Features of the thermal imaging method for quality control of profile heat pipes

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Abstract. A new method for controlling the quality of a heat pipe is proposed and tested by separately using the conductive method of heat input and the optical method of measuring temperature at infrared wavelengths, as well as digital methods for processing the recorded brightness contrast of the heat field. The quality of the heat pipe is judged by the magnitude of the asymmetry coefficient of the isothermal surface relative to the heat supply zone, and the defect zone is visually determined by the distortion of the shape of the isothermal lines.

1. Introduction
Within the framework of technology of high factory readiness, methods and telovision-measuring systems (TMS) for controlling the quality of products in pressure-tight shells, inside which phase transitions occur with absorption and release of heat, are of scientific and practical interest. These products primarily include heat pipes (HP), which carry out high-speed transport of high-intensity heat flows within their own pressure envelope beyond the boundaries of localization of various heat sources. Currently, HP are widely used in systems for providing thermal conditions for microwave electronics, as well as in nuclear energy and, of course, in computer technology [1-3]. Therefore, high requirements are imposed on the reliability of HP, and the methods and means of their diagnosis are constantly being developed and improved. Among the known methods in conditions of uniform start-up of a HP and pulsed heat supply to the center, it is necessary to distinguish probe (thermocouple) and television in the mode of dynamic thermography [4-9]. The competitive advantages of this thermal imaging diagnostics of HP are the ability to visualize the thermal luminance contrast in real time, and the simultaneous measurement of other necessary physical quantities within a single frame (scene). As a disadvantage, one should consider the dependence of the quality of the recorded IR - brightness contrast of the thermal field of the HP on the background radiation entering the input lens of the thermal imaging camera due to the processes of refection of the IR radiation from the pipe surface when the reverse heat flows are excited in it. This work is devoted to questions of improving the quality of the thermal imaging method for the diagnosis of HP.

2. Research Methodology

2.1. Profile heat pipes manufactured by OKB-Planeta JSC, Veliky Novgorod, Russia.
Currently, in the microwave equipment and various technologies, a class of heat pipes has been widely used, the casings of which are made in the form of profiles of a special design made of aluminum alloys (AD-31 according to the Russian standard GOST 4784-74 or alloys 6060, 6061, 6063 according to the
American standard AMS 4116) by the extrusion method, single-channel or two-channel, and longitudinal grooves formed in a single technological cycle are used as a capillary-porous structure (Fig. 1) [10, 11]. Acetone and ammonia of high purity are most often used as a coolant (working fluid) in such low-temperature TTs.

![Image of an aluminum HP with a finned radiator](image)

**Figure 1.** Appearance of an aluminum HP with a finned radiator. Photo. (a) and types of HP profiles (b) [2, 10, 11].

Profile HP have been widely used in areas such as [2]:
- systems for cooling, temperature control or temperature control of space technology devices;
- systems for providing thermal regimes of electronic equipment in various industries;
- refrigeration equipment: household refrigerators, drink coolers, etc. based on Peltier elements and absorption-diffusion effect;
- medical equipment: cryo-instruments and thermal stimuli of living tissue in dermatology, cosmetology, urology, surgery, etc.;
- thermal household appliances: heaters, solar collectors, stoves, etc.

| Table 1. Technical characteristics of ammonia HP JSC "OKB - Planet" |
|---------------------------------------------------------------|
| **Characteristic** | **Value (norm)** |
| HP profile material | AC-KRA6.0 - P2. with drop-shaped grooves |
| Stennel material - tubes | AD-31 |
| Plug material | AD-31 |
2.2. Modeling the temperature field of a heat pipe
When developing the methodology, an aluminum HP with ammonia coolant was chosen as a geometric model. The dimensions of the HP geometric model were respectively (figure 2a): body dyne (1), L = 200mm; thickness, H = 4 mm; width, B = 20 mm; while the wall thickness of the case was taken equal to 0.7 mm. A feature of this model was the central location of the heat flux source (HFS) (2).

In the experiments, round and rectangular HFS were used. This made it possible to create reversible heat fluxes Q, which moved in the material of the body, wick, and vapor channel, and caused a change in time of the corresponding temperatures due to the known heat transfer mechanisms. Thus, a diagnostic signal in the form of thermal contrasts carrying information about morphological changes in temperature fields was formed within the surface of the HP housing. The main mechanisms for the dissipation of thermal energy from the surface of a horizontally oriented HP housing into an air (gas) medium with a temperature $T_c$ in the thermal model were chosen free (natural) convection at normal pressure and thermal radiation [12,13].

When constructing the mathematical model of thermoelectric thermometers, the unsteady heat conduction problem in a plane-parallel formulation was considered. For this case, we used the heat equation (1), as well as the initial (2) and boundary conditions (3 - 5) [13]:

$$
c_p \rho \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q_0
$$

(1)

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

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 HFS, taking into account the surface isothermality, a condition of the first kind was specified:

$$
T = T_p
$$

(3)

3) For the inner ribs forming the vapor channel, the boundary conditions of the second:

$$
\frac{\partial T}{\partial n} = \psi_i
$$

(4)

4) A condition of the third kind was set on the external ribs (case) of the HP model, which describes both convective and radiant heat transfer with the environment:

$$
\lambda_\alpha \frac{dT}{dn} = -\alpha_\alpha(T-T_c) - \beta(T^4-T_c^4)
$$

(5)
where: \( \beta \) – value equal to the product of the Stefan-Boltzmann constant \( (\sigma_0=5.7 \times 10^{-8} \text{ W/m}^2\text{K}^4) \) and 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 known similarity method [13]. Heat flux removal through conductive connections of HP fasteners was not taken into account. The system of equations (1 - 5) was solved numerically (finite element method) on a PC. Using “ANSYS 13.0” Software [14] a series of calculations was performed that made it possible to assess the degree of influence of the power of the induced HFS on the field characteristics of the thermal model of the HP. The grid pitch was chosen optimal, based on the available PC resources, and was 1.4 mm in the model as a whole and 0.5 mm in the field of HFS. Studies performed at ambient temperature \( T_C = 300\text{K} \), the time of the HFS operation was 120 s, and its power varied in the range of values \( P = 0 \div 5 \text{ W} \). The research results showed that when using the model of the uniform starting mode of the HP, the nature of the change in the maximum surface temperature in the time interval 0 \( \div 120 \text{ s} \) in the HFS localization region is close to linear. This character of the dependences also persists with an increase in the power values of the surface current transformer HFS induced on the surface. This made it possible during a computer experiment, for example, to study the conditions for bringing the HP to the operating mode, the nature of the temperature distribution along the pipe, factors that prevent start-up, etc. For example, using the field characteristics method in isoline mode, morphological features were simultaneously visualized unsteady temperature field of the HP from both the front and the back side relative to the induced HFS. Typical examples of simulation results are shown in Figure 2.

It is clearly seen that the temperature field is represented by a system of symmetric isothermal lines. With the growth of HFS power, there was only an increase in the distance between isotherms without a significant change in their morphological features. During the studies, the effect of the delay of the front of the corresponding isotherm on the back surface of the HP relative to the HFS was discovered (Fig. 2b - 2d). This effect, in our opinion, is due to the features of the heat flux transport from the HFS in the transverse direction of the HP [12,13].

Figure 2. Morphology of the temperature field of a heat pipe at various values of the thermal power of a pulsed source (Q). Calculation: Contour mode. "ANSYS 13.0" software. a) HP geometric model; b, c, d - thermal power, respectively: 1W, 3W, 5W.
2.3. Laboratory measuring stand

Experimental studies were carried out on a laboratory bench, a structural diagram of which is shown in figure 3 [9]. He envisaged the possibility of pulsed heating of the HP both with the help of radiation (photon heating), and with the help of resistive. For these purposes, a controlled electric pulse generator (1) was used; the maximum heating time was 120 s.

![Figure 3](Image)

**Figure 3.** Block diagram of laboratory measurement stand [9].

Under the conditions of resistive heating, a film resistor on a ceramic substrate was used as a heat flux source (HFS) (2), which was fixed strictly in the center of the HP (3) on the side (4). The thermal, brightness contrast of the shadow side (5) of the HP was recorded using an TIS consisting of a germanium input lens (7), an IR television transmitting camera (8) based on the uncooled IR-113 module ($\lambda = 8\div14\text{mkm}$). communication channel (9) and PC (10) with software. The distance from the investigated HP to the input lens did not exceed one meter. TIS setup and calibration was carried out using the line of sight (6) and the layout of a completely black body. The developed technique is focused on HP with a symmetrical structure. Therefore, to test the methodology, we selected aluminum profile HP (Table 1) with ammonia coolant, serially manufactured at OKB-Planeta OJSC (Veliky Novgorod, Russia). They are currently sufficiently studied objects, have a symmetrical structure, and therefore, in this paper were considered as model in solving the formulated problems.

3. The results of experimental studies and their discussion.

3.1. Visualization of the morphology of the temperature field of the HP method of dynamic thermography.

Video recording of the thermal brightness contrast of the HP in the uniform start-up mode was carried out using the Plast1.0 software as part of a hardware-software complex based on the PCM. A typical example of this technology is shown in figure 4.

![Figure 4](Image)

**Figure 4.** An example of a video recording of a heat-loaded HP. Experiment. ON "Plast1.0". Photo. 1 - HP housing; 2 – HF.
Formation of thermograms. The sequence of HP image files created during video recording was subjected to digital processing in the framework of well-known algorithms, with the aim of generating thermograms in which pixel amplitudes are expressed in "radiation" temperatures \[15\].

A comparison of the evolution of the morphological patterns of the thermal field from the front and back sides of the HP (Fig. 5) showed that general patterns are observed. For example, characteristic of the two sides of the HP, the structure of the unsteady thermal field of the HP is formed by a system of isothermal zones. Their length, according to the experiments, underwent significant changes along the HP axis in time upward. Such an evolution of the thermal field corresponded to the well-known uniform start-up mode, which was realized automatically due to the high pressure of ammonia vapor even at room temperature. Defective areas of the HP were visualized as separate foci, (example, Fig. 5b, \(t=12\)s – another colour) violating the homogeneity of color zones. Distinctive features of the morphology of the back side were the fragmentation of zones at the initial stage of heating and the delay effect during their formation (for example, Fig. 5b, \(T = 6\)c), which coincides with the results of a computer experiment (figure 2).

3.2 The study of the quality of HP method of asymmetry.

The use of pulsed reversible heat fluxes and basic algorithms for processing the recorded thermal contrast of a HP allows us to actually select a temperature section for any moment in the form of an isothermal zone limited by a isotherm of a certain shape.

Figure 5. An example of evolution and morphology of the temperature field of ammonia TT. Experiment. Software "Plast1.0". Photo. Temperature cut \(T = 26\)˚C; a - the front side, b - the back side.
Thus, the assessment of the quality of HP was reduced to the problem of comparing the geometric shapes formed by these contours using the asymmetry coefficient by features [16]. As such signs in this work, we used: the distance from the center of the heat pipe to the front of the isothermal line (L), the perimeter (length) of the contour of the isothermal line (P) and the surface area of the heat pipe within the isothermal line (S). At the same time, the principle of the “reference tube” allows us to establish a relationship between the quality of the HP and the asymmetry coefficient within the framework of simple criteria: 1) ASi≈ AESi - satisfactory; 2) ASi >> AESi - unsatisfactory or point system, from the standpoint of metrology, providing a technology for sorting a specific type of HP.

Table 2 shows examples of measurements of the asymmetry coefficients on both sides of the HP. Quantitative estimates of AI were obtained using the software “The Geometer's Sketchpad V4”. Their analysis showed that for a HP manufactured by an industrial method and not containing specially introduced defects, the asymmetry coefficients for the signs predominantly turn out to be nonzero. In this case, the reversible sliding of isotherms from the HFS to the edges of the HP (increase in the conditional brightness) causes a change in their values depending on the feature and the resulting edge effects due to the structure of the thermal field (defects).

Table 2. The values of the asymmetry coefficients according to the signs of ammonia HP. Experiment. Example.

| №  | Conditional brightness | Type coefficient asymmetries according to $A_i$ | Coefficient value asymmetries |
|----|------------------------|-----------------------------------------------|------------------------------|
|    |                        | $A_L$                                         | Front side of the HP  | Back side of the HP |
| 1  | 158                    | 0,000                                         | 0,070                       | 0,072                        |
|    |                        | $A_S$                                         |                             | 0,080                       |
|    |                        | $A_P$                                         |                             |                             |
|    |                        | $A_L$                                         |                             | 0,098                       |
| 2  | 170                    | 0,145                                         | 0,099                       | 0,044                       |
|    |                        | $A_S$                                         |                             |                             |
|    |                        | $A_P$                                         |                             |                             |
|    |                        | $A_L$                                         |                             |                             |
| 3  | 180                    | 0,232                                         | 0,152                       | 0,063                       |
|    |                        | $A_S$                                         |                             |                             |
|    |                        | $A_P$                                         |                             |                             |

4. Conclusion
It has been experimentally established that the quality of the brightness contrast recorded using a thermal imaging measuring system from the side of a heat-loaded HP provides the possibility of using the field characteristics method to visualize the thermal field morphology and the sliding isotherm method for quantitative estimates of the asymmetry coefficients by attributes for aluminum profile HP.

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