Word Visualization of the morphology of the temperature field of the heat pipe with defects of the active type

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Abstract. As part of a computer experiment using the finite element method, a method for visualizing the morphology of the temperature field of a heat pipe with defects of the active type – a heat energy source (ITP) was developed. It is shown that when the starting mode of the pipe ($\tau = 0 \div 120$ C) and the ITP power $q \geq 9 \times 10^4$ W/m$^2$, a typical isotherm structure with a convex front is formed. The passage of a rectangular ITP isotherm is accompanied by the formation of a local isothermal contour. Significant variability of the geometric characteristics of isotherms is noted.

1. Introduction
Heat pipes (HP) being special cooling devices effectively provide continuous removal of thermal energy from various electronic devices [1–6]. In the serial production of HPs adapted to the product design, the identification of technological defects at the production stage, their analysis and the elimination of the factors that caused the defect become an important problem. Traditionally, a significant role in solving this problem belongs to visualization methods based on experimentally recorded x-ray and thermal contrasts with subsequent digital image processing [7, 8]. Of scientific and practical interest are computer methods for visualizing the morphology of the temperature field of a HP, which do not require full-scale experiments. Such studies are known in the field of HP quality diagnostics, but mainly they relate to visualization methods for passive defects [9–11]. To assess the degree of influence of localized active defects on the diagnosed characteristics of the temperature field of a HP, it is necessary to develop new thermal and mathematical models of HP. This work is devoted to solving problems.

2. Research methodology
2.1. The geometric model
A well-known basic model was chosen in the form of a flat, steel HP with a symmetrical structure (figure 1) [11]. In the center of the hull of the HP was a rectangular heat source pulsed heat flux (HSPHF). The geometric parameters of the HP model were respectively equal: $L \approx 150 \div 500$ mm; $h \approx 20 \div 30$ mm; $\delta \approx 5 \div 8$ mm. As an active defect, a rectangular defect was used, which located on the longitudinal axis of the HP. Its localization, size could be changed during a computer experiment.
2.2. Features of the thermal and mathematical model

When conducting research, we used the basic thermal and mathematical models of a bounded rod. For an unsteady problem in a plane-parallel formulation the initial heat equation (1), taking into account the formulated limitations, can be written in the form [12, 13]:

\[ C\rho \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + q_o \]  

(1)

where: \( c_p, \rho \) – specific heat and density of the material; \( \lambda_x, \lambda_y \) – thermal conductivity; \( q_o \) – heat output per unit volume of heat energy sources; \( T \) – temperature; \( x, y \) – coordinate.

For the developed basic thermal model, the following initial and boundary conditions were used [12, 13]:

1) at the initial moment of time, for the edges of all the bodies included in the model, a constant temperature was set:

\[ T_{i, t=0} = T_C = \text{const} \]  

(2)

2) for all the edges of the HSPHF, taking into account the surface isothermality, a condition of the first kind was specified:

\[ T = T_b \]  

(3)

3) for all HSPHF edges (defects), a second-order boundary condition was set in the form of heat flux density \( (q, \text{W/m}^2) \) [12, 13].

4) a condition of the third kind was set on the edges of the HP model, which describes both convective and radiant heat transfer with the environment:

\[ \lambda_p \frac{\partial T}{\partial n} = - \alpha_d(T-T_c) - \beta(T^4 - T_c^4) \]  

(4)
where: $\beta$ – value equal to the product of the Stefan-Boltzmann constant ($\sigma_0=5.7 \cdot 10^{-8} \text{W/m}^2\text{K}^4$) the emissivity of the surface of the probe material; $\alpha_k$ – convection heat transfer coefficient. Numerical values of the coefficient $\alpha_k$ were obtained from preliminary calculations using the well-known similarity method [12, 13]. The heat flux through the conductive connections of the HP fasteners was not taken into account.

The numerical values of HS heat production (defects) were selected from preliminary experiments taking into account reliably recorded changes in isothermal lines and amounted to $q = 9 \cdot 10^4 \div 3 \cdot 10^5 \text{W/m}^2$. As the defect material, steel was used with characteristics similar to that of the HP case, while the condition “isotropy” was specified in the “block” label through the equality of the thermal conductivity coefficients [13]. Computer experiments were performed for the maximum temperatures of the HSPHF $T_{\text{HSPHF}} = 350 \div 400 \text{K}$ and a constant ambient temperature (air) $T_a = 300 \text{K}$. All other characteristics of the computer experiment technology were the same as for the case of HP with passive defects [11]. The system of equations (1–5) was solved by a numerical method (finite element method) on a PC [14].

3. Research results and discussion
It is known that the heat production (power) of HS, taking into account secondary factors, determines the main characteristics of the temperature field of an object containing this source [12, 13]. Due to the lack of knowledge, scientific and practical interest is provided by information on the influence of the thermal power of a defect on the evolution of isothermal.

![Figure 2](image-url)  
**Figure 2.** Evolution of an isotherm in a steel HP with an active defect (HS) of a square shape (steel, $a = 1.22 \cdot 10^{-5} \text{m}^2/\text{s}$, dimensions $L_1 \times L_2 = 6\times6 \text{mm}$). Example. Modeling, finite element method, $T_{\text{PHFS}} = 350 \text{K}$, scale 50K, $k_\alpha = 10$. HS power: a – $q = 2 \cdot 10^5 \text{W/m}^2$; b – $q = 3 \cdot 10^5 \text{W/m}^2$. 

Analysis of the temperature field of HPs with defects in the following modes: thermograms, isolines, and selected contours, as well as in the case of passive defects, showed the time variability of the shape of the isotherms and the nature of the temperature distribution along the axis. As an example in figure 2. Figure 2 shows the evolution of the selected isothermal line (50 K scale) for two values of thermal power of the investigated rectangular defect. Two features of the morphology of the temperature field are clearly visible. The first is that noticeable changes in the shape of the isotherm from the defective HP region are already good are observed in the initial period of the transition process ($\tau = 5s$) and these changes gradually increase in time, even beyond the localization of the defect. Computer experiments showed that an increase in the heat output of a rectangular defect only intensifies this process.

Figure 3. Change in field characteristics over time along the HP axis. Modeling, finite element method (HP with active defect (HS) of square shape (steel, $a = 1.22 \cdot 10^{-5} m^2/s$, dimensions $L_1 \times L_2 = 6x6$ mm)). Example: $T_{PHFS} = 350 K$, $T_C = 300 K$. a, b – $\tau = 5$ s; c, d – $\tau = 40$ s.
The second morphological feature is related to the shape of the front of the isothermal line – at the entire stage of evolution from the side of the defective region of the HP, it remains convex. The revealed qualitative features of the morphology of the temperature field were also manifested in changes in the field characteristics (figure 3, figure 4). Thus, studies of the temperature distribution, temperature gradient, and heat flux density along the selected contour along the HP axis at different points in time of the transition process allowed us to fix the formation of local extrema in the defect region and the general asymmetry of the graphs relative to HSPHF, which has been preserved throughout the entire evolutionary period. The presence of a localized active defect in the HP from the standpoint of heat transfer is equivalent to the formation of a system of conductively coupled sources of heat flux in which HSPHF creates background overheating [15]. In this case, overheating of HP temperatures within the localization of a defect is determined on the basis of the principles of superposition and local influence (the scientific foundations of these principles are described in detail in [15]). Therefore, an increase in the thermal power of the defect should lead to an increase in local overheating; therefore, the introduced active defect should become a “generator” of local isothermal circuits. Such an effect for a selected scale of isotherms was discovered during computer experiments when the thermal specific power of a rectangular defect exceeded $P > 3 \times 10^5 \text{W/m}^2$ (figure 5). It should be noted that the “irregular” shape of the isothermal line of the contour outside the defect is due to the thermal conductivity anisotropy introduced in the HP model ($k\lambda = \lambda X / \lambda Y$).

**Figure 4.** Change in heat flux density over time along the HP axis. Modeling, finite element method (GP with active defect (HS) of a square shape (steel, $a = 1.22 \times 10^{-5} \text{m}^2/\text{s}$, dimensions $L_1 \times L_2 = 6 \times 6 \text{mm}$). Example: $T_{PHFS} = 350 \text{K}, T_C = 300 \text{K}$. a – $\tau = 5 \text{s}$; b – $\tau = 40 \text{s}$.
Figure 5. The effect of the formation of a local isothermal circuit with an active defect (HS) of a square shape (steel, a = 1.22 · 10⁻⁵ m²/s, dimensions L₁ x L₂ = 6x6 mm) in a steel HP. Example, Modeling, finite element method, Tₚ_hₚ_s = 350 K, scale 50K, λ = 10, specific power of HS: q > 3 · 10⁵ W/m²; 1 – defect; 2 – isotherm (contour).

The results of the analysis of the morphological features of the temperature field of a HP with an active defect were also confirmed by conducting targeted computer experiments during which measurements of previously introduced geometric characteristics were carried out:

1) the distance from the center of the HP (HSPHF) to the front of the isothermal line (L);
2) the perimeter (length) of the contour of the isothermal line (P);
3) the surface area of the HP within the isothermal line (S) [8].

Table 1. Time-varying average values of the geometric characteristics of the thermal field of a HP with an active defect (HS) of a square shape (steel, a = 1.22 · 10⁻⁵ m²/s, dimensions L₁ x L₂ = 6x6 mm). in the sliding isotherm mode. Computer experiment. Example: TPHFS = 350 K, specific power of ITP, q = 3 · 10⁵ W/m².

| Time, τ с | Distance, L pixels | Perimeter, P pixels | Area, S pixels | Distance, L pixels | Perimeter, P pixels | Area, S pixels |
|-----------|------------------|------------------|---------------|------------------|------------------|---------------|
| 5         | 98.5             | 559.5            | 16250         | 94.2             | 555.4            | 15541         |
| 20        | 119.8            | 607.6            | 19406         | 112.5            | 599.1            | 18235         |
| 40        | 140.0            | 742.9            | 23522         | 125.1            | 731.4            | 21024         |
| 60        | 164.9            | 734.4            | 27870         | 138.8            | 720.8            | 23464         |
| 80        | 197.9            | 796.2            | 33241         | 158.3            | 777.8            | 26603         |
| 120       | 427.5            | 1031.0           | 73100         | 225.3            | 855.4            | 38535         |
| 140       | 418.2            | 1040.7           | 70260         | 287.7            | 928.1            | 48338         |

A typical example is given in table 1. Quantitative estimates were obtained using the well-known software “The Geometer's Sketchpad V4”. An analysis of the obtained data showed that the geometric characteristics at the level of average numerical values have different sensitivity with respect to the active defect localized in the HP, but undergo more significant changes compared to the HP containing a passive defect. The use of local values of the distance L also made it possible at the level of a
computer experiment to assess the degree of influence of the defect's heat production (figure 6).
Considering that the defect in the left block lies on the horizontal axis of the HP, the local change in
the shape of the isotherm (convex front, figure 2), as well as $\Delta L$, are pronounced in time. Regardless
of the location of the isothermal line in the left defective HP block, $\Delta L$ always remains positive and its
increase in time is observed according to a law close to parabolic. An increase in the defect's heat
production only shifts the time dependence of graph (2) to the region of large $\Delta L$ values. Such a
character of the dependences is typical for the studied range of variation of the thermal power $q$.

Figure 6. Change in the absolute value of the local distance from the center of the HP to the front of
the moving isotherm in time. Computer experiment (HP with an active defect (HS) of square shape
(steel, $a = 1.22 \times 10^{-5} \text{ m}^2/\text{s}$, dimensions $L_1 \times L_2 = 6 \times 6 \text{ mm}$)). Example: $T_{\text{PHFS}} = 350 \text{ K}$, $T_C = 300 \text{ K}$. 1 – $q = 2 \times 10^5 \text{ W/m}^2$; 2 – $q = 3 \times 10^5 \text{ W/m}^2$.

4. Conclusion
According to a computer experiment, the presence of a localized active defect, irrespective of shape,
causes variability of the shape of the isotherms and the nature of the temperature distribution along the
HP axis; moreover, the magnitude of the heat production of the defect has the greatest influence on the
morphology of the temperature field; its increase causes the formation of a local isothermal contour.

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