Formation of requirements to the laboratory experimental unit under condition of continuation of researches of processes of heat and mass transfer on a model experimental unit

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Abstract. Theoretical results of modeling of vacuum process of evaporation of model liquid in closed volume, carried out for experimental laboratory unit (ELU) and experimental model unit (EMU), differing in size, boundary and initial conditions are considered. The parameters of EMU are determined on the basis of the theory of similarity to the processes taking place in the tank of the launch vehicle stage in the field of small overloads, and the parameters of the ELU selected from the conditions of the existing laboratory equipment. The correlation functions of the process parameters (mass and temperature), showing the degree of proximity of the processes, have been calculated on the example of the process of liquid evaporation under vacuum effects for ELU and EMU, obtained by using the ANSYS Fluent software package. In the course of numerical experiments the vacuum pump capacity was varied to ensure equality of Nusselt criterion for ELU and EMU.

1. Introduction
In [1] the correlation between two types of fluid boiling processes is considered and a dimensionless parameter is introduced on the basis of similarity analysis. In work [2] the heat transfer process of jets with experimental confirmation of the adopted turbulence model is considered. In work [3] the scaling criteria of experiments at low pressure, low temperature of liquid in a closed tank are considered. It is shown that to ensure the similarity between the prototype and the model it is necessary to keep the ratio of liquid density and evaporation, the number of Froude and the number of Reynolds. In [4] the scaling elements influencing the heat transfer coefficient are considered. It is shown that the use of the scaling procedure allows to clarify the heat transfer coefficient.

In [5], on the basis of similarity theory (Nusselt, Reynolds criteria, geometric similarity) the parameters of EMU corresponding to the processes of heat and mass transfer occurring in the fuel tank of the launch vehicle during evaporation of the fuel component are defined. In [6, 7] the heat and mass transfer processes in the ELU without taking into account the scaling were investigated. In this work the heat and mass transfer processes in ELU and EMU are compared in order to determine the correlation of the processes under consideration and the influence on the correlation of similarity criteria.

2. Problem formulation
The evaporation process of the model liquid (water) in a closed storage tank under the following assumptions is considered:
- The liquid is located at the bottom of the storage tank as a free surface mirror;
- The volume fraction of water vapor in the storage tank volume at the initial moment is 0.001;
- The minimum diameter of water vapor particles is constant and is 0.00001 m.
At mathematical modeling in ANSYS Fluent the laminar model of viscosity is selected, the calculated grid is reduced near the lower edge, the method of solution is selected by the scheme SIMPLE. Liquid evaporation is determined by Hertz-Knudsen formula [8]:

$$m_{lv} = \beta \frac{M}{2\pi RL} \left( \frac{\rho_l}{\rho_v} \right) \left( \frac{T' - T_{sat}}{T_{sat}} \right)$$

where:
- $M$ is molar mass of the liquid,
- $R$ is gas constant,
- $\rho_l$ is liquid phase density,
- $\rho_v$ is vapor phase density,
- $L$ is heat of vaporization,
- $T'$ is steam temperature near the liquid in the tank,
- $T_{sat}$ is water saturation temperature at tank pressure,
- $\beta$ is accommodation coefficient.

Calculation schemes of EMU and ELU in ANSYS Fluent are presented in Figure 1, where 1, 2 are 2D models of EMU and ELU, respectively, 3 are inlet nozzles of the pump, 4 is location of liquid at the initial moment of time.

![Figure 1](image)

**Figure. 1** Calculation 2D schemes: 1 – EMU, 2 – ELU, 3 – pump inlets, 4 – liquid

On the analysis of the results of the evaporation modeling process of liquids in ELU and EMU under vacuum action, using the software package ANSYS Fluent, it is necessary to determine the proximity of the investigated processes. The parameters of the EMU were chosen on the basis of the theory of similarity to the processes taking place in the launch vehicle stage tank in the field of small overloads, and the parameters of ELU were chosen from the conditions of the existing laboratory equipment. Ensuring the equality of the Nusselt criterion for ELU and EMU during the whole numerical experiment is carried out by varying the vacuum pump capacity. Determination of the proximity of the liquid evaporation process parameters in ELU and EMU is based on correlation analysis [9].

3. **Comparative analysis of results and adjustment of ELU parameters**

Studies of liquid evaporation processes in a closed container (circuit diagrams of ELU, EMU are given in Figure 1) were carried out using the Ansys Fluent package under initial and boundary conditions given in Table 1.
Table 1. Initial and boundary modeling conditions

|                                | EMU   | ELU   |
|--------------------------------|-------|-------|
| Initial pressure, Pa           | 101325| 101325|
| Unit height L, m               | 0,72  | 0,78  |
| Characteristic size D, m       | 0,26  | 0,78  |
| Vacuum pump capacity, dm³/s    | 6.5   | 6.5   |
| Initial temperature, K         | 300   | 300   |
| Model Liquid                   | Water | Water |
| Liquid column height, m        | 0,02  | 0,02  |
| Unit volume, m³                | 0,1876| 0,6088|
| Vacuum suction operating time, s | 10    | 10    |

Below in the figure 2 presents the changes in pressure, temperature and volume fraction of liquid in EMU and ELU by initial and boundary conditions from Table 1.
Figure. 2 Graphs of changes: a) pressure, b) temperature, c) volume fraction of liquid in EMU and ELU

In figure 3 shows graphs of Nusselt criterion change for EMU and ELU. The deviation of the Nusselt criterion for EMU and ELU (a) is 42%, which does not correspond to the similarity of these processes. To obtain the similarity of the processes, according to [10], the characteristic size $D = 0.281$ m in ELU by geometric similarity:

$$\frac{L_{EMU}}{D_{EMU}} \sim \frac{L_{ELU}}{D_{ELU}}.$$  (2)
For the equality of $Re_{EMU} \sim Re_{ELU}$ Reynolds criteria, the performance of the ELU vacuum pump has been reduced by 5%. Results of recalculation are shown in figure 3b). As a result of these actions, the maximum deviation of Nusselt criterion during 8 seconds was less than 15%. During the last 2 seconds of calculation the deviation averaged 40%. It is connected with different values of pressure, volume fraction of liquid in EMU and ELU on the given range of time.

![Figure 3](image1.png)

**Figure. 3** Graphs of changes in the Nusselt criterion for EMU, ELU at: a) primary simulation by Table 1, b) after recalculation
In figure 4 shows the results of the correlation analysis of the given Nusselt numbers for: a) the first simulation of the evaporation process under the initial and boundary conditions given in Table 1, b) the simulation after recalculation of the characteristic size, pump capacity.

![Graph](image_url)

**Figure 4.** Correlations of the given Nusselt numbers for: a) the first simulation in Table 1, b) after recalculation

Graph in figure 4b) shows a better relationship of EMU and ELU Nusselt numbers (the closer to the straight line, the better the relationship), compared to the first variant of simulation figure 4a). The correlation showed improvement of EMU and ELU similarity conditions after correction of characteristic size and pump performance. At the same time, there are still areas where the relationship
of Nusselt numbers for EMU and ELU is broken. It is necessary to correct the parameters of the pump in the ELU again at points of greater deviation.

![Graph](image)

**Figure 5.** Deviation of Nusselt numbers in EMU and ELU after recalculation

The graph of deviations of EMU Nusselt number from ELU Nusselt number depending on time is presented as a histogram in the figure 5. According to the graph of deviations (figure 5) it follows that on 4-6 and 8-10 seconds of modeling the liquid evaporation process in the ELU, it is necessary to correct the performance of the pump (on 4-6 seconds reduction of performance, on 8-10 seconds increase of performance) for better correspondence of similarity of processes.

4. **Conclusion**
1. Theoretical results of modeling of vacuum process of evaporation of model liquid in closed volume, carried out for ELU and EMU, differing in size, boundary and initial conditions are considered.
2. The parameters of EMU are determined on the basis of the theory of similarity to the processes taking place in the LV tank in the field of small overloads, and the parameters of ELU are selected from the conditions of the existing laboratory equipment.
3. On the basis of correlation analysis of liquid evaporation processes under vacuum influence for ELU and EMU, requirements to parameters of pressure decrease process from Nusselt criterion proximity condition are considered.

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