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MATHEMATICAL MODELING OF HEAT TRANSFER IN A CLOSED TWO-PHASE THERMOSYPHON

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***Abstract**: We suggested a new approach for describing heat transfer in thermosyphons and determining the characteristic temperatures. The processes of thermogravitation convection in the coolant layer at the lower cap, phase transitions in the evaporation zone, heat transfer as a result of conduction in the lower cap are described at the problem statement. The main assumption, which was used during the problem formulation, is that the characteristic times of steam motion through the thermosyphon channel are much less than the characteristic times of thermal conductivity and free convection in the coolant layer at the lower cap of the thermosyphon. For this reason, the processes of steam motion in the thermosyphon channel, the condensate film on the upper cap and the vertical walls were not considered. The problem solution domain is a thermosyphon through which heat is removed from the energy-saturated equipment. The ranges of heat flow changes were chosen based on experimental data. The geometric parameters of thermosyphon and the fill factors were chosen the same as in the experiments (height is 161 mm, diameter is 42 mm, wall thickness is 1.5 mm, ε=4-16%) for subsequent comparison of numerical simulation results and experimental data. In the numerical analysis it was assumed that the thermophysical properties of thermosyphon and coolant caps do not depend on temperature; laminar flow regime was considered. The dimensionless equations of vortex, Poisson and energy transfer for the liquid coolant under natural convection and the equations of thermal conductivity for the lower cap wall are solved by the method of finite differences. Numerical simulation results showed the relationship between the characteristic temperatures and the heat flow supplied to the bottom cap of thermosyphon. The results of the theoretical analysis are in satisfactory agreement with the known experimental data.*

***Keywords**: two-phase thermosyphon, mathematical modeling, heat flow, heat transfer, evaporation, condensation, thermo-gravitational convection.*

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ТЕПЛОПЕРЕНОСА В ЗАМКНУТОМ ДВУХФАЗНОМ ТЕРМОСИФОНЕ

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Резюме: *Предложен новый подход к описанию процессов теплопереноса в термосифонах и определения характерных температур. При постановке задачи описываются процессы термогравитационной конвекции в слое теплоносителя на нижней крышке, фазовые превращения в зоне испарения, теплоперенос в результате кондукции в нижней крышке. Основное допущение, которое использовалось при постановке задачи, – это положение о том, что характерные времена движения паров по каналу термосифона много меньше характерных времен теплопроводности и свободной конвекции в слое хладагента на нижней крышке термосифона. По этой причине не рассматривались процессы движения пара в канале термосифона, пленке конденсата на верхней крышке и вертикальных стенках. Область решения задачи представляет собой термосифон, через который осуществляется отвод теплоты от энергонасыщенного оборудования. Диапазоны изменения тепловых потоков выбирались исходя из экспериментальных данных. Геометрические параметры термосифона и коэффициенты заполнения выбирались такими же, как и в экспериментах (высота – 161 мм, диметр – 42 мм, толщина стенок – 1,5 мм, ε=4–16%) для последующего сравнения результатов численного моделирования и экспериментальных данных. При проведении численного анализа предполагалось, что теплофизические свойства крышек термосифона и хладагента не зависят от температуры; рассматривался ламинарный режим течения. Безразмерные уравнения переноса вихря, Пуассона и энергии для жидкого теплоносителя в условиях естественной конвекции и уравнения теплопроводности для стенки нижней крышки решены методом конечных разностей. По результатам численного моделирования установлена зависимость характерных температур от величины теплового потока, подводимого к нижней крышке термосифона. Результаты теоретического анализа находятся в удовлетворительном соответствии с известными экспериментальными данными.*

Ключевые слова: *двухфазный термосифон, математическое моделирование, тепловой поток, теплоперенос, испарение, конденсация, термогравитационная конвекция.*

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Introduction

The prerequisite for successful operation of modern energy-saturated equipment (ESE) is the removal of heat from heat-generating parts and modules [1-3]. Utilization of traditional air cooling systems using various kinds of superchargers is not always possible. Failure of such auxiliary equipment leads to an emergency operation of energy-saturated equipment. For this reason, the use of heat transfer devices that are independent of power sources is relevant.

Closed two-phase thermosyphons (TS), which can be used for thermostating and thermoregulation of various technological processes are the autonomous (independent of energy sources) heat exchangers [4, 5]. Evaporation and condensation in heat exchangers of this type are spatially separated, which makes it possible to transform heat flows by changing the ratio of evaporation and condensation surfaces. But at present, thermosyphons are almost not used in industry due to the fact that the physics of heat transfer processes and phase transformations in the steam channel, evaporation and condensation zones, and the condensate film flowing along the side walls in the thermosyphon case is not well understood. For a detailed analysis of these processes, information is needed on the temperature fields in the characteristic zones of the thermosyphon. But due to the difficulties of sealing such heat exchangers when installing temperature sensors, the majority of publications present the results of recording the temperatures of the external surfaces of the thermosyphon walls. Such measurements are insufficient for the analysis of heat transfer processes, because the heat flow through the TS case is intense both along the longitudinal and transverse coordinates. The few results of temperature determination in a closed two-phase thermosyphon [6–8] show its change only at individual points on the inner surface of the heat exchanger under consideration. To analyze the operation efficiency of thermosyphons, one needs information about the temperature distributions in the areas corresponding to the evaporation, transport, and steam condensation zones [7–9].

Analysis of the relevant literature shows that various heat transfer models are currently used for calculation of thermosyphons [10–14]: original researchers' codes [10–11] and commercial software packages [12–13]. Models and methods [10–14] have certain advantages (the completeness of description of hydrodynamic and thermophysical processes in all zones of the thermosyphon; the possibility of solving spatial problems in the conjugate formulation, the mathematical interpretation of various options for structural solutions, taking into account the temperature and steam dependences of the characteristics of steam and condensate, and some others). But the use of commercial packages and original codes for calculation of heat transfer processes in thermosyphons is associated with the solution of a number of complex problems. For example, working with packages of the ANSYS FLUENT type implies a highly-skilled user, which is almost impossible in many cases when such packages are used by heating engineers to solve specific problems. In addition, numerical simulation using such packages involves time-consuming computations even when the processes are described in two-dimensional statements. A well-proven and simple method for calculating heat transfer using balanced models [5, 9] does not allow determining the temperature in the characteristic sections of the thermosyphon. For this reason, it is necessary to develop a mathematical model less complicated than [10–14] and a method for calculating unsteady heat transfer in a two-phase thermosyphon in order to describe heat transfer processes taking into account phase transitions at media interfaces.

Analysis and generalization of the experimental results [15–16] made it possible to develop a new approach to the mathematical modeling of heat transfer processes in two-phase thermosyphons. An important difference between the mathematical model formulated in the article and the known ones [10–14] is that when setting the problem, only thermogravitational convection processes in the coolant layer on the lower cap, phase transformations in the evaporation zone, and heat transfer as a result of conduction in the lower cap are described. The main assumption that was used during the problem formulation is the provision that the characteristic times of steam motion through the thermosyphon channel are much shorter than the characteristic times of heat conduction and free convection in the coolant layer on the bottom cap of the thermosyphon. For this reason, the processes of steam motion in the TS channel, the condensate film on the top cap and the vertical walls of the thermosyphon were not considered. Further the problem statement is presented.

Problem statement and solution method

The problem solution domain is a thermosyphon, through which heat is removed from energy-saturated equipment. At the initial moment of time, the TS case and the coolant have a constant and uniform temperature at all points. The ranges of heat flows variation were selected based on experimental data [16]. Geometrical parameters of the thermosyphon and the filling factors were chosen the same as in the experiments [15–16] (height is 161 mm, diameter is 42 mm, wall thickness is 1.5 mm, ε = 4–16%) for subsequent comparison of the results of numerical modeling and experimental data.

In this formulation, hydrodynamic processes (steam motion) in the steam channel were excluded from consideration, but the processes of conduction and convection in the coolant layer were considered, and the processes of thermal conductivity in the lower cap of the thermosyphon were taken into account. Based on the results of previous experiments [15–16], it was also assumed that in the range of heat flows up to q=1.8 kW/m^2, all water steam formed on the surface of the coolant layer rises very quickly, where it condenses on the lower surface of the top cap of the thermosyphon and manages to return to the evaporation zone when draining along vertical walls. The solution of the heat transfer problem in a thermosyphon in this formulation reduces to solving the system of equations of continuity, motion, and energy for the coolant layer on the bottom cap and thermal conductivity for the plate (Fig. 1) in an axisymmetric formulation.

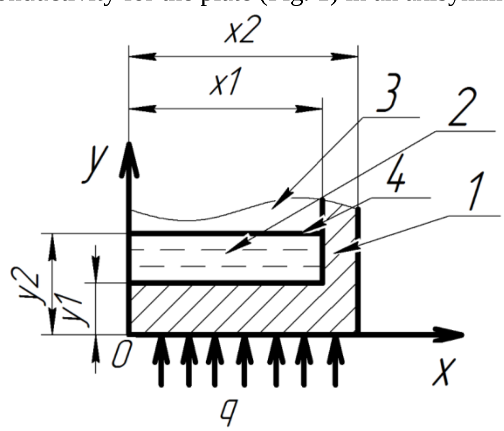


Fig. 1. The problem solution domain: 1 - metal case; 2 - layers of condensate; 3 - steam channel; 4 - evaporation surface

The dimensionless equations of vortex transfer, Poisson, and energy for the liquid coolant under conditions of natural convection and the heat transfer equation for the lower cap wall have the form [11]:

$$\frac{\partial \Omega_2}{\partial \tau} + U_2 \frac{\partial \Omega_2}{\partial X} + V_2 \frac{\partial \Omega_2}{\partial Y} = \sqrt{\frac{\mathrm{Pr}_2}{\mathrm{Ra}_2}} \left(\frac{\partial^2 \Omega}{\partial X^2} + \frac{\partial^2 \Omega}{\partial Y^2} \right) + \frac{\partial \Theta_2}{\partial X}, \tag{1}$$

$$\frac{\partial^2 \Psi_2}{\partial X^2} + \frac{\partial^2 \Psi_2}{\partial Y^2} = -\Omega_2, \tag{2}$$

$$\frac{\partial \Theta_2}{\partial \tau} + U_2 \frac{\partial \Theta_2}{\partial X} + V_2 \frac{\partial \Theta_2}{\partial Y} = \frac{1}{\sqrt{\mathrm{Ra}_2 \, \mathrm{Pr}_2}} \cdot \left(\frac{\partial^2 \Theta_2}{\partial X^2} + \frac{\partial^2 \Theta_2}{\partial Y^2} \right), \tag{3}$$

$$\frac{1}{\mathrm{Fo}_1} \frac{\partial \Theta_1}{\partial \tau} = \frac{\partial^2 \Theta_1}{\partial X^2} + \frac{\partial^2 \Theta_1}{\partial Y^2}. \tag{4}$$

where $\mathrm{Pr} = \frac{\nu}{a}$ is the Prandtl number; $\mathrm{Ra} = \frac{g_y \beta (T_h - T_0) H^3}{\nu a}$ is the Rayleigh number; $\mathrm{Fo} = \frac{a_1 t_0}{H^2}$ is the Fourier number; X, Y are the dimensionless system coordinates corresponding to x, y; a is the thermal diffusivity, m^2/s; ν is the kinematic viscosity coefficient, m^2/s; β is the volume expansivity, 1/K; g is the gravitational acceleration, m/s^2; $H = y_2 - y_1$ is the characteristic dimension, m; t_0 is the time scale, s; τ is the dimensionless time; u, v are the motion rates, m/s; U, V are the dimensionless rates corresponding to u, v; V_{in} is the rate scale, m/s; T_0 is the thermosyphon temperature at the initial time, K; T_h is the boiling temperature of coolant, K; Θ is the dimensionless temperature; ψ is the flow function, m^2/s; ψ_0 is the flow function scale, m^2/s; Ψ is the dimensionless analog of ψ; ω is the vorticity vector, 1/c; ω_0 is the vorticity vector scale, 1/s; Ω is the dimensionless analog of ω.

The initial conditions for equations (1 – 4) are:

$$\Psi(X,Y,0)=\Omega(X,Y,0)=0,\ \Theta_1(X,Y,0)=\Theta_2(X,Y,0)=0, \tag{5}$$

Dimensionless boundary conditions for equations (1 – 4) are:

$$X=0,\quad 0<Y<Y_1:\ \frac{\partial\Theta_1}{\partial X}=0, \tag{6}$$

$$X=0,\quad Y_1<Y<Y_2:\ \frac{\partial\Theta_2}{\partial X}=0,\ \left\{\frac{\partial^2\Psi_2}{\partial X^2}=0,\right. \tag{7}$$

$$X=X_2,\quad 0<Y<Y_2:\ -\lambda\frac{\partial\Theta_1}{\partial X}=0, \tag{8}$$

$$Y=0,\quad 0<X<X_2:-\frac{\partial\Theta_1}{\partial Y}=Ki, \tag{9}$$

$$Y=Y_2,\quad 0<X<X_1:\frac{\partial\Theta_2}{\partial Y}=-\frac{Q_u W_u H}{\lambda(T_h-T_0)},\ \left\{\Psi_2=0,\right. \tag{10}$$

$$Y=Y_2,\quad X_1<X<X_2:-\lambda\frac{\partial\Theta_1}{\partial Y}=0, \tag{11}$$

$$X=X_1,\quad Y_1<Y<Y_2:\ \begin{cases}\Theta_1=\Theta_2,\\ \dfrac{\partial\Theta_1}{\partial X}=\dfrac{\lambda_2}{\lambda_1}\dfrac{\partial\Theta_2}{\partial X},\end{cases}\ \begin{cases}\Psi_2=0,\\ \dfrac{\partial\Psi_2}{\partial X}=0,\end{cases} \tag{12}$$

$$Y=Y_1,\ 0<X<X_1:\ \begin{cases}\Theta_1=\Theta_2,\\ \dfrac{\partial\Theta_1}{\partial Y}=\dfrac{\lambda_2}{\lambda_1}\dfrac{\partial\Theta_2}{\partial Y},\end{cases}\ \begin{cases}\Psi_2=0,\\ \dfrac{\partial\Psi_2}{\partial Y}=0,\end{cases} \tag{13}$$

$$W_u=\frac{A(P_н-P_п)}{\sqrt{\dfrac{2\pi RT}{M}}} \tag{14}$$

where $\mathrm{Ki}=\dfrac{qH}{\lambda_1(T_h-T_0)}$ is the Kirpichev number; $\mathrm{Bi}=\dfrac{\alpha\cdot H}{\lambda_1}$ is the Biot number; Q_e is the evaporation heat; W_e is the evaporation rate; q is the heat flow; A is the accomodation coefficient; P_s is the saturated steam pressure; P_p is the partial steam pressure above the liquid surface; R = 8314 J/kmol·K is the universal gas constant; M is the molecular weight; 1 is for the cap material; 2 is for liquid.

For numerical analysis it was assumed that the thermophysical properties of the thermosyphon and coolant caps are independent of temperature; the laminar flow regime was considered. The fluid was assumed to be Newtonian, incompressible, and satisfying the Boussinesq approximation [11, 18].

The system of equations (1–4) with the corresponding initial and boundary conditions was solved by the finite difference method [18]. Mass rates of evaporation and condensation were calculated by the Hertz – Knudsen formula [19]. When solving the Poisson equation for the flow function, the implicit method of variable directions was used, similarly to [18–20]. In determining the boundary condition for the velocity vortex, the Woods formula was used.

Numerical studies of heat transfer in TS under conditions of energy removal from energy-saturated equipment were carried out in typical ranges of heat flow changes corresponding to operating modes of energy-saturated equipment [21]. Heat flows to the bottom cap of the thermosyphon ranged from 0.3 kW/m^2 to 1.8 kW/m^2.

Results and discussion

Figures 2–3 show thermograms obtained from numerical simulation of heat transfer process and conducting experiments when filling the thermosyphon cavity with distilled water in the range of heat flows q=0.4–1.8 kW/m^2.

It can be seen from Fig. 2 that the time to reach the steady-state regime of characteristic temperatures obtained in numerical studies and experiments is quite large in the entire range of changes in heat flows. Temperatures grow rapidly in the first 5000 - 6000 s, and then slowly. This is due to the fact that within 2.5 hours the walls, the TS cap and the coolant itself are evenly heated.

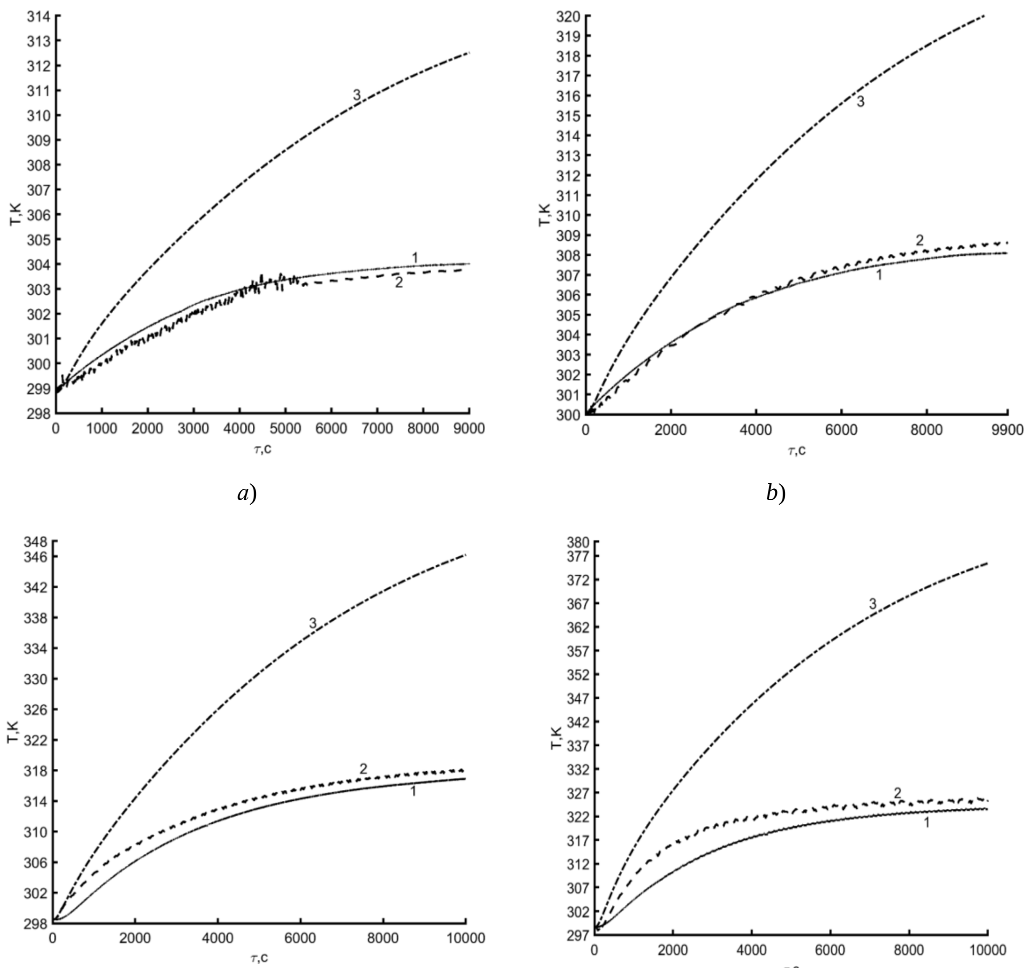
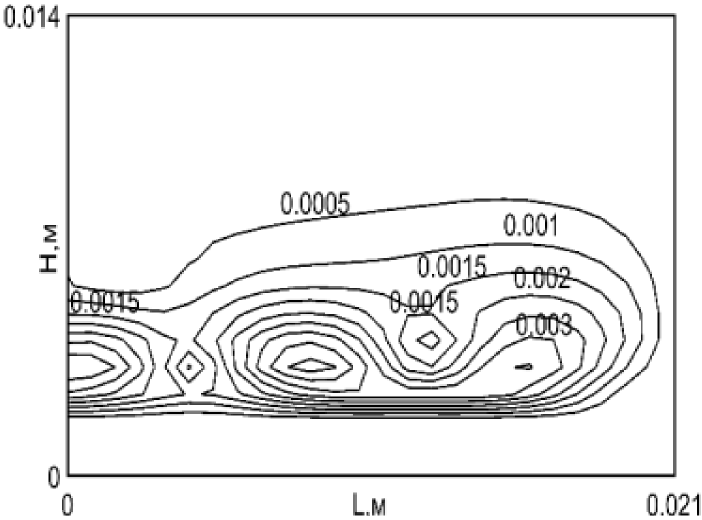
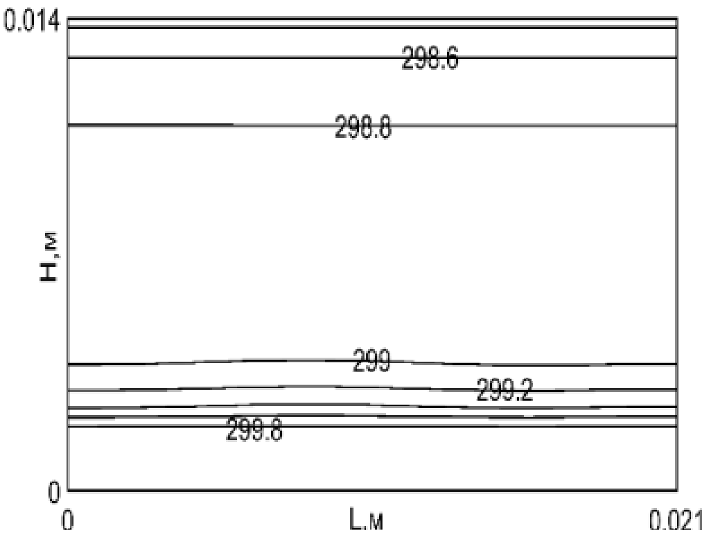


Fig. 2. Relationship between temperatures in the coolant layer on the bottom cap of the thermosyphon (x=0 mm, y=6 mm) and time for a thermosyphon fill factor of 8% and heat load q, kW/m^2: a) 0.3; b) 0.4; c) 0.9; d) 1.8.
1 - experiment (-); 2 - numerical modeling (model taking into account thermal conductivity and free convection) (- - -); 3 - numerical modeling (model taking into account only conduction) (-·-·-)

As the heat flow increases to 1.8 kW/m^2, the changes in T in the coolant layer on the bottom cap increase both in numerical simulation and in experiment. In the initial period of time (up to 500 s), the growth dynamics and temperatures are the same for two cases of numerical simulation (Fig. 2, curves 2, 3) and are in good agreement with experimental data (Fig. 2, curve 1). This is explained by the fact that during this period of time convective flows are just beginning to form, their intensity is minimal (Fig. 3, a), and they do not significantly affect the heat transfer in liquid (Fig. 3, b).



a)



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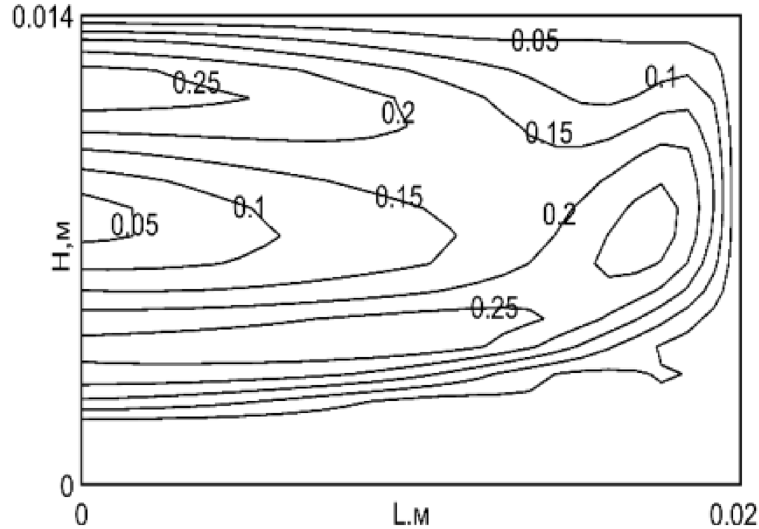
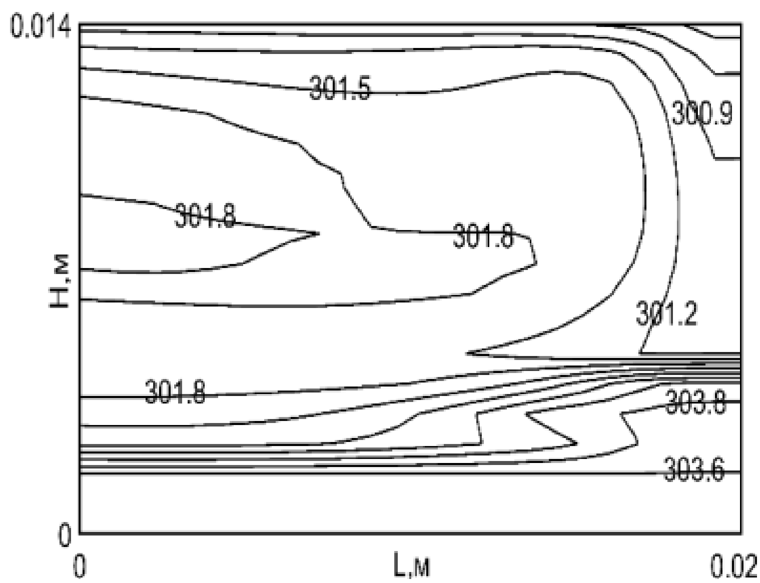


c)



d)

Fig. 3. Isolines of velocities (isotaches) (a, c) and temperature fields (b, d) in the coolant layer on the bottom cap of the thermosyphon at q=300 W/m^2 and time: a, b - 100 s; c, d - 3000 s. Temperature, K; velocity, cm/s

The energy transfer in this case is predominantly conductive. Over time, the forces of thermogravitational convection increase, which leads to the formation of intense circulation flows in the studied area (Fig. 3, c). The heated liquid rises up to the free surface, where heat is removed due to evaporation (Fig. 3, d), the cold one drops down. The temperature difference (curves 2 and 3, Fig. 2) increases with time up to reaching the stationary mode. The temperatures (curve 2, Fig. 2) obtained from numerical simulation (using a model that takes into account thermogravitational convection) are in good agreement with experimental data (discrepancy of not more than 5%), while the temperatures obtained taking into account only conduction in the bottom cap and the coolant layer differ from experimental ones up to 50%.

Conclusion

Modeling of heat transfer processes in TS can be performed with a fairly high reliability, without description of processes of steam motion in the steam channel, when solving the problem of heat transfer in the heat transfer layer on the bottom cap of the thermosyphon and heat conduction in this cap.

References

1. Fu W, Li X, Wu X, Zhang Z. Investigation of a long term passive cooling system using two-phase thermosyphon loops for the nuclear reactor spent fuel pool. *Annals of Nuclear Energy*. 2015. Vol. 85. P. 346–356.

2. Parida PR, Sridhar A, Vega A, Buyuktosunoglu A., Chainer T. Thermal model for embedded two-phase liquid cooled microprocessor: *Proceedings of the 16th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITherm;*30May 2- Jun, 2017;Orlando, USA. 2017. pp. 441-449.

3. Fluder PF, Marzec P, Kos A. Compact model of microprocessor cooling system based on ambient circumstances. *Proceedings of the 24th International Conference on Mixed Design of Integrated Circuits and Systems*, *MIXDES* 2017. P. 341-344.

4. Karavaev IS, Shtern YI, Kozhevnikov YS., Shtern MY, Degtyarev AA. Thermostating Components for Control of Heat-Transfer Agent Flow. *Measurement Techniques*. 2016. Vol. 59(9). P. 964-970.

5. Vasilyev LL. Perspectives of application of heat pumps in the Republic of Belarus. *IFZh.* 2005; 78(1):23–34. (In Russ.).

6. Ibrahim E, Moawed M, Berbish NS. Heat transfer characteristics of rotating triangular thermosyphon. *Heat Mass Transfer*. 2012; 48:1539–1548. (In Russ).

7.Oh SH, Choi JW, Lee KJ, Cho HH, Kim SI. Experimental study on heat transfer performance of a two-phase single thermosyphon using HFE-7100. *Journal of Mechanical Science and Technology*. 2017; 31(10):4957-4964.

8. Zhang P, Wang B, Shi W, Li X, Experimental investigation on two-phase thermosyphon loop with partially liquid-filled downcomer. *Applied Energy.* 2015. Vol. 160. P. 10–17.

9. Bezrodnyy MK, *Transfer processes in the biphasic thermal siphon systems.* Bezrodnyy MK., Pioro IL, Kostyuk TO. Kiev: Fact, 2005. P. 704. (In Russ.).

10. Kuznetsov GV., Sitnikov AE. *Numerical analysis of basic regularities of heat and mass transfer in*

Литература

1. Fu W., Li X., Wu X., Zhang Z. Investigation of a long term passive cooling system using two-phase thermosyphon loops for the nuclear reactor spent fuel pool // Annals of Nuclear Energy. 2015. Vol. 85. P. 346–356.

2. Parida P.R., Sridhar A., Vega A., Buyuktosunoglu A., Chainer T. Thermal model for embedded two-phase liquid cooled microprocessor // Proceedings of the 16th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITherm 2017. P. 441-449.

3. Fluder P.F., Marzec P., Kos A. Compact model of microprocessor cooling system based on ambient circumstances // Proceedings of the 24th International Conference on Mixed Design of Integrated Circuits and Systems, MIXDES 2017. P. 341-344.

4. Karavaev I.S., Shtern Y.I., Kozhevnikov Y.S., Shtern M.Y., Degtyarev A.A. Thermostating Components for Control of Heat-Transfer Agent Flow // Measurement Techniques. 2016. Vol. 59(9). P. 964-970.

5. Васильев Л.Л. Перспективы применения тепловых насосов в Республике Беларусь // ИФЖ. 2005. Т. 78, №1. С. 23–34.

6. Ibrahim E., Moawed M., Berbish N. S. Heat transfer characteristics of rotating triangular thermosyphon // Heat Mass Transfer. 2012. Vol. 48. pp. 1539 –1548.

7. Oh S.H., Choi J.W., Lee K.J., Cho H.H., Kim S.I. Experimental study on heat transfer performance of a two-phase single thermosyphon using HFE-7100 // Journal of Mechanical Science and Technology. 2017. Vol. 31(10), pp. 4957-4964.

8. P. Zhang, B. Wang, W. Shi, X. Li, Experimental investigation on two-phase thermosyphon loop with partially liquid-filled downcomer. // Applied Energy. 2015. Vol. 160. pp. 10–17.

9. Безродный М.К. Процессы переноса в двухфазных термосифонных системах / М.К. Безродный, И.Л. Пиоро, Т.О. Костюк. Киев: Факт, 2005. 704 с.

high-temperature heat pipe. TVT, 40:6 (2002), 964–970.

11. Kuznetsov GV, Al-Ani MA, Sheremet MA. Numerical analyses of convective heat transfer in a closed two-phase thermosiphon. *Journal of Engineering Thermophysics.* 2011; 20 (2): 201–210. (In Russ).

12. Fadhl B, Wrobel LC, Jouhara H. Numerical modelling of the temperature distribution in a two-phase closed thermosyphon. *Applied Thermal Engineering*. 2013. Vol. 60 P. 122–131.

13. Wang X, Zhu Y, Chen H, Wang Y, Fan H. CFD modeling of phase change heat transfer behaviors in thermosyphons. Zhongnan Daxue Xuebao (Ziran Kexue Ban). *Journal of Central South University (Science and Technology).* 2017. Vol. 48(5). P. 1391-1397.

14. Jafari D, Franco A, Filippeschi S, Di Marco P. Two–phase closed thermosyphons: A review of studies and solar applications. *Renewable and Sustainable Energy Reviews.* 2016. Vol. 53. P. 575–593.

15. Feoktistov EA, Vympin EA, Nurpeiis AE. *Experimental research of thermophysical processes in a closed two–phase thermosyphon. MATEC Web of Conf*. 2016.

16. Nurpeiis AE, Orlova EG, Ponomarev KO. *An experimental study of the influence of a thermosyphon filling ratio on a temperature distribution in characteristic points along the vapor channel height. MATEC Web of Conferences.* Les Ulis: EDP Sciences. 2017. Vol. 110: *Heat and Mass Transfer in the Thermal Control System of Technical and Technological Energy Equipment.*

17. Strakhov VL, Garaschenko AN, Kuznetsov GV, Rudzinskii VP. Mathematical simulation of thermophysical and thermos chemical processes during combustion of intumescent fire-protective coating. *Combustion, Explosion and Shock Waves*. 2001; 37:1178–186.(In Russ).

18. Samarskiy AA. *Numerical methods for solving convection – diffusion.* Samarskiy AA, Vabishchevich PN. URSS, 2009. pp 246. (In Russ.).

19. Kuznetsov GV, Strizhak PA. Evaporation of single droplets and dispersed liquid flow in motion through high-temperature combustion products. *High Temperature.* 2014; 52: 568–575. (In Russ).
doi: https://doi.org/10.7868/S0040364414030181.

20. Kuznetsov GV, Strizhak PA. Numerical investigation of the influence of convection in a mixture of combustion products on the integral

10. Kuznetsov G.V., Sitnikov A.E. Numerical analysis of basic regularities of heat and mass transfer in high-temperature heat pipe // TVT. 2002. Vol. 40(6).pp 964–970.

11. Kuznetsov G.V., Al-Ani M.A., Sheremet M.A. Numerical analyses of convective heat transfer in a closed two-phase thermosiphon // Journal of Engineering Thermophysics. 2011. Vol. 20 (2). pp. 201–210.

12. Fadhl B., Wrobel L.C., Jouhara H. Three-dimensional CFD simulation of geyser boiling in a two-phase closed thermosyphon // International Journal of Hydrogen Energy. 2019. Vol. 41(37), pp. 16463-16476.

13. Wang X., Zhu Y., Chen H., Wang Y., Fan H. CFD modeling of phase change heat transfer behaviors in thermosyphons // Zhongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Central South University (Science and Technology). 2017. Vol. 48(5). pp. 1391-1397.

14. Jafari D., Franco A., Filippeschi S., Di Marco P. Two–phase closed thermosyphons: A review of studies and solar applications // Renewable and Sustainable Energy Reviews. 2016. Vol. 53. P. 575–593.

15. Feoktistov E.A., Vympin E.A., Nurpeiis A.E. Experimental research of thermophysical processes in a closed two–phase thermosyphon // MATEC Web of Conf. 2016. Vol. 72.

16. Nurpeiis A.E., Orlova E.G., Ponomarev K.O. An experimental study of the influence of a thermosyphon filling ratio on a temperature distribution in characteristic points along the vapor channel height // MATEC Web of Conferences. Les Ulis: EDP Sciences. 2017. Vol. 110: Heat and Mass Transfer in the Thermal Control System of Technical and Technological Energy Equipment.

17. Strakhov V.L., Garaschenko A.N., Kuznetsov G.V., et al. Mathematical simulation of thermophysical and thermos chemical processes during combustion of intumescent fire-protective coating // Combustion, Explosion and Shock Waves. 2001.Vol. 37. pp 1178–186.

18. Самарский А.А. Численные методы решения задач конвекции – диффузии / А.А. Самарский, П.Н. Вабищевич. URSS, 2009. 246 с.

19. Kuznetsov G.V., Strizhak P.A. Evaporation of single droplets and dispersed liquid flow in motionthrough high-temperature combustion products // High Temperature. 2014. Vol. 52: pp. 568–575.

characteristics of the evaporation of a finely atomized water drop. *Journal of Engineering Physics and Thermophysics.* 2014; 87:103–111. (In Russ) doi.org/10.1007/s10891-014-0990-8.
21. Nurpeiis A, Nemova T. *The Opportunity Analyses of Using Thermosyphons in Cooling Systems of Power Transformers on Thermal Stations. MATEC Web of Conferences* 72, 01077 (2016).

20. Kuznetsov G.V., Strizhak P.A. Numerical investigation of the influence of convection in a mixture of combustion products on the integral characteristics of the evaporation of a finely atomized water drop // Journal of Engineering Physics and Thermophysics. 2014. Vol. 87.pp 103–111.
21. Nurpeiis A., Nemova T. The Opportunity Analyses of Using Thermosyphons in Cooling Systems of Power Transformers on Thermal Stations // MATEC Web of Conferences 72, 01077 (2016).

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