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Developing a Test Stand to Verify Accuracy of Conducted Research at the Early Design Stages of Active Descent Systems of Spent Launcher Stages

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Abstract

Background/Objectives: This article deals with the make-up of a test bench and justifies selected parameters of an experimental model unit, heat carrier and model liquid. **Methods:** The authors employed mathematical and physical simulation. It should be stated that the necessity of solving a number of specific problems arises during physical simulation. **Findings:** A physical model of model liquid gasification has been described. A methodological approach has been suggested to assure accuracy of physical simulation as exemplified by investigation the model liquid gasification process based on a set of criteria that ensure accuracy and objectiveness of the physical model. The efficiency of suggested measures for enhancing experimental research accuracy has been provided. Due to the application of the suggested methodological approach on the developed test bench, the following results are achieved: experimental research data accuracy is enhanced; measurement reliability is enhanced; and fewer resources are spent for the experiments. **Application/Improvements:** Basic criteria of physical simulation in the field of heat and mass transfer that were developed are universal, simple and easy to be applied to research of a great variety of sophisticated technical systems.

Keywords: Accuracy, Assumptions, Criteria, Design, Gasification, Physical Model, Test Bench

1. Introduction

Great attention should be paid to the necessity of application of any procedures that allow us to determine the quality of developments, when developing aircraft and rocket engineering visions at the research and any further stages.

The concept of quality means a degree of conformity of a set of inherent characteristics of an object to the requirements according to ISO 9000:2015; however, it is suggested that the quality should imply accuracy, i.e. a degree of closeness to actual results, for this research for the research stage. Accordingly, accurate and justified scientific and technical documentation should be developed. Actual research results shall mean any results that are verified by experimental tests for this research.

Basic requirements to any developed sophisticated technical system that does not have any prototypes are at the formative stage at the initial design stage and appropriate research techniques are in need of additional adaptation. Accordingly, there are not any reference bases usually available, and the probability of erroneous project solutions is rather high.

As long as any errors that are made at the research stage lead to non-optimum tactical and technical characteristics of the developed systems and devices that may not manifest at further design stages, but in operating conditions only (increased operation and maintenance costs, low efficiency, lower performance, as compared to competitive devices, reduced reliability etc.), which ultimately result in a low-performance developed system.

Accuracy assurance techniques for theoretical research by using known equations of the investigated process, licensed software applications, confirmable

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experimental computational data and fair convergence of computational and experimental data were usually applied at the research stage[1–4].

According to our analysis of research associated with this problem on the basis of open materials, approaches, concepts and methods that reflect the specifics of a developed sophisticated system are considered in each case of development of such system, at the same time design stages are not considered but after formation of the given design parameters, i.e. after the research stage[5–7].

Therefore, there is a necessity to develop appropriate tools to resolve this problem. A class of design problems of developing an active on-board system of descent of space-related rocket stages from orbits and ascent trajectory after they fulfilled their mission involves recovery of energy resources that are contained in non-used liquid rocket fuel residues in the space-related rocket stages following shut-off of a liquid propellant propulsion engine and utilization is unique and unprecedented. Implementation is associated with serious financial costs and time, therefore minimization of any errors (methodical, mechanical etc.) is highly relevant.

A design stage comprises mathematical simulation, methodical approach that ensures quality (accuracy) of mathematical description of an object at the research stage (described in[8]) and physical simulation as well. It should be stated that the necessity of solving a number of specific problems, i.e. a degree of conformity of an Experimental Model Unit (EMU) with the research objectives, a degree of accuracy of findings and their correlation with natural physical processes, arises in physical simulation.

The proposed methodological approach to assuring accuracy (quality) of physical simulation is exemplified by investigation of heat and mass exchange processes in operation of an autonomous on-board descent system of space-related spent rocket stages using sustainer liquid propulsion engines[9].

The main specifics of this physical simulation is multi-attribute limitations of the heat and mass exchange process in conditions of uncertainty of the initial and border-line set-up of conditions.

2. Concept Headings

2.1 Developing a Test Bench

The necessity of physical simulation of a gasification process is determined by the following objective reasons:

- the necessity of determining heat and mass exchange factors that are determined exclusively by an experiment for the given process conditions;
- verifying correctness of basic assumptions taken and accuracy of mathematical simulation results of the previous stage;
- discovering specifics of the dynamic nature of the process that are not accounted for at the stage mathematical simulation (angles of incident of a heat carrier, structural tank members etc.).

The analysis of the existing physical model of the gasification process and results of earlier experimental research[10,11], using a test bench (Figure 1), revealed the necessity of assuring accuracy of the research results.

2.2 Justifying Adequacy of a Physical Model of the Explored Process

A test bench that is used for physical simulation comprises the following (see Figure 1):

- an experimental model unit, comprising devices for placement of a model liquid and introduction of a heat carrier;
- a compressor, a receiver, and a heater;
- a filtration system designed for cleaning the heat carrier of moisture, oil and mechanical impurities;
- connecting fittings and shut-off valves;
- a measurement and data registration system, with an accuracy: pressure (0.075%), heat carrier rate (0.3%), temperature (1%), gas humidity (1%), heat carrier flow (4%) sensors and a speed camera.

An experimental model unit has been designed and manufactured for simulating thermodynamical processes to simulate an elementary separated volume of an actual construction. Design parameters of the experimental model unit were determined based on the conditions of imitating heat and mass transfer processes that take place in actual second stage tanks (block I) of the Soyuz-2.1v space rocket at gasification of rocket fuel at the ballistic phase of flight.

Using the condition of similarity of criteria Sh=idem, Re=idem, experimental research of processes of heat carrier flowing to the surface and liquid evaporating in various border-line conditions can be conducted [12].

The configuration of the test bench and basic parameters are given in Table 1.

Table 1. Test bench configuration

	System	Configuration	Designation	Basic parameters
1	Experimental model unit	Insulated vessel with liquid placement and heat carrier introduction units	Simulates the separated volume of the liquid-containing fuel tank and process of interaction between the heat carrier and gas-supplied liquid at acoustic effect.	Dimensions: HxWx-D=500x500x200 Evaporated liquid weight - up to 100 g Liquid placement alternatives: 'mirror', 'drops'.
2	Heat carrier processing system	Compressor, receiver, heater	Simulates gas generator operation	Rates per second: 100 – 200 L/min; Temperature: 70 – 100^{0}C
3	Gasification variable measurement and data processing system	Pressure, gas, temperature and humidity sensors, speed camera	Monitoring input and output gasification process variables	Measurement accuracy in accordance with the specification, simulation accuracy up to 15-20%,

When designing the test bench, developing gasification experiment techniques and schedule for model liquids, a control volume approach[13] that relies on adhering to macroscopic physical laws is most preferred.

The key idea of this method is dividing a computational domain into a certain number of non-overlapping volumes and integrating initial differential equations.

While taking the hypothesis for slow rate of curvature of the fuel tank lip, the wall may be assumed flat and heat exchange conditions for a flat wall may be considered. Availability of vibration dampers of free liquid fuel surfaces in flight allows considering the total fuel tank volume as divided into several separated volumes. At the same time, behavior of thermodynamic processes in all the separated volumes is assumed identical.

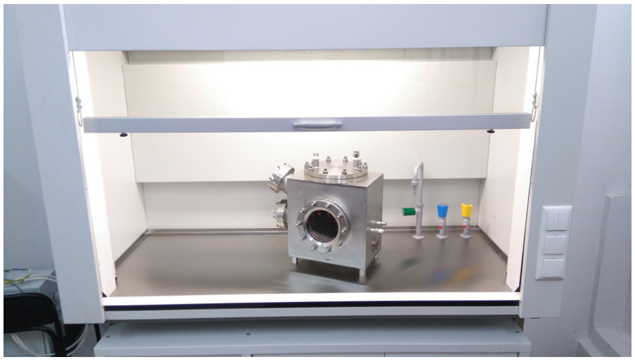

Figure 1. Experimental model unit for exploring a model liquid gasification process.

According to these conditions, the following parameters of the experimental model unit, heat carrier and model liquid are taken:[11]

- heat carrier velocity and flow rate at the input of the experimental model unit are taken based on the similarity condition according to Reynolds number and correspond to the following: V_{HC} = 4 - 7 m/sec; $\dot{m}_{HC} = 4-5$ g/sec;
- dimensions of the experimental model unit are selected according to the condition of reference length that is required for calculation of similarity numbers and simulation of heat and mass transfer processes at gage pressure and correspond to the following: HxWxD=500x500x200 mm;
- weight of evaporated model liquid is 5-100 g, which is enough for simulating various border-line conditions of model liquid position of 'mirror' or 'drop' type that are determined by the possible placement of rocket fuel component residues in launcher tanks at the ballistic phase of flight following shut-off of a liquid propulsion engine;
- parameters of the heat carrier that is introduced into the experimental unit and selected based on the similarity condition according to Prandtl numbers in the range of Pr = 0,7 ÷ 0,76. Temperature of the introduced heat carrier is in the range of T_{HC} = 340 ÷ 360K, which corresponds to the gasification process temperature of fuel residues in actual space-related rocket stage fuel tanks.
- the model liquid was selected under the condition of assuring similarity according to Kutateladze criterion. The following were taken as model liquids: kerosene (it corresponds fully to the fuel that is used in space-related rockets), water and water and alcohol mixes (to be close to actual rocket fuel components, correlations factors were determined for these compositions according to criterial equations.

2.3 Ensuring Accuracy of Physical Simulation

The proposed method of experimental research accuracy (physical model quality and measurement quality) enhancement involves the following stages that aim at brining experimental research to conformity with the given conditions and evaluating process criteria[14]:

- The second law of thermodynamics (heat is transferred from a hotter to a colder body) must be observed in experiment at any time, and temperature of the heat carrier T_{HC} and temperature of the experimental model unit T_i is compared to verify abidance by the above law:

$$T_{HC} \geq T_i,\ i = 1...N, \quad (1)$$

where, N is number of temperature sensors installed inside the experimental model unit.

If condition (1) is violated, the experiment is stopped and any faults in the measurement and data registration system are identified.

- Gas temperature and pressure inside the experimental model unit are determined according to sensors in the steady state of the liquid gasification process with the gas temperature inside the experimental model unit constant $\left(\frac{dT_G}{d\tau}=0\right)$, and the process is stopped and any faults in the measurement and registration system are identified, if condition $\frac{P_G}{T_G}=const$ is not satisfied.
- Based on the measurements of relative gas humidity in the experimental model unit volume, partial pressure at gas temperature in the experimental model unit is calculated T_G:

$$P_n^* = \varphi \cdot P_{SAT}, \quad (2)$$

where, P_n^* - partial gas pressure in the experimental model unit, P_{SAT} - saturated gas vapor pressure in the experimental model unit, φ - relative gas humidity in the experimental model unit.

The resulted value is compared with the table value P_n^0:

$$\left|P_n^0 - P_n^*\right| \geq E_p, \quad (3)$$

where, E_p includes all instrumental and methodological errors, and the experiment is stopped and any faults of the measurement and data registration system are identified, provided this condition is satisfied.

- The first law of thermodynamics (law of conservation of energy inside the system) must be observed in experiment at any time, and heat amount at the input of the experimental model unit $Q_0^*(\tau)$ and heat amount spent to maintain the model liquid gasification process $Q_0^*(\tau)$ are compared, according to the measurements, to verify abidance by the above law.

Total heat amount spent for heating all EMU heat exchange members at any time is calculated as follows:

$$Q_\Sigma^*(\tau) = Q_G(\tau) + Q_L(\tau) + Q_P(\tau) + Q_S(\tau) + Q_{EVP}(\tau) + Q_D(\tau) \quad (4)$$

where, $Q_G(\tau) + Q_L(\tau) + Q_P(\tau) + Q_S(\tau) + Q_{EVP}(\tau)$ - accordingly, heat amount spent for heating gas, liquid, plate in the vessel, experimental model unit structure, model liquid evaporation; $Q_D(\tau)$ - heat amount taken out of the experimental model unit volume for drainage at any moment.

Based on the measurements at current time, total heat amount introduced into the experimental model unit volume throughout the experiment is calculated as follows:

$$Q_\Sigma^0(\tau) = c_{HC} \cdot \dot{m}_{HC}(\tau) \cdot T_{HC}(\tau), \quad (5)$$

where, c_{HC} - specific heat carrier heat (table value); $\dot{m}_{HC}(\tau)$ - measured heat carrier consumption rate;

$T_{HC}(\tau)$- measured heat carrier temperature; τ - measured experiment time, and calculated values $Q_0^*(\tau)$ are compared with $Q_\Sigma^*(\tau)$, and provided condition is satisfied:

$$\left|Q_\Sigma^0(\tau) - Q_\Sigma^*(\tau)\right| \geq E_Q(\tau), \quad (6)$$

where, $E_Q(\tau)$ includes all instrumental and methodological errors, experiment results are considered incorrect, the experiment is stopped and any faults of the measurement and data registration system are identified.

- Components $Q_L(\tau)$, $Q_P(\tau)$, $Q_S(\tau)$, $Q_{EVP}(\tau)$ will be functionally defined in expression (4) by the heat exchange surface and heat and mass transfer factors.

The law of heat exchange between the gaseous phase in the experimental model unit and heat exchange surfaces is determined for the laminar boundary layer by:

$$St(\tau) = f\left(\Psi(\tau), \mathrm{Re}_H^{**}(\tau), \mathrm{Pr}(\tau)\right) \quad (7)$$

where, $\Psi(\tau)$ - wall permeability factor; $\mathrm{Re}_H^{**}(\tau)$ - Reynolds number, calculated for the boundary heat layer, $\mathrm{Pr}(\tau)$ - Prandtl number for the gaseous phase inside the experimental model unit.

The law of heat exchange between the gaseous phase in the experimental model unit and heat exchange surfaces is determined for the turbulent boundary layer by:

$$St(\tau) = f\left(\Psi_{HC}(\tau), \Psi_W(\tau), \mathrm{Re}_H^{**}(\tau), \mathrm{Pr}(\tau)\right), \quad (8)$$

where, $\Psi_{HC}(\tau)$ - HC flow non-isothermality parameter; $\Psi_W(\tau)$ - wall permeability factor.

- Energy-related gasification process behavior may be determined, using the following partial criteria:[12]

$$J_{Qi} = \frac{Q_i}{Q_\Sigma^0} \quad (9)$$

where, Q_i is total heat amount spent for heating of all heat exchange members of the EMU and included in equation (4).

Experimental research that was conducted allowed us to determine heat transfer factors from the gas to the plate and from the heat carrier to the gas, which reduce research accuracy, as long as heat transfer factors from the gas to the liquid and experimental model unit walls and from the liquid to the plate must be determined additionally.

A number of additional measures aiming at modernization of the existing test bench[14,15], make-up of the measurement equipment (Figure 2) and concurrent simulation of gasification process behavior of the model liquid in the experimental model unit, using standardized software complexes, are required to implement the research quality improvement program:

- installation of a new electric heater comprising a proportioning integral differentiating control to maintain heat carrier temperature constant;
- heat insulation of the electric heater for the heat carrier and fittings to reduce heat losses;
- reduction in hydraulic losses and enhancement of efficiency due to a shortened length of connecting pipelines and increased flow cross-section;
- installation of mobile heat carrier flow sensors inside the experimental model unit;
- installation of a gas humidity sensor (hydrometer) inside the experimental model unit;
- installation of extra mobile temperature sensors inside the experimental model unit;
- division of the plate surface into smaller cells of 40x40 mm;
- alignment and metrological calibration testing of all devices (setting the required measurement range and accuracy, installation of speed, humidity and mobile temperature sensors in the required points of the experimental model unit);
- development of an additional experiment schedule with account for the above accuracy criteria introduced.

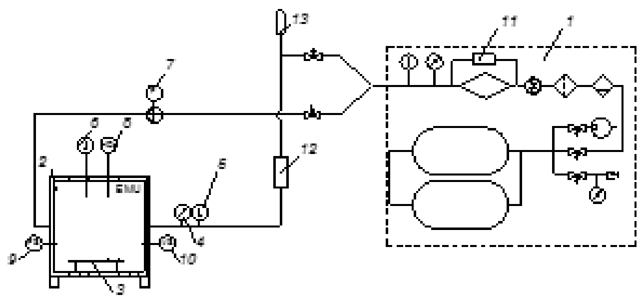

Figure 2. Modernized test bench layout: 1 – heat carrier processing system; 2 – experimental model unit; 3 – plate surface, where model liquid is located; 4 – pressure sensors; 5 – temperature sensors; 6 – mobile temperature sensors; 7 – heat carrier flow rate sensors; 8 – gas humidity sensor (hydrometer); 9 – mobile sound frequency and amplitude sensor; 10 – mobile heat carrier flow velocity sensor; 11 – heat-insulated electric heater; 12 – gas analyzer; 13 – utilizer.

3. Results

Experimental research conducted with the use of a modernized test bench allows us to enhance research accuracy and objectivity due to the following made possible[16]:

- determine heat carrier flow velocity in various points of an experimental model unit and compare with computer simulation data;
- determine gas humidity at the output of the experimental model unit;
- reduce heat carrier temperature differential at the input of the experimental model unit;
- determine temperatures of all heat exchange members (model liquid, plate, structural members of

the experimental model unit, and heat carrier);

- determine more precisely surface area of evaporated model liquid, using meshing method for the explored surface;
- discover any measurement errors and faults of measurement system elements at any time and stop the experiment properly.

Based on the above, the following results are achieved:

- due to screening of inaccurate measurements and properly discovered faults, the accuracy of experimental research results improves;
- measurement reliability is enhanced; and
- less resources are spent for the experiments.

Cost diagram of energy resources for 3 experiments before and after modernization of the physical model is provided in Figure 3.

According to the results presented in Figure 3, cost of energy resources for the experimental research was reduced approximately by 20-25% following modernization of the physical model.

At the same time, man-hours for 3 experiments, based on the condition that at least two persons must conduct an experiment for it to be safe, are[17]:

- before modernization of the physical model: 2 men *0.66 Hr * 3 exper. =3.96 man-hours;
- after modernization of the physical model: 2 men *0.5 Hr * 3 exper.=3 man-hours.
- Reduced labor inputs after modernization of the physical model is determined by the following:
- stopping the experiment at the onset of the steady-state of the gas-liquid system temperature;
- reduced processing (heating) time of the heat carrier to the given temperature due to heat insulation of the electric heater and fittings.

Measurement accuracy increased by approximately 10-15% due to the following:

- reduced heat carrier temperature differential at the input of the experimental model unit following insulation of the electric heater and fittings from (342-361) K to (348-356) K.
- determining evaporated liquid area, using meshing of the plate surface into smaller cells of 40 x40 mm.

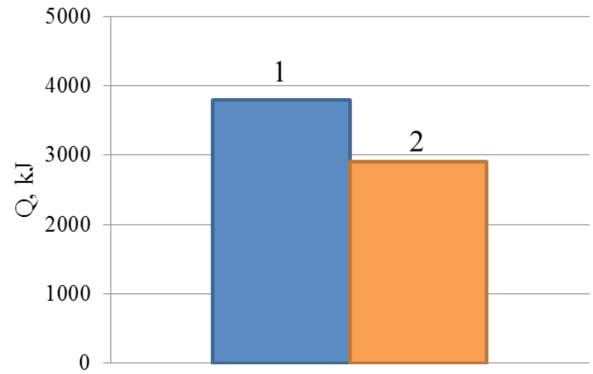

Figure 3. Cost diagram of energy resources for experiments: 1 – before modernization of a physical model; 2 – after modernization of a physical model.

4. Conclusion

The proposed methodological approach to enhancing accuracy of physical simulation, using a liquid gasification process as an example, allows us to improve quality of our results.

Basic criteria of physical simulation in the field of heat and mass transfer that were developed are universal, simple and easy to be applied to research of a great variety of sophisticated technical systems.

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