Study of Heat Transfer Rate in Electric Evaporators of Liquefied Petroleum Gas Using Electrothermal Modeling

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Abstract. In modern domestic and foreign experience of gas power supply to houses and industrial facilities located remotely from the main power station, decentralized gas power supply systems fed with propane-butane mixtures of liquefied petroleum gases from tanks are increasingly used. When using liquefied petroleum gases as the main energy carrier in gas tank systems, they are evaporated artificially in evaporators with an intermediate solid-state or liquid heat transfer agent, under conditions of its natural convection. The main operational characteristic of industrial tube evaporators of propane-butane mixtures of liquefied petroleum gases used for gas power supply from tank installations of housing and communal, industrial and industrial facilities that are remote from the main power supply stations is evaporation capacity. The evaporation capacity of industrial tube evaporators of propane-butane mixtures with a solid-state intermediate heat transfer medium is determined by the heat input from the tubular electric heaters through the aluminum casting layer. Therefore, the study of heat transfer in the solid-state intermediate heat transfer medium-evaporation coil system is the most important prerequisite for the effective operation of industrial tube evaporators of propane-butane mixtures and requires detailed research. To solve the problem of determining the heat transfer resistance between the layers of aluminum casting in contact with the surface of the tubular electric heaters group and the outer evaporation coil surface studies were performed on an electrical model. The average value of the total error of the results of experimental studies on electrothermal modeling is 3.7 %, with a confidence probability of 95 %. Recommendations are given for reducing the thickness of the layers in clear from the lower coil of the evaporative tube coil to the lower generatrix of the solid-state aluminum mass and the upper coil of the evaporative tube coil to the upper generatrix of the solid-state aluminum mass.

1. Introduction

The main operational characteristic of industrial tube evaporators of propane-butane mixtures of liquefied petroleum gases (LPG) used for gas power supply from tank installations of housing and communal, industrial and industrial facilities that are remote from the main power supply stations [1-4] is evaporation capacity. The evaporation capacity of industrial electric evaporators of propane-butane mixtures of LPG with tubular electric heaters (TEH) of high specific power welded into a solid-state aluminum intermediate heat transfer medium is determined by the heat input from TEH.

Therefore, the study of heat transfer in the system "tubular electric heaters - evaporation pipeline" through a layer of solid-state intermediate heat transfer medium is the most important prerequisite for the effective operation of industrial LPG tube evaporators.
The issues of heat transfer in a mass with internal heat sources have been studied by many domestic and foreign authors. At the end of the XIX century, Forchheimer first proposed a formula that described the steady-state heat transfer between a semi-infinite mass and a linear source (drain) of heat energy of infinite length [5].

The issues of heat transfer in a mass of internal heat sources was studied by O. Krisher [5] A. Aronson and S. S. Kutateladze [6], P. J. Fine, H. V. Nguyen [7], R. Z. Homod, F. A. Abood [8].

G. Carslaw [9] and the L. R. Ingersoll [10] studied the features of unsteady heat transfer in mass with internal heat sources. The solutions proposed by these scientists are based on the assumption of isotropy of the thermophysical properties of the surrounding mass and differ from the known ones by the boundary condition description on the surface of the heat source.

Here, the authors use the principles of quasi-steady thermal states and superposition of temperature fields as the initial prerequisite for solving the heat transfer problem. This methodological technique has been tested in the practice of engineering calculations and has used both in experiments and on research simulators [6].

At the same time, the thermal interaction between the TEH and the propane-butane mixture evaporation pipeline in industrial tube evaporators with an intermediate heat transfer medium is poor studied.

A significant contribution to the formation and further development of the heat exchange theory was made by the research conducted by scientists P. M. Hoffman-Zakharov and N. E. Sapunov [11].

2. Methods

The evaporation capacity of industrial tube evaporators of propane-butane mixtures with a solid-state intermediate heat transfer medium is determined by the heat input from the TEH through the aluminum casting layer. The heat transfer resistance $R$ between the layers of the aluminum casting in contact with the surface of the TEH group and the outer surface of the evaporation coil characterizes the external heat transfer rate. Therefore, the study of heat transfer in the solid–state intermediate heat transfer medium-evaporation coil system is the most important prerequisite for the effective operation of industrial tube evaporators of propane-butane mixtures and requires detailed research.

At present, the method of electrothermal modeling is widely used in solving spatial problems of steady thermal conductivity in mass. The founders of this method were Langmuir and McAdams [12], who used it to study the steady heat flow passing through the ribs and corners of the furnace. This method is used widely in determining heat losses through the walls of rooms, flat temperature fields, and in other problems of steady thermal conductivity under complex boundary conditions with the impossibility of their analytical solution [12].

The electrothermal analogy is simple and clear and allows you to minimize the impact of so-called external sources associated with changes in the temperature and humidity of the environment. In addition, the electrical process is easily controlled and allows you to change and measure its physical parameters.

In order to determine the influence of: the step between the turns of the evaporation coil $S_2$, the distance $\delta_2$ between the outer side surfaces of the evaporation coil and the aluminum casting; the distance $\delta_3$ between the group of U-shaped TEH arranged in a circle and the vertical evaporation coil (EC); the thicknesses of the layers $C_2$ & $b_2$, respectively, the upper and lower ends of the solid-state mass, by the value of the heat transfer resistance $R$ in the system "vertical ECs - TEH group welded into a cylindrical aluminum mass", studies were carried out on the installation of electrothermal modeling (Figure 1).

The heat transfer resistance $R$ between the layers of the aluminum casting in contact with the surface of the TEN group and the EC outer surface characterizes the external heat transfer rate, in contrast to the known distance dependences $\delta_1, C_2, b_2$, is determined by the results of electrothermal modeling as:

$$R = \frac{F}{\lambda h_2} \left( S_2, \delta_2, \delta_3, C_2, b_2 \right),$$

Here $\lambda$ is the thermal conductivity coefficient of the aluminum mass, W/m*K; $F$ is the value of the shape factor of the heat exchanger in the "TEHs – EC" system; $h_2$ is the characteristic size of the heat
exchanger with a height equal to the aluminum casting. The system of restrictions of independent parameters $S_2, \delta_2, \delta_0, C_2, b_2$ is shown below:

$$\delta_2 = \delta_{2\text{min}}, \delta_{2\text{max}}; \delta_3 = \delta_{3\text{min}}, \delta_{3\text{max}}; S_2 = S_{2\text{min}}, S_{2\text{max}}; C_2 = C_{2\text{min}}, C_{2\text{max}}; b_2 = b_{2\text{min}}, b_{2\text{max}}$$ (2)

In the electrothermal modeling of volumetric steady temperature fields, a bath filled with an aqueous solution of electrically conducting salts was used as a conductive medium. The electrical model was made geometrically similar to the industrial evaporator under study (Figure 1), here the size of the evaporator $h_2$ is comparable to the size of the model $m \cdot h_2$ ($m$ - model similarity coefficient), the temperature difference $t_1 - t_0$ corresponds to the difference in electrical potentials $V_1 - V_0$, the value $\lambda$ corresponds to the value $\gamma$.

Given that the shape factor of geometrically similar devices for temperature and electric fields is the same, the study on the electrical model is to determine its value, according to the formula (3):

$$F(\delta_2, S_2, \delta_3, C_2, b_2) = I / \gamma (V_1 - V_0) h_2 \times m,$$ (3)

$I$ – the electric current, A; $\gamma$ – the coefficient of electrical conductivity of an aqueous solution of electrically conducting salts, A / m·V; $F$ – the value of the shape factor for the electrical model.

Here, the value of the form factor in formula (3) is numerically equal to the value of the form factor in formula (1).

**Figure 1.** Schematic diagram of the installation of electric thermal modelling.

1 –copper coil; 2 – an aqueous salt electrically conductive; 3 –U-shaped copper electrode simulating a TEH; 4 - housing.
The minimum and maximum values of independent variables in the system of limiting independent parameters (2) are justified as follows.

The minimum values $\delta_{\min}, S_{2\min}, \delta_{2\min}, C_{2\min}, b_{2\min}$ are determined by the method of casting molten aluminum into an integral mold, crystallization and cooling of the aluminum casting [13-15]. To ensure optimal conditions for crystallization, cooling aluminum casting, with a dense metal structure, to avoid voids, cracks, with the required adhesion of molten aluminum to the surface of the tubular electric heating elements and the evaporative tube coil during casting, as well as to achieve the required alloy strength and service life of the industrial evaporator, it is proposed to accept the following: $\delta_2 \geq 8.0 \text{ mm}$; $S_2 \geq 8.0 \text{ mm}$; $\delta_0 \geq 8.0 \text{ mm}$; $C_2 \geq 8.0 \text{ mm}$; $b_2 \geq 8.0 \text{ mm}$.

The maximum limit for changing the parameters $S_2, \delta_2, \delta_0, C_2, b_2$ is due to the fact that when they are increased to a certain value, the increasing of the evaporation capacity of the electric evaporator stops.

Let's assume that the electrical model is made similar to the industrial tube evaporator and the size $h_2$ of the evaporator corresponds to the size of the model $m \cdot h_2$, the potential difference $V_1 - V_0$ applied to the boundary surfaces of the electrical model corresponds to the temperature difference $t_1 - t_0$.

Let's transform and write down the equation for determining the value of the electric current value as follows:

$$ I = \gamma (V_1 - V_0) F_e (\delta_2, S_2, \delta_0, C_2, b_2) h_2 m, \quad (4) $$

where $F_e$ is the form factor of the electric model of an industrial evaporator of propane-butane mixtures; $m$ - similarity coefficient of the electric model.

The form factor of the model is numerically equal to the form factor of the thermal original of the industrial evaporator of propane-butane mixtures:

$$ F_e (\delta_2, S_2, \delta_0, C_2, b_2) = F_s (\delta_2, S_2, \delta_0, C_2, b_2) \quad (5) $$

Therefore, research on the model is to determine the form factor value:

$$ F_e = \frac{I}{\gamma (V_1 - V_0) h_2 m} \quad (6) $$

Given the known electrical conductivity of the medium and the size of the electrical model, the potential difference $V_1 - V_0$ applied to the model, and the value of the resulting current, we calculate the value of the form factor $F_e = F_s$.

Then we substitute the form factor determined by formula (6) into formula (7), and get the value of the heat transfer resistance $R$ between the layers of the aluminum casting in contact with the surface of the TEH group and the outer EC surface.

The heat transfer resistance $R$ between the layers of the aluminum casting in contact with the surface of the TEH group and the outer EC surface characterizes the external heat transfer rate and is defined as:

$$ R = \frac{F_s h_2}{h} F (S_2, \delta_2, \delta_0, C_2, b_2), \quad (7) $$

3. Experimental study

To solve the problem of determining the heat transfer resistance $R$ between the layers of aluminum casting in contact with the surface of the TEH group and the outer EC surface, according to the above method, studies were performed on an electrical model. Figure 1 shows a schematic diagram of an electrothermal modeling unit.

When performing experiments on electrothermal modeling, an electrolytic bath, which was filled with tap water we used a heat exchanger filled with aluminum. Experiments on electrothermal modeling [16-18] have shown that the use of natural electrolyte is quite justified. To minimize the effect of electrolysis, the electrical model was connected to an alternating current source with a frequency of 50 Hz.

The electrothermal unit for experimental studies was made with a similarity coefficient $m = 2.2$. The electrolytic bath in which the research was carried out was made of a piece of polyethylene pipe (PE-80
brand) with a diameter of 160 mm and a wall thickness of 15 mm and height of 145 mm (Figure 1). The analogues of the HEH and the evaporation coil were made of a copper wire with a diameter of 5.0 mm and a copper tube with a diameter of 10.1 mm, respectively (Figure 2).

We note that during the operation of tubular electric heaters, the energy per unit length of TEH is the same. At the same time, due to the voltage drop along the length of the U-shaped electrode in the model there is a change in current strength $I_{cond}$ along the length of the conductor $L_{cond}$.

In this regard, U-shaped copper conductors in the model were made of three separate stages of equal length, which were divided between a dielectric insert that ensure consistent current strength per unit length of the electrode (Figure 2).

Copper electrodes simulating TEH were placed radially at a distance of $\delta_3$ from the copper coil simulating EC. The copper coil was positioned so that its outer side surface locates at a distance from the inner surface of the electrolytic bath by $\delta_2$. The values $S_2, \delta_2, \delta_3, C_2, b_2$ were used taken into account the similarity coefficient of the model.

![Figure 2. Heat exchange elements of the electric model.](image)

In the first series of experiments on electrothermal modeling, all measurements were carried out at one fixed and constant value of the distance along the normal line, between the side surfaces of the EC and the tubular electric heater $\delta_3=6.0$ mm and fixed values of the step between the turns $S_2=6; 8; 12; 16; 20; 22$ mm with varying values of the distances between the side surfaces of the evaporative tube coil and the aluminum casting $\delta_3=6; 8; 12; 16; 20; 24; 30$ mm; so, for example, at constant values $\delta_3=6$ mm $=\text{const}$ and $S_2=6$ mm $=\text{const}$, the values of $\delta_3=8; 12; 16; 20; 24; 30$ mm varied.

Then, with fixed values $\delta_3$, the thickness of the intermediate heat transfer medium layer $C_2$ in clear was determined, from the top of the evaporation pipeline to the top of the intermediate heat transfer medium: 8; 16; 32; 40; 48; 56; 64; 70. With fixed values $C_2$ the thickness of the intermediate heat transfer medium layer $b_2$, was determined, in clear, along the normal line, from the bottom of the evaporation pipeline to the base of the heat transfer medium: 8; 16; 32; 40; 48; 56; 64; 70.

In the second series of experiments on electrothermal modeling, all measurements were carried out at a different fixed and constant distance along the normal line, between the side surfaces of the electric
heater and the tubular electric heater $\delta = 8.0 \text{mm}$; and fixed values of the step between the turns $S_2 = 6$; 8; 12; 16; 20; 22 mm, similar to the experiments of the first series of the study.

The analytical studies have shown that in the range of values –
- thickness of the intermediate heat transfer medium layer $C_2$, in clear, from 70 to 18 mm;
- thickness of the intermediate heat transfer medium layer $b_2$, in clear along the normal line, from 70 to 20 mm;

the value of the heat transfer resistance $R$ in the system "vertical evaporative coil - tubular electric heaters welded into a cylindrical aluminum mass" varies slightly.

This makes it possible, after an appropriate economic justification, to significantly reduce the thickness of the layers of the upper and lower ends of the solid-state mass, which in existing analogues are $C_{2, \text{est}} = 0.05 \text{ m}$ and $b_{2, \text{est}} = 0.07 \text{ m}$.

To determine the degree of reliability of the results of the conducted experiments on electrothermal modeling, according to [19-20], the error of the experimental data was estimated. The value of the average value of the total error of the results of experimental studies on electrothermal modeling is 3.7 %, with a confidence probability of 95%.

4. Conclusions

The calculated value (7) is obtained for determining the heat transfer resistance $R$ between the layers of the aluminum casting in contact with the surface of the TEH group and the outer EC surface, depending on a number of geometric parameters $S_2, \delta_2, \delta_1, C_2, b_2$. Using the method of electrothermal analogy, the values of the form factor $F_r = F_e$ are determined depending on a number of parameters $S_2, \delta_2, \delta_1, C_2, b_2$ in a wide range of their changes. The reliability of the results of the electrothermal modeling method is determined. The average value of the total error of the results of experimental studies on electrothermal modeling is 3.7 %, with a confidence probability of 95 %.

Recommendations are given for reducing the thickness of the layers in clear from the lower coil of the evaporative tube coil to the lower generatrix of the solid-state aluminum mass and the upper coil of the evaporative tube coil to the upper generatrix of the solid-state aluminum mass.

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