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METHODS OF COMPUTATIONAL THERMOGRAPHY IN THE NONDESTRUCTIVE TESTING OF THE QUALITY OF HEAT PIPES AND HEAT EXCHANGE DEVICES BASED ON THEM

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In order to have a non-contact method of diagnosing the quality of heat exchangers, a scanning IR system has been developed and tested which records and analyzes the characteristic IR radiation of the heat exchanger under steady-state or transient conditions.

At present devices based on heat pipes have found applications in various technical fields. By making it possible to transfer large quantities of heat at high efficiency and with minimum losses and transforming heat flux densities over a wide range of temperatures they have successfully replaced more traditional constructions. To a considerable extent, the economics of heat pipe devices and the probable fields of their application are determined by their reliability, which depends both on the design itself of the heat pipes and also on the quality of their construction. As the mass construction of heat pipes has developed and their designs have become more complicated, the problem of checking the parameters (temperature conditions) of heat pipes both in the construction stage and in the period of use has assumed increasing importance [1].

The use of non-contact methods of IR diagnosis using thermographic systems for nondestructive testing ensures a high efficiency of the measurements with respect to time, space, temperature resolution, and reproducibility. An important extension in the functional possibilities of the IR imager as a measuring device was achieved by digital treatment of the infrared images which are obtained by the use of a computer operating in an interactive mode.

In the investigations which have been carried out to develop a method for testing the quality of heat pipes, use has been made of an automated system based on the TV-03 infrared imager which makes it possible to achieve a temperature resolution of at least 0.2 K at a level of 300 K. The determination of the absolute value of the temperature from the measured electrical signal of the photodetector U is carried out by means of the polynomial

$$T = \sum_{i=0}^{n} C_i U^i, \tag{1}$$

the coefficients C_i of which are calculated from the known spectral characteristics of the object, the IR imager, and the atmosphere [2], or are determined directly in the course of the experiment from results of comparisons with data from contact measurements to an accuracy of about 1 K.

The isothermal nature of the temperature distribution over the condensing zone of a heat pipe is a criterion for its ability to operate efficiently at the corresponding thermal load

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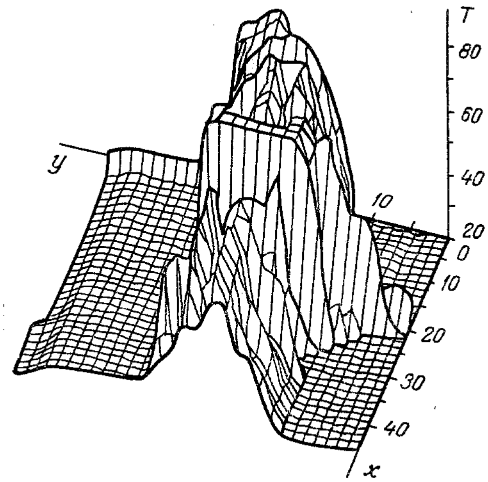

Fig. 1. Temperature distribution over the surface of a finned heat removal system based on four heat pipes with input power 300 W. The units of x, y are cm, and of T, °C.

being transferred. The presence of a defect in the transport structure of the heat pipe or of gas-liquid choking of the condensing zone causes a disruption of the isothermicity along the axis of the heat pipe, which is easily detected by a thermographic test [3].

In analyzing systems consisting of several heat pipes with a common radiator and with an increase in the degree of shielding of the body of the heat pipe from the surface of the radiator (finning), the nature of the thermal picture which is observed can become considerably more complicated (see Fig. 1).

In the characteristic radiation of the heated plates of radiators and heat pipes is included re-reflected radiation and radiation from the surrounding background. In order to increase the radiation contrast, in a number of experiments coatings were deposited with known radiation properties which were greater than the emissivity factor of the metallic elements of the heat pipes and radiator. The spectral characteristics of the radiating surfaces were investigated using an IKS-29 spectrophotometer. The analysis of the thermal fields which were recorded was carried out on the screen of a colored raster television display in the form of colored images (with a specified temperature – color coding) and in the form of isothermal or three-dimensional images. The latter method of presenting the information is the most natural form of representation when the coordinates are laid out along two of the axes in space and the absolute temperature is plotted along the third axis. Here 0.06-1 sec is required for the formation of thermovision images, 30-160 sec for the generation of the graphic images, and 5-15 sec for the presentation of the information, depending on the quantity of information involved. Thus, the testing of the quality of a heat pipe under conditions of mass production should be carried out either by comparing the image of the item being checked with a reference image, or on the basis of corresponding reproducible criteria.

In comparing the thermal field of the item being tested with the IR image of a reference object which is stored in the computer memory, errors in determining the degree of acceptibility can be caused by small features in the manufacture of real designs, particularly if these consist of several heat pipes, or if there is a change in their spatial orientation relative to the thermographic system. As a criterion for the efficiency of operation of a block consisting of several heat pipes it is possible to take (as in the case of a single heat pipe) the temperature distribution along the axis of each of the heat pipes, but where this is not recorded directly but as a smoothed quantity. In this case, the temperature at each point on the surface of the heat pipe is replaced by a value defined by its environment, and in this way the effect of various spatial orientations of the fins of the radiator is correspondingly reduced. In the smoothed method using least squares the function $T(x)$ specified at the points x_j ($j = 1, 2, \ldots, m$) is approximated by a polynomial of power $n < m$:

$$T(x) = \sum_{i=0}^{n} a_i x^i, \tag{2}$$

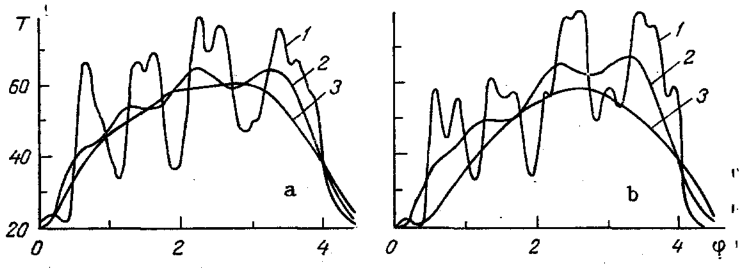

Fig. 2. Temperature distributions along the axes of heat pipes (a: reference heat pipe; b: heat pipe being tested). 1) recorded distribution; 2) smoothed distribution (n = 2); 3) smoothed distribution with n = 3. The units of φ are degrees.

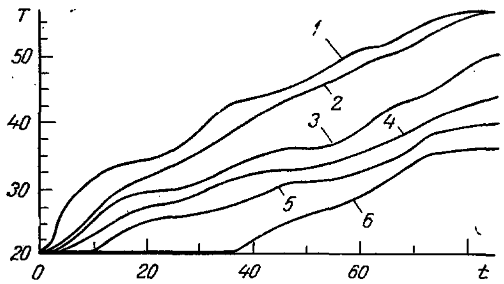

Fig. 3. Dependence of the temperatures of equally spaced points along the axis of the condensation zone of a heat pipe on the time of heating with a transferred power of 20 W (curve 1 corresponds to the evaporator, curve 6 to the peripheral part of the condenser, and curves 2-5 to the intermediate positions). The time t is given in seconds.

where the choice of the polynomial must ensure a minimum value of the sum

$$\sum_{j=1}^{m} \rho_j (T_j - \sum_{i=0}^{n} a_i x_j^i)^2, \tag{3}$$

with $0 \leq \rho \leq 1$ as the weighting of the point j.

When linear filtering is carried out for a function which is specified at equally spaced nodes x_j ($j = 1, 2, \ldots, n$), then

$$\tilde{T}_j = \Big(\sum_{i=j-m}^{j+m} T_j\Big)/(2m+1),\ j = 1, 2, \ldots, n. \tag{4}$$

where $m < j \leq n-m$.

Figure 2 shows the temperature distributions along the axes of two heat pipes and the results of smoothing the values by means of a linear filter with various values of n. The nature of the distribution suggests the presence of defects in the second pipe, which was confirmed by the results of a destructive test.

The use of smoothing makes it possible to simplify to the greatest extent the procedure for comparing several identical heat pipes. However, in this case it is necessary to take into account that the nature of the temperature distribution is determined to a considerable degree by the constancy of the value of the power being dissipated. At large values of the transferred power the non-isothermal nature of defective heat pipes becomes obvious.

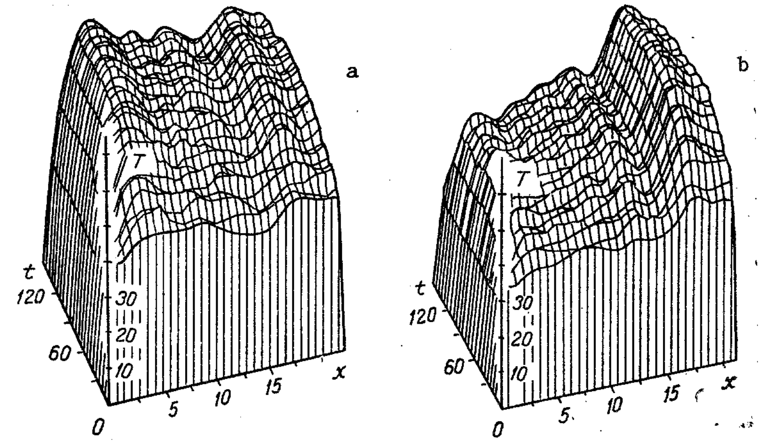

Fig. 4. Temperature distributions over the length of the condensing section of a heat pipe as a function of the time of heating: a) without making allowances for the radiation properties of the surface; b) with allowances made for the emissivity factors of the condenser.

The realization of such a method of thermovision testing of the quality of heat pipes and equipment based on them under mass production conditions is also possible by replacing the thermovision inspection of all of the object as a whole by the measurement of the temperature by an infrared radiometer at several characteristic points which have been determined from the results of thermovision observations, for example, at the ends of the heat pipes after some interval of time after the start of the heating process (Fig. 3). In this procedure the test is reduced to determining the values of the temperatures being measured relative to the limiting possible values using a two-threshold analog comparator. Tests of groups of vertically arranged heat pipes placed on a rotating base and partially submerged in a hot liquid are carried out in a system developed on the basis of this principle.

However, in measurements of this type it is difficult to avoid errors caused by variations in the emissivity along the axis of the heat pipe.

In fact, in carrying out thermovision experiments during tests with IR radiometers without taking into account the emissivity factors of the surfaces, the recorded temperature field of an isothermal object may be of a non-uniform nature. The accuracy of the measurements can be increased by making use of the fact that for most of the materials which are used the emissivity factor depends little on the temperature over the range being investigated (20-130°C). At the initial moment of time, before the heating begins, the infrared imager receives a flux of radiation from the isothermal surfaces of the heat pipe, which are then at room temperature. Any nonuniformity in the radiation flux in this case is caused only by differences in the emissivity factor and is proportional to it. After the heating process begins the flux of radiation from the heat pipe depends not only on the emissivity factor, but also on the temperature of the wall surface. Bearing in mind that $\varepsilon(T) = \mathrm{const}$, we can obtain the actual temperature distribution along the axis of the heat pipe by dividing the intensity of the element of the image of the heated heat pipe which is recorded by the normalized intensity of the same element of the distribution of the IR radiation of the heat pipe at room temperature. This algorithm set up in the form of a program makes it possible to carry out the required correction of the results as the experiment is performed (Fig. 4) [4]. The nonuniformities in the temperature distributions were caused by the presence of non-condensible gases in the cavity of the heat pipe.

However, the greatest interest lies in the conditions for testing heat pipes which are based on measuring the main parameters characterizing the quality of the heat removal system or of the individual heat pipes, namely, the temperature resistance R_T, which is defined as the ratio of the difference in the surface-averaged temperatures of the evaporator $\bar{T}_e$ and of the condenser $\bar{T}_c$ of the heat pipe to the heat flux Q being transferred by it:

$$R_T = \frac{\bar{T}_e - \bar{T}_c}{Q}. \tag{5}$$

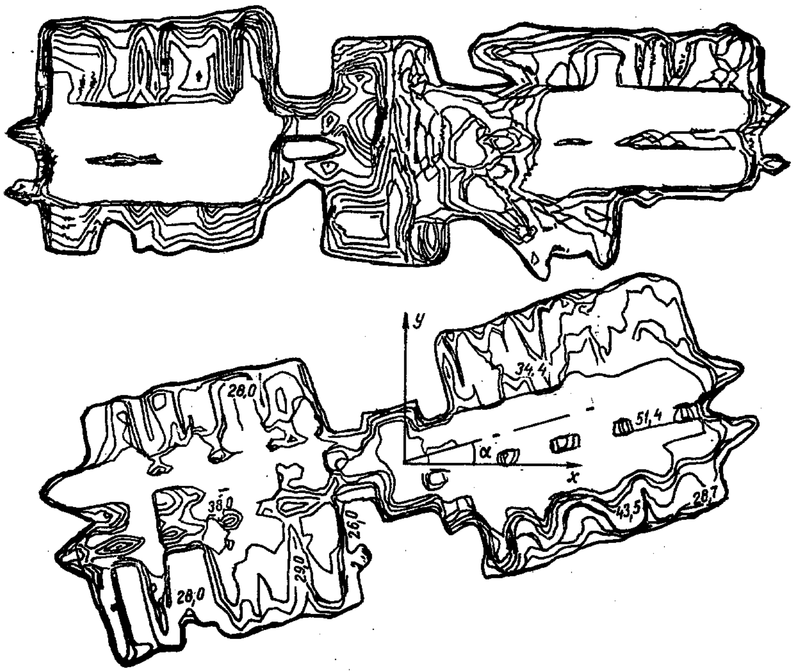

Fig. 5. Temperature distributions in the form of isotherms over the surfaces of ribbed heat removal systems consisting of four heat pipes placed horizontally and at an angle to the horizontal.

In the investigations carried out using the automated thermovision systems the value of the temperature resistance of a heat transfer system can be determined by simultaneously carrying out measurements of the heat flux being transferred by the heat pipe and the temperature field on its surface. By measuring the temperatures of the stream of air from a blower having a fixed rate of rotation which is heated by the heat pipe or heat exchanger assembly, Q can be expressed as

$$Q = C_p G \Delta T, \tag{6}$$

where C_p, G are the heat capacity and flow rate of the air; $\Delta T = T_2 - T_1$ is the temperature difference of the air before and after the exchange of heat.

Figure 5 shows the temperature distributions obtained experimentally in the form of isotherms over the surfaces of heat removal systems in the horizontal and sloped positions with forced air cooling. The nonuniformity of the temperature distribution in the lower parts of the infrared imager is caused by changes in the operating conditions of the heat pipes.

The results of the measurements make it possible to evaluate the thermal loads being dissipated and to show that considerable temperature differences (up to 10 K) occur between symmetrical points of the heat transfer device at a slope of +45° which are related to changes in the operating conditions of the heat pipes and to the forced air cooling.

The use of digital evaluation of the images reduces the errors of determining the mean temperatures of the evaporation and condensation zones and increases the accuracy of determining the temperature resistance, the absolute value of which is used for grading the products being tested.

The investigations carried out over a number of years in the Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR have made it possible to show that the application of thermovision equipment is highly effective both in developing the designs of heat pipes and also in carrying out tests on them.

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HYDRODYNAMICS, HEAT AND MASS TRANSFER, AND SOLIDIFICATION IN THE FORMATION OF INGOTS AND CASTINGS

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UDC 536.42

A set of interrelated mathematical models is developed for processes of heat and mass transfer and solidification. Its scope is illustrated on specific examples of the calculation of cast-ingot formation.

The quality of metal is determined, to a considerable extent, by the interrelated processes of hydrodynamics, heat and mass transfer, and solidification in the period of transition from the liquid to the solid state.

The most acceptable investigation procedure in this case is mathematical modeling, as an effective instrument in the study, prediction, and optimization of complex nonlinear transfer processes occurring in solidifying alloys.

A generalized mathematical model of conjugate processes of momentum, heat, and mass transfer in the solidification of an Fe–C binary melt, taking account of the two-phase zone (TPZ), is formulated from the perspective of continuum thermomechanics [1], and includes averaged macrocontinuum equations of motion, heat transfer, mass transfer, continuity, magnetic induction (noninductive approximation), and electric-charge balance and the equilibrium condition at the boundary between melt and solid phase (the equation for the liquidus line in accordance with the quasi-equilibrium theory of the two-phase zone [2])

$$\rho_2\left[\frac{\partial\langle \mathbf{U}_2\rangle}{\partial t}+\left(\frac{\langle \mathbf{U}_2\rangle}{1-\xi}\nabla\right)\langle \mathbf{U}_2\rangle\right]=-\nabla\langle P_2\rangle+ \\ +\mu\Delta\langle \mathbf{U}_2\rangle+\mathbf{g}\langle\rho_2\rangle-\frac{\mu}{k(\xi)}\langle \mathbf{U}_2\rangle+\langle(\mathbf{j}\times\mathbf{B})_2\rangle; \tag{1}$$

$$[(c_1\rho_1-c_2\rho_2)\xi+c_2\rho_2]\frac{\partial T}{\partial t}+\nabla(c_2\rho_2T\langle \mathbf{U}_2\rangle)=\nabla[\lambda_1-\lambda_2)\xi+\lambda_2]\nabla T+ \\ +L\rho_1\frac{\partial\xi}{\partial t}\pm Q; \tag{2}$$

$$(1-\xi)\frac{\partial C_2}{\partial t}+\nabla(C_2\langle \mathbf{U}_2\rangle)=\nabla[D_2(1-\xi)\nabla C_2]+k_*C_2\frac{\partial\xi}{\partial t}; \tag{3}$$

$$\frac{\partial}{\partial t}[\xi\rho_1+(1-\xi)\rho_2]+\nabla[(1-\xi)\rho_2\langle \mathbf{U}\rangle_2]=0; \tag{4}$$

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