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# Numerical investigation of heat transfer in thermosyphon under the emergency mode of operation of lithium-ion batteries of aircraft

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**Abstract.** Numerical study of heat transfer in a closed two-phase thermosyphon using the software package ANSYS FLUENT is carried out. Characteristic temperature distributions, current lines and velocity vectors are obtained at critical thermal loads. The temperature difference in the investigated region decreases with increasing heat load was obtained.

## 1 Introduction

Rechargeable batteries are one of the main parts of the emergency power supply system for aircraft [1, 2]. Their resource characteristics determine the efficiency and safety of the entire power supply system. Nowadays, lithium-ion batteries are attracting the attention of researchers of power sources [3]. But the use of these batteries in aviation technology is associated with the danger of an emergency. This is confirmed by a number of fire-hazardous accidents on board the aircraft model Boeing 787 [4, 5]. The cause of the emergency situation is overheating of the battery.

During the operation of lithium-ion batteries, the thermal runaway effect [6] occurs, followed by a short circuit of the electrical circuit, when the temperature of the individual parts of the battery increases significantly from 10 °C to 150 °C in a short period of time (2 min) [3]. The main cause of thermal runaway of the battery is its overheating as a result of insufficient heat emission from the battery surface.

It should be noted that the system for removing heat from accumulator batteries based on two-phase closed thermosyphons has not been developed, since the theory of processes in the steam channel and the flowing fluid film has not been formulated. The models described in [7, 8] do not take into account the entire complex of heat transfer processes in the vapor and liquid phases of the working fluid.

Purpose of the work: mathematical modeling of the heat transfer process in two-phase closed thermosyphons at critical temperatures of rechargeable batteries of aircraft.

When setting the task, a number of assumptions are adopted. Steam was considered an ideal gas. It was assumed that the thickness of the liquid film does not vary in height.

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## 2 Formulation of the problem

A schematic diagram of the thermosyphon is shown in Fig.1.

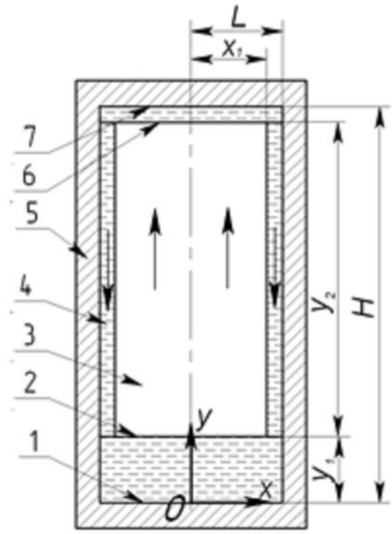


**Fig.1.** Schematic diagram of the thermosyphon. 1 – bottom cover; 2 – surface evaporation; 3 – vapor flow; 4 – liquid film; 5 – vertical wall; 6 – condensing surface; 7 – top cover.

Mathematical modeling of heat transfer in a two-phase thermosyphon of a rectangular cross-section was performed using the ANSYS FLUENT package [9].

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

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

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

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

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

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

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

where $u$, $\upsilon$ – the velocity components in the projection on the axis $x$, $y$, respectively; $P$ – pressure; $T$ – temperature; $\rho$ – density; $x$, $y$ – Cartesian coordinates; $t$ – time; $Cp$ – heat capacity; $g$ – acceleration of gravity; $\lambda$ – coefficient of thermal conductivity; $\mu$ – dynamic viscosity; indices 1, 2 – properties of the liquid and vapor.

The initial conditions for the system of equations (1-7) are given in the form:

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

The boundary conditions for the equations (1-7) have the form:

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

$$x=L,\ 0\le y\le H,\quad \lambda_1\frac{\partial T_1}{\partial x}=0;\quad u_1=\upsilon_1=0,$$

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

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

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

$$y=0,\ 0\le x\le L,\ \lambda_1\frac{\partial T_1}{\partial y}=q_h,\ u_1=\upsilon_1=0,$$

where $\alpha$ – heat transfer coefficient, W/(m²·K).

Mathematical modeling of the task carried out in the package ANSYS FLUENT software. Mass rate of evaporation and condensation were calculated according to the formula [7]:

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

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

To verify the solution method used, the results of mathematical modeling were compared with experimental studies.

An experimental study [10] was carried out for different values of the heat flux. To compare the results of numerical simulation with experimental data, two typical values of the heat flux to the outer walls of the thermosyphon body in the evaporation zone (100 W, 261 W) were chosen. Figure 2 shows that the results of mathematical modeling are in good agreement with the experimental data [10].

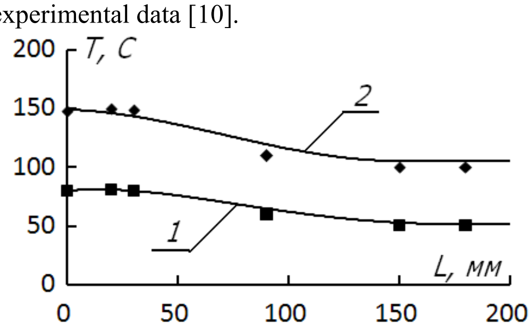


**Fig.2.** Temperature distributions for the height of the thermosyphon: numerical simulation (solid curves), experimental data [10]. Curve 1 - 100 W, curve 2 - 261 W.

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# 3 Results and Discussion

Numerical modeling of heat and mass transfer processes in a two-phase closed thermosyphon of a rectangular shape is performed in the emergency mode of operation (Fig.1) with dimensions: height H = 200 mm, transverse dimension L = 100 mm. The choice of geometric dimensions is due to the characteristic dimensions of a typical lithium-ion battery of the Boeing 787 aircraft. The following variants of the heat flux densities on the bottom cover of the thermosyphon in the section y = 0: $0.82\cdot10^3$ W/m$^2$; $1.76\cdot10^3$ W/m$^2$ in accordance with the critical temperatures obtained in [3].

Figure 3a shows the temperature distributions, current lines, and velocity vectors that characterize the main regularities of the processes under consideration in the region under study at a thermal load $q_h$=$0.82\cdot10^3$ W/m$^2$. It is seen that in the region of vertical walls symmetrical circulation flows are formed. The lines of constant temperatures here are oriented in the direction *y*. It should be noted that in the region of the vortex currents, low velocities of steam have been obtained, increasing toward the center of the steam channel. Analysis of the isotherms shows that the temperature difference in the region under study in the direction of y is about 4 °K.

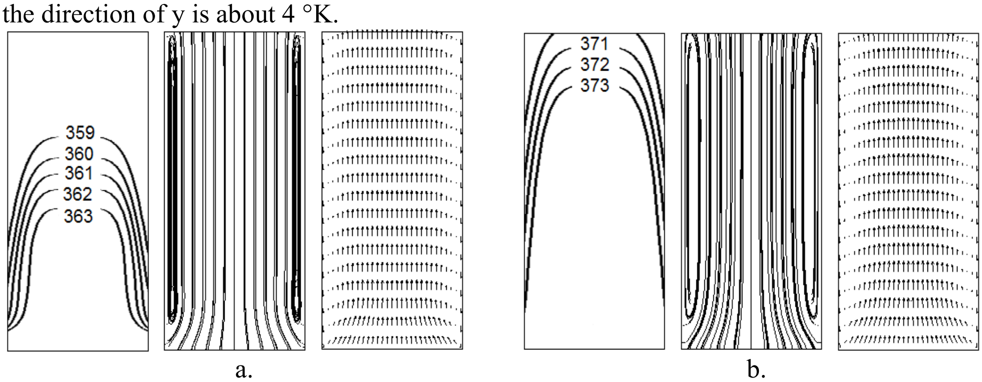


**Fig.3.** Lines of constant temperature, streamlines and velocity vectors in the study area. a - $q_h$=$0.82\cdot10^3$ W/m$^2$, b - $q_h$=$1.76\cdot10^3$ W/m$^2$.

It should be noted that with the increase of $q_h$ to $1.76\cdot10^3$ W/m$^2$ (Fig. 3b), the configuration of the lines corresponding to the main characteristics of the steam flow does not change significantly. The temperature difference along the height of the steam channel decreases by approximately 2 °K due to the intensification of heat transfer in the direction of *y* due to the more intensive evaporation of the coolant on the lower lid.

# 4 Conclusion

As a result of numerical investigation, characteristic lines of constant temperatures, current and velocity vectors were obtained.

In the practice of using closed two-phase thermosyphons, the temperature drop from the evaporation zone to the condensation zone is one of the main parameters characterizing the efficiency of its operation. It was found that the increase in the thermal load on the lower cover from $0.82\cdot10^3$ W/m$^2$ to $1.76\cdot10^3$ W/m$^2$ leads to a decrease in the temperature difference in the investigated region by 2 °K. This is probably due to the intensification of heat transfer and the increase in the vapor velocity in the device under study.

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