Modelling the dynamics of temperature field morphology of a heat pipe with a case defect

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Abstract. As part of a computer experiment with the use of the finite element method, a method was developed for analyzing the morphology of the non-stationary temperature field of a heat pipe which has a localized structure defect in its case. It is shown that within the model of a steady start of HP (τ = 0 ÷ 120 s.) and maximum temperatures of PHFS T_{PHFS} = 350 ÷ 400 K, the presence of a defect causes the variability of the shape of isotherms over time and the nature of the temperature distribution along the HP axis. In this case, the distance from the center of the HP to the front of the isothermal line uniquely determines changes in the morphology of the temperature field.

1. Introduction
Heat pipes (HPs) belong to the class of special cooling devices and most of them are intended for isothermal operation [1-3]. However, in practical use, virtually every HP goes through a starting mode. It is known that its duration, as well as the nature of changes in the temperature field, depends on the HP design features, methods of heat supply and cooling. In addition, the duration of the starting mode is significantly affected by the law of change in the input thermal power. Depending on the shape of the temperature profile along the length of the HP, there are three main types of start-up mode, which should be considered as limiting [2]: 1) uniform start; 2) frontal start; 3) frontal start in the presence of non-condensable gases. It should be noted that, in the general case of the start-up mode, the temperature field of the HP at different points in time is determined both by the above (previously) noted factors, and by various technological defects (including the second phase, grains localized in the housing, etc.) [1, 2, 4]

Historically, analytical methods for calculating the nonstationary thermal regime of HPs were based on a model in the form of a system of bodies connected by ideal thermal couplings, and the basis of mathematical models was the well-known analytical expressions for the regular mode [2, 5, 6]. In the scientific literature, some models and examples of the analysis of the dynamics of HP start are considered, for example, Kotter et al. [2, 7]. At the same time, certain works are known in which numerical calculation methods were used [1, 8]. Consideration of the increased information content of the launch mode in the development of new thermal imaging methods for diagnosing the quality of HP arouses a certain interest in computer studies that provide visualization of the effect of defects on the morphology of the temperature field of the HP case with the central localization of the source of thermal power [9–11]. And this in turn requires the creation of new thermal and mathematical models of HPs with localized defects.

2. Research methods
Geometric model. It was taken into account that the thermal imaging method of monitoring the quality of HP is oriented to tubes with a symmetrical structure. Therefore, as one of the options, we chose a flat, steel HP of the classical construction (figure 1) [1, 3, 12]. In the center of the body of the HP was located the
source of heat flow (HFS). During the calculations, a rectangular HFS model was used. The geometrical parameters of the HP in the models on average were respectively: L ≈ 150 ÷ 500 mm; h ≈ 20 ÷ 30 mm; δ ≈ 5 ÷ 8 mm. An additional element of the model was the case defect, which, on the basis of clarity and convenience, was placed on the HP axis on a methodical plane. Its shape, size and physical properties could be changed during a computer experiment.

**Thermal model.** As a base case, a nonstationary thermal model of a HP was developed, consisting of four bodies: a HP case (limited horizontal rod); heat flow pulsed source (PHFS); defect; environment. A steady start (duration, τ = 0 ÷ 120 s., figure 2) was considered as a model of the start HP mode. Within the framework of the model, the transition from an isotropic to anisotropic rod was provided by specifying the corresponding coefficients of thermal conductivity λx and λy.

It should be noted that the main mechanisms for the dissipation of thermal energy from the surface of the rod into the air (gas) ambient with a temperature Tm were free (natural) convection at normal pressure and thermal radiation. The following simplifications are valid for this thermal model: ideal thermal contact of the HFS with the surface of the HP, the absence of loss of thermal energy of the HFS into the environment, and also the condition of isothermality of the fins and the surface of the HFS.

Thus, HFS forms a heat flux with the same density along the selected directions of the rod. In addition, the accumulation of thermal energy in the PHFS was not taken into account and the contact thermal resistance between the defect and the HP case (the ideal thermal contact) was not taken into account, and the body of the defect was considered as an isotropic medium. An example of a nonstationary thermal model of HP is shown in figure 3.
Mathematical model. At present, various methods have been developed for the numerical calculation of temperature fields in plates and rods, including with sources of heat flow \cite{5, 13, 14}. They are based on the solution of the general heat equation \cite{5}:

$$
c p \rho \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q_0
$$  \hspace{1cm} (1)

For a non-stationary problem in the plane-parallel formulation, the initial heat conduction equation (1), taking into account the formulated constraints, can be written as:

$$
c p \rho \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + q_0
$$  \hspace{1cm} (2)

where: \(c_p\) and \(\rho\) – specific heat and material density; \(\lambda_x, \lambda_y\) – thermal conductivity; \(q_0\) – heat output per unit volume of thermal energy sources; \(T\) – temperature; \(x, y\) – coordinates.

For the developed base thermal model, the following initial and boundary conditions were used \cite{5}:

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

\[ T_{i,\tau} = T_C = \text{const} \]  \hspace{1cm} (3)

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

\[ T = T_P \]  \hspace{1cm} (4)

3) on the edges of the HP model, a third kind condition was specified, which describes both convective and radiative heat exchange with the environment:

\[ \lambda_n \frac{\partial T}{\partial n} = -\alpha_k (T - T_C) - \beta (T^4 - T^4_C) \]  \hspace{1cm} (5)

where: \(\beta\) – value equal to the product of Stefan-Boltzmann constant \((\sigma_0=5.7-10^{-8} \text{ Bt/m}^2\text{K}^4)\) by the coefficient of radiance of the surface of the probe material; \(\alpha_k\) – convection heat transfer coefficient. The numerical values of the coefficient \(\alpha\) were obtained from preliminary calculations using the well-known similarity method. The removal of heat flow through conductive connections of HP fasteners was not taken into account. The system of equations (2-5) was solved by a numerical method (finite element method) on a PC \cite{13, 15}. Computer experiments were performed for maximum temperatures of PHFS \(T_{PHFS} = 350\div400 \text{ K}\) and constant ambient temperature (air) \(T_C = 300\text{K}\). A series of calculations were performed which, taking into account the anisotropy of the thermal conductivity coefficient, made it possible to reveal the effect of a hull defect on the field characteristics of the proposed thermal model of HP.

3. Research results and discussion

It is known that in non-stationary processes the rate of transfer of thermal energy is determined by the coefficient of thermal diffusivity of the material \cite{5}. Therefore, studies of the effect of the defect material on the morphology and characteristics of the temperature field of the HP present a scientific interest. Among
the starting materials (table 1), which most often determine the structure of real defects of HP structures and differ in the value of thermal diffusivity coefficient, we chose air [1, 4].

**Table 1.** Type of material defect of HP structure. Example.

| Material defect | Alumina  | Air       | Iron     | Copper    |
|-----------------|----------|-----------|----------|-----------|
| Thermal diffusivity, a, m²/s | 7.6·10⁻⁸ | 2.57·10⁻⁵ | 3.28·10⁻⁵ | 1.19·10⁻⁴ |

For a detailed study over time of changes in the morphological features of the temperature field, the sliding isotherm method was implemented [8]. The essence of this method is that the effect of a defect on the morphology of the temperature field is estimated by changing the shape of a single isotherm as it moves within the time interval of the transition process from the PHFS to the condensation zone. This compares the field characteristics of the HP areas with and without a defect (for example, to the left and to the right of the PHFS). An analysis of the nonstationary temperature field of HPs in the modes: thermograms, isolines, and selected contours showed the variability of the shape of isotherms (figure 4a) and the nature of the temperature distribution of the gradient along the axis (figure 4b, c).

**Figure 4.** Morphological features of non-stationary thermal field of HP with defective square shape (air, dimensions L1 x L2 =6x6 mm). Example

a - Evolution of the isotherm. Scale 50K, anisotropy ratio kλ=λx/λy = 10;

b – The graph of temperature distribution in HP along the X axis. Example, τ = 120 s;

c - The graph of the distribution of temperature gradient in HP along the X axis. Example, τ = 120 s.
As follows from figure 4a, noticeable changes in the shape of the isotherm are already well seen in the initial period of the transition process (\(\tau = 5\) s), and the most significant changes are observed when the isotherm of the defect region passes (\(\tau = 100\) s). It should be noted that with the gradual removal of the isotherm from the defect (\(\tau > 100\) s), the shapes of the lines to the left and right of the PHFS did not differ much.

The presence of a localized defect (air pore) with a small value of thermal diffusivity from the standpoint of heat transfer is equivalent to the formation of an adiabatic region, which during the transition period delays the propagation of heat flow and warms up much slower compared to figure 4a where noticeable changes in the shape of the isotherm are already well seen in the initial period of the transition process (\(\tau = 5\) s), and the most significant changes are observed when the isotherm of the defect region passes (\(\tau = 100\) s). It should be noted that with the gradual removal of the isotherm from the defect (\(\tau > 100\) s), the shapes of the lines to the left and right of the PHFS did not differ much.

The presence of a localized defect (air pore) with a small value of thermal diffusivity from the standpoint of heat transfer is equivalent to the formation of an adiabatic region, which during the transition period delays the movement of heat flux and warms up much slower compared to the surrounding layer of HP material [5]. It is also necessary to note the general tendency revealed during the simulation of a significant decrease in the influence of a passive defect on the morphology of the HP temperature field with a decrease in the size of the defect.

![Figure 5](image_url)

**Figure 5.** The change in the absolute value of the local distance from the HP center to the front of the sliding isotherm in time. Computer experiment.

The analysis of the morphological features of the temperature field made it possible to introduce seemingly obvious and relatively simple quantitative characteristics that, in the process of sliding isotherms, undergo noticeable changes. As such a characteristic, for example, we chose the distance from the center of the HP (PHFS) to the front of the isothermal line (L) (figure 5).

The use of local values of the distance L makes it possible to classify defects by the value of the thermal diffusivity coefficient at the level of a computer experiment. In figure 5, the ordinate shows the value \(\Delta L = L\) LEFT – L RIGHT (in the left block of the HP there is a defect). Here L LEFT and L RIGHT are the distance from the center of the HP along the axis to the front of the isothermal line in the left and right blocks, respectively. Given that the defect in the left block lies on the horizontal axis of the HP, then the local change in the shape of the isotherm (figure 4a), as well as \(\Delta L\), is clearly expressed in time. The presence of extremes on the graph (figure 5) should be attributed to the competing nature of the change in the rate of heat flow in the HP blocks on both sides of the PHFS due to the change in thermal diffusivity [5]. It should be noted that after the passage of the defect, \(\Delta L \to 0\). This type of dependence is typical for the studied HP models.

4. Conclusion
In the framework of the HP steady start model according to a computer experiment, the presence of a localized passive defect in the form of air pores in the body of the HP causes the variability of the shape of isotherms over time and the nature of temperature distribution along the HP axis, while the distance from
the center of the HP to the front of the isothermal line definitely determines changes in the morphology of the temperature field.

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