Improving the quality of modeling thermodynamic processes

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Abstract. On the example of modeling thermodynamic processes occurring in the on-board gasification system (OGS) of unprocessed liquid fuel residues in the tanks of the launch vehicle stage (LV), using a reduced physical model of the fuel tank – an experimental model installation (EMI) as part of an experimental stand (ES), the design parameters of which are determined (geometric parameters, coolant and characteristics of the model fluid) based on the theory of similarity of thermophysical processes occurring in the real design of the fuel tank of the LV stage according to the criteria of Reynolds, Nusselt, Prandtl, methodological recommendations are proposed to improve the quality of the process of theoretical and experimental research at the stage of scientific research (R&D).

1. Introduction

At present, the task of quality assurance at the stage of production, when the controlled parameters of the manufactured object can be checked against the normative and technical documentation, is well developed and widely used in all areas of industry.

The analysis of the current level of theoretical and practical achievements in the field of quality assurance at the stage of research showed that traditionally used methods to ensure the reliability of theoretical results by using known solutions for the process under study and licensed software products, confirmed by experiments and satisfactory convergence of the calculated and experimental data.

The known methods used in the design in the product creation cycle are aimed at ensuring the specified tactical and technical characteristics, reliability and manufacturability of the created complex technical system (CTS), when the specific design parameters of the CTS are defined [1-3].

At the stage of R&D to ensure the creation of CTS samples, in accordance with GOST R 58876-2020 [4], the introduction of validation and verification processes, ensuring the validity of mathematical and physical modeling, but for each specific problem solved it is necessary to develop appropriate tools to improve the quality of theoretical-experimental studies. In the proposed work, this problem is solved in the application to the creation of OGS.

The considered OGS is based on supplying a hot coolant into the tank, providing evaporation of the fuel component. In addition to solving the problem of passivation of fuel residues, gasification is an opportunity to extract unused energy resources, contained in the unreleased fuel residues, which in the future can be used, for example, for boostering a booster stage with a payload after shutdown of a boostering liquid-propellant rocket, descent from orbit, angular stabilization, etc. [5, 6].

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After conducting theoretical and experimental studies of the process functioning, the development of a methodology for selecting the optimal design parameters of the unreleased liquid fuel residue OGS begins. Obviously, the methodological, algorithmic and technical errors in the mathematical modeling, as well as methodological and technical errors in the physical modeling of the studied heat and mass exchange process lead to the fact that the developed methodology for selecting the design parameters of the created OGS will not only be suboptimal, but also unreliable. Accordingly, the further process of creating the OGS will be carried out according to incorrect initial data.

2. Problem statement

The purpose of the ongoing research is to develop a methodology to improve the quality of research of the heat and mass transfer process in the OGS of liquid rocket fuel residues in the tank.

It is proposed to consider the concept of "quality" at the stage of R&D as reliability. Accordingly, the formulation of the research problem is reduced to ensuring the reliability of mathematical and physical modeling by introducing validation and verification processes, in accordance with the underlying normative and technical documentation [4, 7]. Thus, after the validation and verification of the physical and mathematical model (PMM), presented in the form of a system of equations, and the physical model (PM) in the form of an EMI (the PM means a reduced fuel compartment element with a model fluid, where the heat carrier (HC) is fed at different angles), it will be possible to state that the developed PMM is acceptable for calculating the design parameters of the OGS.

Ensuring the reliability of the results of mathematical and physical modeling of the process under study is achieved through:

a) introduction of validation criteria for the PM, which allows, through the application of similarity theory, to ensure the closeness of the PM to the real heat and mass exchange process under study;

b) introduction of PM verification criteria, revealing violation of basic fundamental laws and determining numerical estimates, which allows timely eliminating methodical and technical errors, revealing failures of measurement system elements;

c) introduction of PMM validation criteria, corresponding to similarity of heat and mass exchange processes, occurring in real object for evaluation of proximity of values of similarity criteria of real object and PM;

d) introduction of PMM verification criteria, revealing violation of basic fundamental laws and determining numerical evaluations, in order to find and eliminate methodical, algorithmic violations.

e) introduction of quantitative criteria when comparing results of numerical and physical modeling, as well as comparing obtained data with known results.

3. Physical modeling of the heat and mass transfer process

When developing the PM process of heat and mass exchange in the OGS of liquid rocket fuel residue in the tank, the main criterion for the quality of physical modeling is the closeness of the PM (EMI) to the real spent stage of the LV. Ensuring the proximity of the physical model to the process under study requires the introduction and calculation of similarity criteria (Reynolds, Nusselt, Prandtl), for which both PMM and PM are used. Therefore, validation at the level of development of the physical model consists in assessing the proximity of similarity criteria values for the EMI and the real LV exhaust stage on the basis of similarity theory (determination of proximity of Reynolds, Nusselt and Prandtl criteria of processes occurring in the EMI to the processes occurring in the real tank of the spent stage LV).

Table 1 shows the values of similarity criteria Nu, Pr, Re for a real spent stage of the LV (the second spent stage of the «Soyuz-2.1.v» LV, on which the OGS is installed, by the example of the oxidizer tank (O)) in orbit, and EMI.

As the initial data are taken:

1. The spent second stage of the LV:

- diameter of the oxidizer tank 3.7 m (characteristic size);
- temperature of liquid oxygen 88 K, density 1140 kg/m^3,

- as a part of real stage of LV there is no OGS and accordingly no heat carrier system; as an example, a heat carrier with parameters: heat carrier temperature – 550C, heat carrier density at pressure of 5 atm. and temperature 550C is 0.72 kg/m^3.
2. EMI:
- model liquid - water;
- pressure in the EMI chamber: 3 atm;
- HC temperature: 100C;
- geometrical characteristics of EMI (Height x Width x Thickness, mm): 500*500*200 mm, height is the characteristic size;
- HC velocity near liquid surface: 5–7 m/s.

Fig. 1 shows the scheme of the developed methodology for improving the quality of research of the heat and mass transfer process in the OGS of liquid rocket fuel residues in the tank.

According to the scheme of the developed methodology for improving the quality of scientific research, after checking the correctness of the initial data by analyzing the open reference literature, the developed PMM is subjected to the validation process, that is, checking the compliance of the PMM with the real processes occurring in the in the tanks of LV.

To determine the closeness of the values of the Reynolds and Nusselt similarity criteria, the values of the following EMI parameters were varied: characteristic size, HC flow rate, inlet diameter. The Prandtl number for gases practically does not change with temperature change and is equal to 0.7–0.75 for polyatomic gases.

In the case under consideration, the Nusselt Nu, Prandtl Pr, Reynolds Re similarity criteria for the O tank of the «Soyuz-2.1.v». type LV with OGS and EMI must satisfy the following condition when carrying out the PM validation:

$$\frac{\boldsymbol{Re}_{\mathbf{LV}}}{\boldsymbol{Re}_{\mathbf{EMI}}} \approx \mathbf{1};\ \frac{\boldsymbol{Nu}_{\mathbf{LV}}}{\boldsymbol{Nu}_{\mathbf{EMI}}} \approx \mathbf{1};\ \frac{\boldsymbol{Pr}_{\mathbf{LV}}}{\boldsymbol{Pr}_{\mathbf{EMI}}} \approx \mathbf{1} \quad (1)$$

The similarity criteria are determined by the formulas:

$$Pr = \frac{\nu}{\mathrm{a}}; Re = \frac{wD}{\nu}; Nu = \frac{\alpha l}{\lambda}, \quad (2)$$

where: w is the HC input rate, λ is the thermal conductivity, α is the heat transfer coefficient, ν is the kinematic viscosity, a is the thermal conductivity coefficient, $\boldsymbol{l}$ is the characteristic size.

Table 1. Values of similarity criteria of the oxidizer tank of the real spent stage of LV of «Soyuz-2.1.v» type launch vehicle with OGS and EMI

		Oxidizer tank of the real spent stage of LV	EMI
1	Characteristic size, m	3.7	0.5
2	Diameter of the inlet, m	0.03	0.03
3	Speed HC, m/s	15–25	5–7
4	Kinematic viscosity HC, m^2/s	$1\cdot10^{-4}$	$15\cdot10^{-6}$
5	Reynolds criterion, Re	$1.5\cdot10^5$–$3\cdot10^5$	$1.5\cdot10^5$–$3\cdot10^5$
6	Nusselt criterion, Nu	370–420	370–420
7	Prandtl criterion, Pr	0.7–0.75	0.7–0.75

As follows from Table 1, the similarity criteria for the O tank of the «Soyuz-2.1.v» type carrier rocket with the OGS and EMI are in the same design range. The similarity criteria satisfy the condition: $\frac{\boldsymbol{Re}_{\mathbf{LV}}}{\boldsymbol{Re}_{\mathbf{EMI}}} \approx \mathbf{1};\ \frac{\boldsymbol{Nu}_{\mathbf{LV}}}{\boldsymbol{Nu}_{\mathbf{EMI}}} \approx \mathbf{1};\ \frac{\boldsymbol{Pr}_{\mathbf{LV}}}{\boldsymbol{Pr}_{\mathbf{EMI}}} \approx \mathbf{1}$

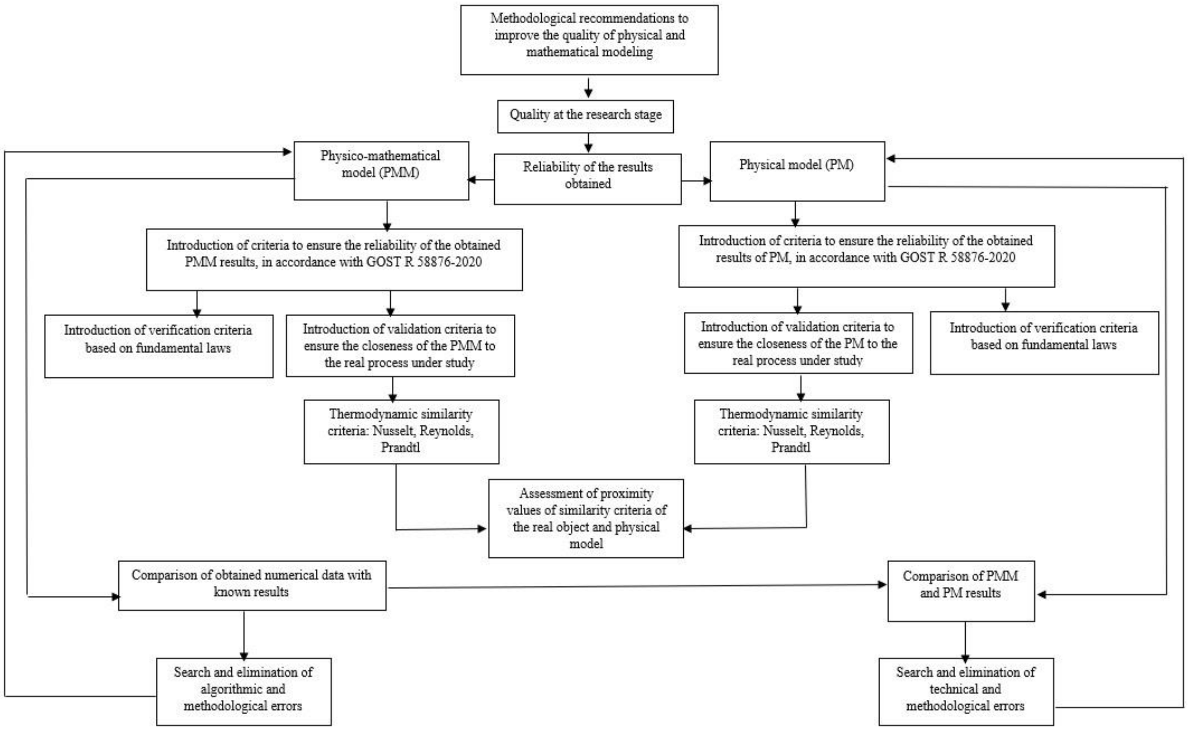

Figure 1. Scheme of the developed methodology to improve the quality of research

To improve the quality of scientific research, it was necessary to carry out a number of additional measures aimed at modernizing the existing ES and the composition of the measuring equipment outlined in [5].

Figure 2 below shows the scheme of the process of application of the proposed approach in order to improve the reliability of PM [5]. By introducing the proposed requirements and validation and verification criteria [8], which allow improving the quality of theoretical-experimental studies, the following results are achieved:

- rejection of invalid measurements;
- timely troubleshooting;
- reduction of the resources spent on the experiment.

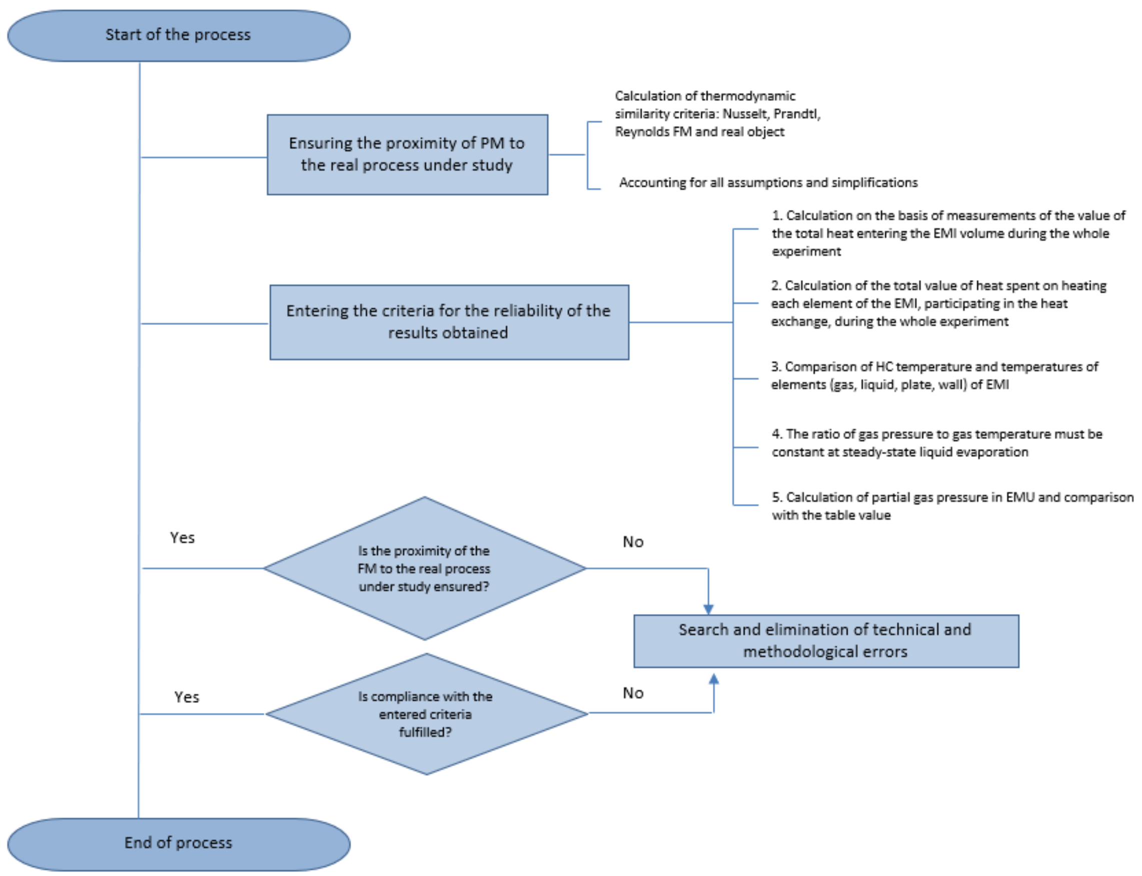

Figure 2. Schematic of the process of increasing the reliability of PM

4. Conclusions

Evaluation of the effectiveness of the proposed approach to improve the quality at the stage of scientific research showed that the reliability of the obtained information (calculated and experimental) increased by 10 – 15% [5], the cost of resources for research decreased by 20–25%, the time for debugging the program of numerical simulation reduced by 15–20%, increased productivity was 22%.

5. Discussion of results

The proposed approach in the particular case under consideration covers mathematical and physical modeling, for each of which a set of mechanisms for ensuring the reliability of the obtained results of modeling is presented, which corresponds to the requirements of the main normative and technical documentation [4, 7]. However, when solving the problems of increasing the reliability of simulation results in the application to the creation of any new CTS, it is necessary to develop appropriate methodological recommendations to improve the quality of theoretical and experimental research.

The implementation of the methodology for improving the quality of theoretical and experimental research is based on the well-known management formula PDCA (Plan-Do-Check-Act). The main provisions of the developed method do not contradict the classical method of process quality management. Application of the process approach in the creation cycle at the stage of research and development works allows to present reliable scientific and technical products at the output, which, in its turn, is the input of the stage of development works for formation of optimal tactical and technical characteristics of CTS.

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