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Numerical analysis of influence of heat load on temperature of battery surface with cooling by a two-phase closed thermosyphon

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Abstract. Numerical analysis of thermal conditions of a two-phase closed thermosyphon using the software package ANSYS FLUENT has been carried out. Time dependence of temperature of heat source surface, which characterize the efficiency of thermosyphon at critical temperatures of batteries have been obtained.

1 Introduction

Problem with aircraft operation are the system thermal control heat-loaded aircraft equipment (batteries, controls, electronics) [1-2]. For example, when charging the lithium-ion battery of the aircraft there is a possibility of ignition due to its thermal runaway effect [3].

Two-phase closed thermosyphon are promising devices cooling and thermal control of various energy and technical systems [1, 4, 5].

Application thermosyphons allows increase cooling efficiency by reducing temperature gradients in the system.

Thermosyphons not been widely used, because so far not developed a general theory of heat transfer processes in such devices.

Modern studies of heat transfer through a two-phase closed thermosyphon mainly presented experimental data on heat and mass transfer processes [6-8]. At the same time, the number of works dealing with mathematical modeling of such processes is insignificant (for example, [9, 10]). Model [9, 10] describe only some particular cases of operation of such heat transfer devices, and do not consider the whole set of heat transfer processes in the vapor and liquid phases of the working fluid.

Purpose of the work - defining surface temperature of the battery when using a two-phase closed thermosyphon for cooling.

2 Formulation of the problem

Chart of the closed thermosyphon rectangular cross section considered in figure1.

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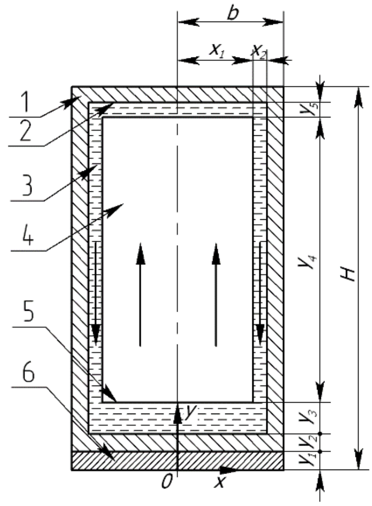

Fig. 1. Schematic diagram of the thermosyphon. 1 – body of thermosyphon; 2 – surface of condensation; 3 – liquid film; 4 – vapor flow; 5 – surface of evaporation; 6 – surface of heating source.

Mathematical model of thermal processes occurring in the study area is as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho \upsilon)}{\partial y}=0;, \quad (1)$$

$$\frac{\partial \rho_1 u_1}{\partial t}+\frac{\partial(\rho_1 u_1 u_1)}{\partial x}+\frac{\partial(\rho_1 \upsilon_1 u_1)}{\partial y}=\rho_1 g_x-\frac{\partial P_1}{\partial x}+\frac{\partial}{\partial x}\left(\mu_1\frac{\partial u_1}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_1\frac{\partial u_1}{\partial y}\right);, \quad (2)$$

$$\frac{\partial \rho_1 \upsilon_1}{\partial t}+\frac{\partial(\rho_1 u_1 \upsilon_1)}{\partial x}+\frac{\partial(\rho_1 \upsilon_1 \upsilon_1)}{\partial y}=\frac{\partial P_1}{\partial y}+\frac{\partial}{\partial x}\left(\mu_1\frac{\partial \upsilon_1}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_1\frac{\partial \upsilon_1}{\partial y}\right);, \quad (3)$$

$$\frac{\partial \rho_2 u_2}{\partial t}+\frac{\partial(\rho_2 u_2 u_2)}{\partial x}+\frac{\partial(\rho_2 \upsilon_2 u_2)}{\partial y}=\rho_2 g_x-\frac{\partial P_2}{\partial x}+\frac{\partial}{\partial x}\left(\mu_2\frac{\partial u_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_2\frac{\partial u_2}{\partial y}\right);, \quad (4)$$

$$\frac{\partial \rho_2 \upsilon_2}{\partial t}+\frac{\partial(\rho_2 u_2 \upsilon_2)}{\partial x}+\frac{\partial(\rho_2 \upsilon_2 \upsilon_2)}{\partial y}=\frac{\partial P_2}{\partial y}+\frac{\partial}{\partial x}\left(\mu_2\frac{\partial \upsilon_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_2\frac{\partial \upsilon_2}{\partial y}\right);, \quad (5)$$

$$\rho_1 C_{p1}\left(\frac{\partial T_1}{\partial t}+u_1\frac{\partial T_1}{\partial x}+\upsilon_1\frac{\partial T_1}{\partial y}\right)=\lambda_1\left(\frac{\partial^2 T_1}{\partial x^2}+\frac{\partial^2 T_1}{\partial y^2}\right);, \quad (6)$$

$$\rho_2 C_{p2}\left(\frac{\partial T_2}{\partial t}+u_2\frac{\partial T_2}{\partial x}+\upsilon_2\frac{\partial T_2}{\partial y}\right)=\lambda_2\left(\frac{\partial^2 T_2}{\partial x^2}+\frac{\partial^2 T_2}{\partial y^2}\right)., \quad (7)$$

The heat equation for a solid wall thermosyphon:

$$\rho_3 C_{p3}\frac{\partial T_3}{\partial t}=\lambda_3\left(\frac{\partial^2 T_3}{\partial x^2}+\frac{\partial^2 T_3}{\partial y^2}\right). \quad (8)$$

where u, υ – the velocity components in the projection on the axis x, y, respectively; P – pressure; T – temperature; ρ – density; x, y – Cartesian coordinates; t – time; C_p – heat capacity; g – acceleration of gravity; λ – coefficient of thermal conductivity; μ – dynamic viscosity; indices *1*, *2*, *3* – properties of the liquid, vapor and the solid material wall of thermosyphon.

The initial conditions for the system of equations (1–8) are as follows:

$$u(x,y)=0;\ T(x,y)=T_0;\ P(x,y)=P_0.$$

The boundary conditions for the equations (1–8) have the form:

$$x=0, 0<y<H,\quad \frac{\partial T_2}{\partial x}=0;\quad \frac{\partial u_2}{\partial x}=0,\ \frac{\partial \upsilon_2}{\partial x}=0,$$

$$x=b,\ 0\le y\le H,\quad \lambda_3\frac{\partial T_3}{\partial x}=0,$$

$$x=x_1, y_1+y_2+y_3\le y\le y_1+y_2+y_3+y_4,\ \begin{cases}T_1=T_2\\ \lambda_1\dfrac{\partial T_1}{\partial x}=\lambda_2\dfrac{\partial T_2}{\partial x}\end{cases};\ \begin{cases}u_1=u_2=0\\ \upsilon_2=0\end{cases},\ \frac{\partial \upsilon_1}{\partial x}=0,$$

$$x=x_1+x_2,\ y_1+y_2\le y\le y_1+y_2+y_3+y_4+y_5,\ \begin{cases}T_1=T_3\\ \lambda_1\dfrac{\partial T_1}{\partial x}=\lambda_3\dfrac{\partial T_3}{\partial x}\end{cases};\ \begin{cases}u_1=0\\ \upsilon_1=0\end{cases},$$

$$y=y_1+y_2,\ 0\le x\le x_1+x_2,\ \begin{cases}T_1=T_3\\ \lambda_1\dfrac{\partial T_1}{\partial x}=\lambda_3\dfrac{\partial T_3}{\partial x}\end{cases};\ \begin{cases}u_1=0\\ \upsilon_1=0\end{cases},$$

$$y=y_1+y_2+y_3+y_4+y_5,\ 0\le x\le x_1+x_2,\ \begin{cases}T_1=T_3\\ \lambda_1\dfrac{\partial T_1}{\partial x}=\lambda_3\dfrac{\partial T_3}{\partial x}\end{cases};\ \begin{cases}u_1=0\\ \upsilon_1=0\end{cases},$$

$$y=y_1+y_2+y_3, 0\le x\le x_1,\ \begin{cases}T_1=T_2\\ \lambda_1\dfrac{\partial T_1}{\partial y}=\lambda_2\dfrac{\partial T_2}{\partial y}-Q_e w_e-\upsilon_2 C_p\rho\left(T_2-T_0\right)\end{cases};\ \begin{cases}\upsilon_2=\dfrac{w_e}{\rho_2},\\ \upsilon_1=\dfrac{w_e}{\rho_1},\end{cases}$$

$$y = y_1 + y_2 + y_3 + y_4,\ 0 \le x \le x_1,\ \begin{cases} T_2 = T_1 \\ \lambda_2 \dfrac{\partial T_2}{\partial y} = \lambda_1 \dfrac{\partial T_1}{\partial y} + Q_c w_c + \upsilon_2 C_p \rho \left(T_1 - T_0\right) \end{cases};\ \begin{cases} \upsilon_1 = \dfrac{w_c}{\rho_1}, \\ \upsilon_2 = 0, \end{cases}$$

$$y = 0,\ 0 \le x \le b,\ \lambda_3 \frac{\partial T_3}{\partial y} = q_h,$$

$$y = H,\ 0 \le x \le b,\ \lambda_3 \frac{\partial T_3}{\partial y} = \alpha (T_3 - T_{oc}).$$

where – Q_e, Q_c – heat of condensation and evaporation, respectively; w_e, w_c – mass rate of evaporation and condensation, respectively;

Mathematical modeling of the task carried out in the package ANSYS FLUENT software. [11].

Mass rate of evaporation and condensation were calculated according to the formula:

$$w_c = \beta \sqrt{\frac{M}{2\pi R T_H}} \left(P_2 - P_H\right),$$

where $P_н$ – saturation pressure; $T_н$ – saturation temperature; R – universal gas constant; M – molar weight; β – accommodation coefficient.

3 Results and Discussion

Numerical study of thermal processes in the two-phase closed thermosyphon rectangular performed under the following geometrical parameters (Figure 1): height H = 300 mm, the transverse dimension L = 70 mm. The water is considered as a working fluid.

It was assumed that the lower cover of thermosyphon can reach a temperature corresponding to the critical thermal regime of a typical lithium-ion battery [3]. Operating temperature of a battery operation ability is from -60 to +60°C [3].

In accordance with this range, the following variations the heat flux from the heat source: $1.1 \cdot 10^4$ W/m^2; $1.7 \cdot 10^4$ W/m^2; $2.3 \cdot 10^4$ W/m^2.

Figure 2 shows time dependence of temperature of surface of heat (battery) at different heat flux densities.

It can be seen that when the heat load q_h=$1.1 \cdot 10^4$ W/m^2, the temperature of the battery surface for 800 seconds, reaches a constant value of 340 *K*. By increasing the thermal load to $1.7 \cdot 10^4$ W/m^2 is the reduced time to 600 seconds. However, the surface temperature of the heat source is not raised above 341 *K*. Further increase in heat flux from the heat source to $2.3 \cdot 10^4$ W/m^2 leads to rapid having linear, increase T (Figure 2).

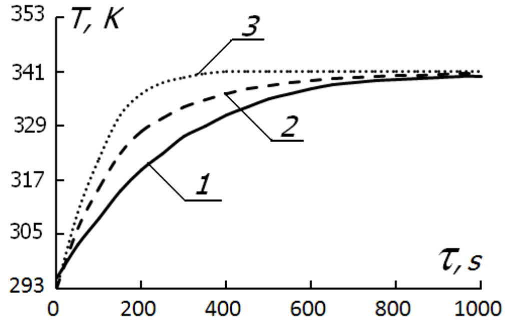

Fig. 2. Temperature on the lower cover of the thermosyphon depending on time at various heat flux density. 1 – q_h=1.1·10^4 W/m^2; 2 – q_h=1.7·10^4 W/m^2; 3 – q_h=2.3·10^4 W/m^2.

4 Conclusion

The results of numerical studies characterize the battery temperature at various thermal loads.

At temperatures, corresponding to the critical temperature batteries (over 60 °C) aircraft equipment in the heating zone is intensification of the evaporation process.

It was found that in the range of heat flux densities of 1.1·10^4 Вт/м^2 to 2.3·10^4 Вт/м^2 the boiling conditions of crisis and emergency operation of lithium-ion batteries are not reached.

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