for experimental determination of hydraulic non-uniformity of fuel distribution is described. Schemes of hydraulic and gas-dynamic test benches are given. The results of the planned factor experiment to determine the array of flow rates through individual sprayers are presented. Neural network regression factor models were created to evaluate the criterion of non-uniformity. The influence of various factors on the parameters of non-uniformity is estimated

1. Introduction

A model experiment is widely used to determine the non-uniformity of the distribution of fuel components over the mixing elements of the nozzle head of the chamber of a liquid rocket engine (LRE). Moreover, as a rule, the non-uniformity parameters are determined during the so-called “cold” blowdowns of full-scale mixing heads with the model working fluid, i.e., full geometric similarity of the model is provided, whereas the similarity in flow regimes when using the model working fluids is achieved by observing the equality of the parameters Re and Eu (if possible). For almost every mixing head of the combustion chambers and gas generators of existing LREs, there is an array of experimental data on the analysis of non-uniformity parameters. At the same time, there are relatively few works that present the results of a planned multi-factor experiment conducted not only to determine the level of non-uniformity, but also to assess the significance of various factors in order to find out which of the geometric or regime factors can then be controlled to ensure a given component distribution over the nozzles [1-7].

The analysis of applicable mathematical models and calculation algorithms leads to the obvious conclusion about the possibility of increasing the accuracy and adequacy of mathematical simulation. Primarily, it is necessary to consider the dependence between the irregular distribution of components over mixing head sprayers and jacket cooling paths on non-uniform distribution of thermodynamical and thermal parameters in the fire box, the cooling path and chamber walls. Secondly, it is obvious, that the accuracy of calculated results can be significantly enhanced by removing the sources of numerical errors, mainly connected with discretization of derivatives in solvable differential equations, and, besides, with low accuracy of boundary representation. Another way of increasing the calculation
accuracy is the application of high-precision methods of multivariate approximation, based on the neural-network computing architecture.

The neural-network computational structures can be applied for obtaining the calculation algorithms in the conditions of non-uniform distribution of components, the discharge intensity in the chamber cross-section, and the irregular discharge distribution over the channels of the cooling path. If we use the principles of quasi-two-dimensional formulation of heat transfer problem, then, for each design section of the chamber, it is possible to perform the calculation of convective thermal flow toward the chamber wall, with regard to parameters of the wall layer. The wall layer is determined by its adjacent sprayer (provided that binary fuel sprayers are used, being located in the concentric circles). The parameters of heat transfer to a liquid are determined with account of local (but not average) rate of discharge in the cooling channel. Next, the «stitching» of the obtained solutions, specified for temperatures of chamber walls, is performed, and the resulting thermal field of the construction is applied to calculate the parameters of heat-stressed state. Specific computational algorithms are based on iterative calculations, which require the analytical approximating dependencies of the empirical reference data. If thermophysical properties depend on a single parameter (let us say, on temperature), then the calculation of approximations, made by means of the least-squares method, does not cause any problem. For approximation of non-unidimensional dependencies, it is effective to apply the neural-network computational structure.

The main goal of the experimental studies in the present work is to determine the sensitivity of the non-uniformity criteria to various factors that can be controlled for optimization, i.e. providing a given non-uniformity level.

The objectives of experimental studies are:
1. Creation of a model device.
2. Development of an experimental design.
3. Carrying out autonomous hydraulic blowdowns of the model device.
4. Construction of factorial regression models.
5. Estimation of the influence of various factors on the non-uniformity parameters.

2. Materials and methods

2.1. Creation of a model device. Applied test-bench equipment
To experimentally study the physical picture of hydrodynamic processes in the cavity of the nozzle head and to estimate the influence of various factors on the component flow through the nozzle, a model of the 444-nozzle head of the engine combustion chamber developed at the Chair of Rocket Engines is used. In this model, 444 nozzles are arranged along concentric circles according to the pattern (12+18+24+30+36+42+48+54+60+60+60).

Experimental studies of the processes of component distribution over nozzles in the studied model are carried out on a hydraulic bench (figure 1). The electrically driven screw pump 1 creates a pressure in the hydraulic line. As the working fluid for the pump, water is used which is supplied to the pump inlet from the collection tank 2. Valves 3 and 4 are designed to control the fluid flow in the line. From the line, the working fluid is supplied to the experimental unit 5, after which it again enters the collection tank 2. To visualize the flow pattern, the upper cover is made of plexiglass.
Figure 2 presents a photograph of the working process in the third mode in terms of the value of the mass flow rate of the blowdown (the Reynolds number in the inlet branch Re=2.26·10^5). In the first mode, the outflowing jet from the inlet is maintained until it collides with the side wall, where a zone of increased pressure is created due to the sharp deceleration of the fluid. The flow pattern in the rest of the zone is homogeneous except for the near-wall layer. As the supply flow rate to the cavity of the nozzle head increases, the jet is destroyed at a shorter distance from the inlet, whereas the jet braking zone becomes significant. The boundaries of the indicated zones in the first two modes are unstable and change all the time, probably, because of sensitivity of the flow parameters to instability at the input. In the third mode, the supply jet is not visible, the boundaries of the zones practically do not change in time; the contrast of the picture becomes more uniform, which is a sign of a more uniform distribution of the flow parameters.

The following parameters are taken as factors during the planned active experiment: $\bar{R} = r/R_{out}$, $\phi (x_n, y_n)$ are radial and angular (or Cartesian) coordinates of the nozzle location on the head (here $R_{out}$ is the radius of the outer peripheral row of nozzles); $\dot{m}_n$ is the total flow rate of the blowdown; $Kr = \dot{m}_{aux} / \dot{m}_{g,aux}$ is the coefficient reflecting the design features of individual nozzle, including technological errors determined during the autonomous blowdowns of each nozzle.
The output variable is the value of the relative mass flow through the nozzle \( \frac{\dot{m}_n}{\dot{m}_{av}} = f(x_n, y_n, \dot{m}_x, K_{R_n}) \). In this case, the Cartesian relative coordinates of the nozzles are used.

To reduce the complexity of the research, 18 nozzles are taken into consideration out of 444 nozzles located in the mixing head (the flow values through them are determined): 12 in the first peripheral row and 6 in the fifth core row.

The blowdown of these nozzles is performed autonomously and preliminarily to determine the flow coefficient and the coefficient \( K_{R_n} \) for each of them. Three different modes are studied according to the total mass flow rate of the working fluid at the inlet (the blowdown flow rate):

a) \( \dot{m}_p = 2.36 \text{ kg/s, } \text{Re}_p = 1.49 \cdot 10^5 \);

b) \( \dot{m}_p = 2.98 \text{ kg/s, } \text{Re}_p = 1.88 \cdot 10^5 \);

c) \( \dot{m}_p = 3.6 \text{ kg/s, } \text{Re}_p = 2.26 \cdot 10^5 \),

where \( \dot{m}_p \) is the mass flow rate of water in the divided inlet manifold, \( \text{Re}_p \) is the Reynolds number of the flow in the inlet manifold.

2.2. Carrying out autonomous hydraulic blowdowns of the model device

At each point of the experimental design, the values of the flows through all 18 nozzles are determined using a weight method. The accuracy of this method of determining the flow rate is sufficient to assume that the test results do not contain a systematic instrumental error. The number of repetitions at each point in the plan is 5 experiments. Figure 3 represents the isolines of the flow rate non-uniformity in the first regime in terms of the blowdown flow rate, which indicate a substantially nonlinear dependence \( \frac{\dot{m}_n}{\dot{m}_{av}} = f(x_n, y_n, \dot{m}_x, K_{R_n}) \). Therefore, to construct factor models, it is necessary to use nonlinear programming methods together with modern powerful approximation algorithms.
In a number of works [8], it is noted that the main factor influencing the non-uniform distribution of the component over the nozzles is the non-uniform distribution of the total pressure in the cavity of the mixing head in front of the nozzles, obtained during the turbulent flow in the inter-nozzle space. To determine the distribution field of the total pressure, the model device is tested on a gas-dynamic bench (figure 4). To supply air to the bench pneumatic system, valve 1 is used. The input air pressure is measured by the pressure gauge 2. Through the damper 3 and the needle throttle 4, which are designed to set the test mode according to the flow rate, air is supplied through valve 5 to the rotameter 6. Then, air is supplied to the studied model 8, the input pressure of which is measured by the manometer 7. The total pressure at the nozzle is recalculated according to the pressure drop measured by the differential pressure gauge 9.
The modeling technique for blowdown planning is described in [9]. When blowing the mixing head, the equality of the Reynolds numbers in the inlet branch of the mixing device with similar water tests is ensured. Besides, in all blowdown modes, the Mach number in the inlet branch does not exceed \( M = 0.3 \); therefore, the compressibility of the working fluid is not taken into account in the experiments. Figure 5 shows the results of studying the non-uniformity of the pressure distribution in the cavity of the mixing head. It can be concluded that, firstly, the level of non-uniformity in total pressure is small, much lower than the level of the flow rate non-uniformity, and, secondly, the nature of the flow rate distribution over the nozzles does not correspond to the nature of the total pressure distribution in front of the nozzles (comparison of figure 5 and figure 7).

Thus, the conducted blowdowns have shown that the non-uniformity of the pressure distribution in front of the nozzles is not a determining factor in the formation of an uneven distribution of flow rates over nozzles. That is, those measures that are aimed at equalizing the pressure field in the cavity of the mixing head cannot always yield a positive effect. Therefore, it is necessary to study the influence of other factors, in particular, the design differences of each specific nozzle.

![Figure 5. Isobars \( p_0 / p_{\text{ave}} \).](image)

When conducting the planned active experiment, four factors are taken into consideration. While the influence of the geometrical coordinates of the nozzles on the non-uniformity parameters is obvious and can be confirmed by the results of numerous tests, the estimation of the influence of other factors is not a well-studied problem. On one hand, concerning the influence of the blowdown flow rate, there is a number of studies [10], in which it is shown that the non-uniformity level can change with the change of the former. At the same time, it was shown in [11–12] that, with a change in the blowdown flow rate, the character of the component distribution over the nozzles practically does not change, and for a number of modes the non-uniformity level does not change either. It is probable that for hydrodynamic processes of component distribution in the cavity of the mixing head, a self-similarity mode with respect to the regime parameter is possible (Reynolds criterion at the input) and this is quite typical for hydrodynamic processes. The influence of the design features of an individual nozzle is interesting for studying, because this factor can be purposefully controlled to optimize the distribution processes [13].

Figure 6 presents the analysis of sensitivity of the non-uniformity criterion with respect to the considered factors, performed using the ANSYS DesignXplore engineering analysis environment. As follows from the figure, the first, second, and fourth factors are significant.
Further, this conclusion is confirmed as follows. Based on the results of the experiment, a number of regression models are constructed with a gradual sophistication of their structure, namely, with an increase in the number of model arguments, factors. That is, the dependence $\hat{m}_n / \hat{m}_m = f(x_n, y_n)$ is first constructed, then $\hat{m}_n / \hat{m}_m = f(x_n, y_n, \hat{m}_2)$, and, finally, $\hat{m}_n / \hat{m}_m = f(x_n, y_n, \hat{m}_2, K_n)$. Then it is tracked how the approximation error changes with the sophistication of the model. If the approximation accuracy increases significantly when adding a new factor to the model, then this factor is significant, and it is included in the model. If an increase in accuracy does not take place (or it is small), then, consequently, the influence of this factor can be neglected.

In the case of the dependence $\hat{m}_n / \hat{m}_m = f(x_n, y_n)$, the regression equation has the form:

$$x = 0.5x_n + 0.5, \quad y = 0.5y_n + 0.5;$$

$$\hat{m}_{NN} = 16.1846 \frac{1}{1 + \exp(-30.32298x - 1.58556y + 15.82484)} - 17.12495 \frac{1}{1 + \exp(-16.7123x - 1.610292y + 8.976079)} - 4.219266 \frac{1}{1 + \exp(5.64236x - 2.688651y + 1.932858)} - 21.45143 \frac{1}{1 + \exp(-0.3009444x - 1.879881y + 2.409203)} - 8.105892 \frac{1}{1 + \exp(1.366727x + 4.625359y - 4.539601)};$$

$$\hat{m}_n / \hat{m}_m = (\hat{m}_{NN} - 10.2325) / 10.78729.$$

In this case, the standard structure of the neural network computing architecture based on the perceptron with 5 neurons in one hidden layer is used (this explains the NN index – Neural Network).
Carrying out similar calculations, we obtain the dependences

\[ \bar{m}_n / \bar{m}_w = f (x_n, y_n, \bar{m}_N) \]

and

\[ \bar{m}_n / \bar{m}_w = f (x_n, y_n, \bar{m}_N, K_{r_n}) \].

Moreover, the approximation error when adding the blowdown flow rate \( \bar{m}_N \) to the number of factors decreases from 0.004825 to 0.004686, i.e. a change in the blowdown flow rate does not lead to a significant change in the character of the component distribution over the nozzles. When the parameter \( K_{r_n} = \bar{m}_{\text{aut}} / \bar{m}_{\text{aut}} \) is added to the number of factors, the approximation error further decreases from 0.004686 to 0.002739, which confirms the significance of the factor \( K_{r_n} \) which reflects the design differences of individual nozzle.

Figure 7 presents a comparative graphical analysis of the approximation dependences

\[ \bar{m}_n / \bar{m}_w = f (x_n, y_n, \bar{m}_N, K_{r_n}) \]

and experimental results.

![Figure 7. Comparison of approximation with experiment (Re_p=226000).](image)

It should be noted that the formed regression dependences are valid only for this particular arrangement of nozzles and their number. The obtained dependences are supposed to be used at the stage of refining this nozzle head in terms of the non-uniformity level of the component distribution over the nozzles.

2.3. Results and discussion. Processing the physical experiment results

The simulation of hydraulic non-uniformity of fuel distribution among the sprayers of mixing devices, along with prognostication of its level, are urgent tasks, related to the design of heat exchangers and fuel distribution systems of combustion chambers in power systems. While solving the problems of LPRE efficiency and reliability, caused by imperfection of the carburetion system, it is advisable to conduct the planned experiment, using neuron-network response surfaces. The acquisition of the neuron-network dependence of discharge, occurring through the separate sprayer of the mixing head, determines the possibility of optimizing the hydraulic sprayer parameters, in order to reduce non-uniformity. The practical outcome of such optimization is the classification of sprayers. The use of sprayer classification solves the problem of non-uniformity of combustion product temperature in the nominal, throttling and forced draft modes. The elaborated procedure of tuning the groups of sprayers, combined into classes, to a specific discharge rate, is used as a supplementary method of mathematical simulation during the final development of the mixer head. It also allows us to reduce non-uniformity of combustion products in the chamber cross-section to the preset level, without reprofiling the air-gas channel of supply collectors, and reconfiguring the sprayer head, which will help to automate the development procedure, while reducing the product cost.
According to the results of experimental spills, which were carried for testing the mixer heads of combustion chambers and the gas generator, the research was conducted to examine the impact of the following factors on non-uniformity of discharge distribution over the sprayers, namely: 1) the geometric coordinates of sprayers; 2) the error of hydraulic sprayer parameters, resulting from technological defects; 3) the total mass rate of discharge through the mixer head, 5) the non-uniformity of static pressure distribution in the pre-sprayer cavity and the feed line. The statistical analysis testifies to considerable redistribution of discharge through the sprayers of the mixer head, in comparison with the autonomous spill of sprayers. Meanwhile, in different modes of spill, the pattern of redistribution does not practically vary. For example, the peripheral sprayers demonstrate the reduced rate of component discharge, while in central ones, the rate of discharge is higher, respectively. During experimental testing, the measurements of differential pressure in sprayers were conducted. The analysis of resulting dependencies shows that the pressure in the mixer head changes insignificantly, and, at least, the redistribution of the component over the sprayers can not be only reduced to non-uniformity of pressure distribution.

The most serious problem of thermophysical process study, closely related to the systematic approach, is the multidisciplinary character of the tasks being analysed, which require complex solution using knowledge from various scientific disciplines: hydrodynamics, heat transmission, chemical thermodynamics, strength study and materials science. The strategy of design optimization may involve the generation of effective methods of numerical calculation for simulating the conjugate heat-and-mass transfer in turbulent flows, as well as calculation of thermodynamic and thermophysical parameter distribution of combustion products, the estimation of convective and radiant heat exchange parameters, and the impact of operating temperature conditions of systems on their deformation mode.

3. Conclusion
Based on the results of the conducted research, the following conclusions can be drawn.

A plan of an active experiment was developed and the blowdowns of the model device of the mixing head were carried out. Arrays of experimental values of flow rates through the selected 18 out of 444 nozzles in various modes according to the blowdown flow rate are obtained. These 18 nozzles were autonomously tested. The errors in the hydraulic characteristics of the nozzles by the flow coefficient are -2.5% – +1.5% of the nominal value during autonomous tests. The non-uniformity level during the tests in the composition of the mixing head was -5.2% - +4.2%.

The nature and level of the flow rate non-uniformity of the component distribution over the nozzles does not correspond to the total pressure distribution in the cavity of the mixing head in front of the nozzles. The measures aimed at equalizing the pressure in front of the nozzles may not have a significant effect.

Regression nonlinear factorial models \( \dot{m}_n \), \( \dot{m}_w \) = \( f(x_n, y_n) \), \( \dot{m}_n \), \( \dot{m}_w \) = \( f(x_n, y_n, \dot{m}_w, Kr) \) are formed. The accuracy of the 4-factor model was RMS Error = 0.002739 compared to the value of RMS Error = 0.003686 for the 3 factor model and RMS Error = 0.004825 for the two-factor model. This comparison confirms the significance of the factor \( Kr = \dot{m}_{n,crit} / \dot{m}_{w,crit} \), which reflects the effect of the structural differences of individual nozzles on the component distribution over the nozzles. This conclusion allows further using this controllable factor to influence the nature of the distribution and optimize the component distribution over the nozzles to obtain a given distribution.

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