IDENTIFICATION OF UNSTEADY BOUNDARY CONDITIONS IN SURFACE BOILING OF UNDERHEATED LIQUIDS

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The article presents a method and the results of determining the boundary conditions in surface boiling by the solution of the inverse heat-conduction problem with the use of the method of dynamic filtration.

The high intensity of heat exchange in nonsteady cooling of the surface of an atomized underheated (not heated to boiling point) liquid is an incentive to the widespread technical utilization of this process in a number of power generation installations and in ferrous metallurgy. On the other hand, the lack of information (or its insufficient reliability) on the conditions of heat exchange on a cooled surface limits the possibilities of designing new cooling systems and of improving existing ones. In connection with that, identification of the boundary conditions (BC) is a topical problem.

For determining the heat transfer coefficients under conditions of boiling of a dispersed liquid on a hot surface, a thermometer was devised whose design was described in detail in [1], and the arrangement of the measurements is shown in Fig. 1. In a cylindrical copper rod 2 of the thermometer, protected from the lateral surface by a shielding insulation and provided with an electric heater 11, thermocouples are soldered in, and the signals from them are transmitted either to the manually operated switch 4 (when it is necessary to record the indications of one of the thermocouples during the entire experiment) or via a connecting block 10 to the electronic switch 8 which was specially made to match the parameters of the other units of the installation. The electronic switch makes it possible to supply information from the thermocouples in turn to the input of the universal digital voltmeter 5 and then to the digital printout 6 connected to a computer. The time of "interrogation" of the thermocouples is 0.08 sec, and the maximum printing speed is not less than 30 lines per second. Current to the electric heater is supplied from the autotransformer 12. The cold thermocouple junctions are thermostated in the Dewar vessel 9.

As a specified distance form the working end face of the thermometer rod there is the nozzle 1 which sprays water. When the thermometer rod is being heated to the specified temperature, the heater 11 and the copper curtain 3 are in the position shown in Fig. 1. When heating is completed and the required nozzle regime is established, the place of the heater is taken by the heat-insulated end cap 13, a special release mechanism removes the curtain, and the dispersed water is sprayed onto the working surface of the thermometer rod. During the experiment we recorded the temperatures in the body of the thermometer rod, the temperature of the cooling water, and the pressure gradient of the liquid in the nozzle. Before and after the experiment we measured the specific flow rate of the water per unit cooled surface.

The obtained dependences $T(\tau)$ at individual points of the thermometer were used for the identification of the boundary conditions of heat exchange by solving the inverse problem of heat conduction (IPHC). For solving the IPHC, the method of optimum filtration was chosen; the effectiveness of using this method was demonstrated in numerous investigations [2, 3].

The complete algorithm for solving the IPHC with the use of filtration [2] is presented in Fig. 2. The method used, which is highly noiseproof in regard to changes in the initial data, makes it possible to eliminate the operation of smoothing the experimental dependences,

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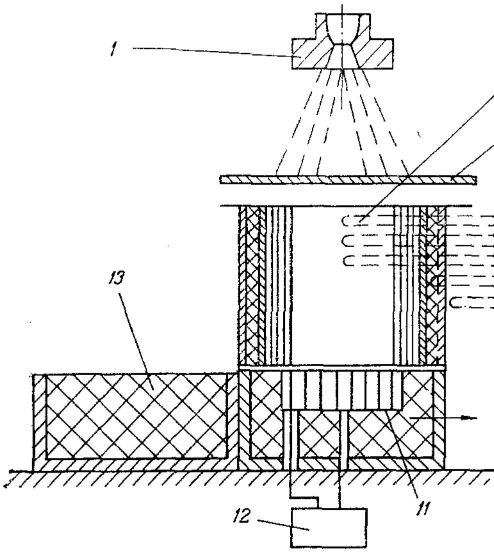


Fig. 1. Arrangement of the measurements.

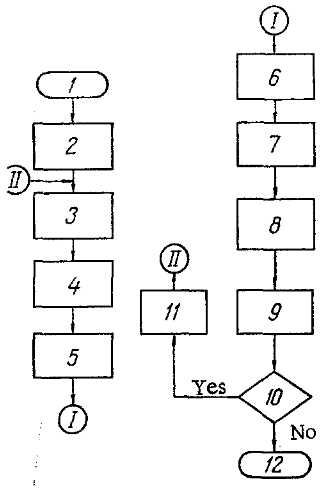


Fig. 2

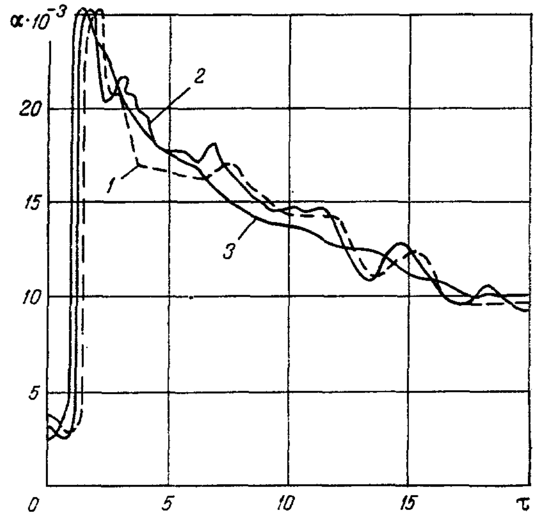
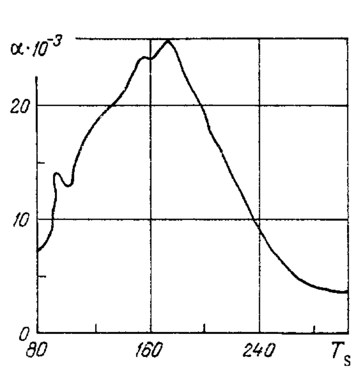


Fig. 3

Fig. 2. Algorithm for solving the IPHC: 1) start; 2) input of initial data; 3) calculation of the coefficients of the equation of heat conduction; 4) calculation of the transition matrix; 5) calculation of the prediction of the vector of state; 6) calculation of the covariance matrix of the errors of prediction; 7) calculation of the weight matrix; 8) calculation of the estimate of the vector of state; 9) calculation of the covariance matrix of the error of estimate; 10) ($\tau < \tau_c$); 11) ($\tau + \Delta\tau$); 12) end.

Fig. 3. Results of the identification of the boundary conditions. α, $W/m^2 \cdot {}^\circ K$; τ, sec.

and thus to take into account all the features of the thermal process without requiring the initial conditions to fulfill stringent requirements. Moreover, our investigations showed that with the aid of the suggested method it is possible to determine simultaneously with the conditions of heat exchange also the thermophysical characteristics (TPC), i.e., to solve a combined IPHC. In the case under examination this permits establishing the reliability of identification of the boundary conditions by comparing the known TPC (data of handbook) of the material of the thermometer rod with the corresponding characteristics calculated in solving the IPHC. The investigations showed that when a combined IPHC is solved. the unambiguous determination of several parameters of the thermal system (λ and C_V: λ, C_V, and α or q) requires that the known thermal parameters contain at least one caloric magnitude (e.g., q in the BC of the second kind or α in the BC of the third kind). If such a magnitude is not specified, then there must be at least one particular value λ(T) or C_V(T).



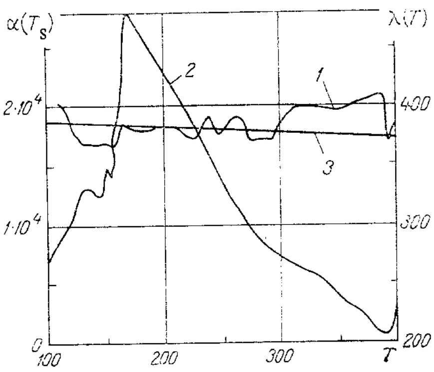


Fig. 4 Fig. 5

Fig. 4. Dependence of the heat transfer coefficient α on the surface temperature. α, $W/(m^2\cdot°K)$; T_s, °C.

Fig. 5. Results of identification of thermal conductivity and of the heat transfer coefficient. α, $W/(m^2\cdot°K)$; λ, $W/(m\cdot°K)$; T, °C.

The solution of an arbitrary nonsteady IPHC is unique if the number of equations of measurement (in the space—time sense) is not smaller than the number of the identified parameters.

The thermometer rod was divided into 10 sections with a pitch of $h = 5\cdot10^{-3}$ m, and the temperature was measured at the tenth and eighth nodes which were at a distance of 5 and 15 mm, respectively, from the cooled surface. The time step was $\Delta\tau = 0.2$ sec.

It was assumed that the error of measurement of the temperature, determined by the experimental conditions, lay within the limits $\sigma = (0.03\text{-}0.05)\ T_{max}$. The initial temperature distribution was $T_0(i) = 300°C$; the initial approximation of the sought heat transfer coefficient in solving the IPHC was taken as $\hat{\alpha}_{\%} = 7\cdot10^3\ W/m^2\cdot°K$.

The problem was solved with TPC specified in the form of polynomials: $\lambda = 384 - 0.05T$; $C_V = (3.45 - 0.00072T)\cdot10^6$. The covariance matrix of the errors of estimate was $P_{\%} = \mathrm{diag}\ \{(1;1;1;1;1;1;1;1;1;1;10^6)\}\cdot5\cdot10^3$.

On the lower surface of the thermometer rod boundary conditions (BC) of the second kind were specified:

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0,$$

and on the upper (working) surface, where the heat transfer coefficient was identified, BC of the third kind with the coolant temperature $T_i = 17°C$.

The results of identification of the heat transfer coefficient are presented in Fig. 3, where curve 1 was obtained with the covariance matrix of the errors of measurement R_C calculated for $\sigma = 0.05T_{max}$, and curve 2 for $\sigma = 0.03T_{max}$. In both cases the maximum value of the heat-transfer coefficient corresponding to the transition from film to bubble regime of surface boiling occurred 1.2 sec after the onset of the cooling process with $T_s = 167°C$. $\alpha_{max} = 25.5\cdot10^3\ W/m^2\cdot°K$ when $\sigma = 0.03T_{max}$, and $\alpha_{max} = 26\cdot10^3$ when $\sigma = 0.05T_{max}$.

Since it is practically indispensable to have the correlation of the heat transfer coefficient with the surface temperature determining the cooling regime of the object, Fig. 4 presents the dependence $\alpha(T_s)$.

Parallel with the use of the filtration method, the IPHC was solved with the aid of the explicit and implicit finite difference schema by inverting the solution of the primal problem. The establishment of the thermal flux from the known temperature field calculated by some difference schema reduced to obtaining the derivative of the temperature with respect to the coordinate for points lying on the working surface of the thermometer rod. The derivative of the temperature with respect to the coordinate for these points was approximated by finite differences with an error of second order [4]. A comparison of the derivatives calculated by both schemata showed that their values did not differ by more than 1%.

To eliminate random errors of measurement, the results of observations were smoothed by the least squares method and by piecewise polynomial approximation. The identification of the BC was carried out, and its results are also presented in Fig. 3 (curve 3). This curve is smoother than curves 1 and 2; however, the latter, having been obtained without preliminary smoothing of the experimental data, give a more accurate thermophysical pattern of the process.

In some cases the TPC of the material of the investigated object, in particular thermal conductivity, may be specified extremely approximately. In that case, to evaluate the quality of the results of identification of the boundary conditions, the combined IPHC can be solved for the simultaneous determination of the TPC and the BC. The solution of such a problem presupposes the preliminary rearrangement of the initial finite-difference equations, and this is somewhat more complex than in the solution of an external IPHC. To solve a combined problem is therefore expedient only if the TPC are unknown or approximately specified.

In our present work we identified simultaneously the heat transfer coefficient and thermal conductivity but in principle, it is possible to determine together with them also specific heat capacity per unit volume. The conditions of uniqueness of the solution presented above remain valid.

Since in the investigated process thermal conductivity of the material of the thermometer rod is specified with an error of ±15%, the solution of the combined IPHC is indispensable. Here, we solved the same problem as in the preceding case, with the same initial data with $\sigma = 5\%$ and the covariance matrix of errors of estimate equal to $P_{\%} = \mathrm{diag}\ \{(1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 1;\ 10^4;\ 10^6)5 \cdot 10^3\}$. The sought thermal conductivity at each time step was determined pointwise.

The results of the identification are presented in Fig. 5, where curve 1 represents $\lambda(T)$, curve 2 $\alpha(T_s)$, which were obtained from the results of identification of $\alpha(\tau)$ and $T_s(\tau)$.

The nature of the dependence $\alpha(T_s)$ agrees on the whole with the results of identification of $\alpha(T_s)$ illustrated in Fig. 4, where $\alpha_{max}(T_s) = 25 \cdot 10^3$ W/m²·°K, whereas in simultaneous identification $\lambda(T)$ and $\alpha(T_s) - \alpha(T_s) = 28 \cdot 10^3$ W/m²·°K.

It should be noted that curve 1 coincides satisfactorily with curve 3 of the corresponding dependence $\lambda(T)$ taken from handbook data [5]. Such coincidence of calculated and handbook values of $\lambda(T)$ shows the reliability of the results of identification in boiling of a liquid under conditions of unsteady cooling of the surface. Therefore, with highly intense processes, where the dependence $\alpha(T_s)$ has extremal points on a small interval of change of surface temperature, it is expedient to use an iteration filter for the identification of the conditions of heat exchange.

NOTATION

T, temperature; α, heat-transfer coefficient; C_V, heat capacity; λ, thermal conductivity; h, space step; τ, time; $\Delta\tau$, time step; σ, rms deviation. Subscripts: s, surface; m, medium.

LITERATURE CITED

1. É. G. Bratuga, S. F. Kravtsov, and N. A. Tarasenko, "Thermal probe for investigating the unsteady process of heat exchange in sprayer cooling," Énergeticheskoe Mashinostr., No. 32, 91-95 (1981).
2. Yu. M. Matsevityi and A. V. Multanovskii, Identification in Problems of Heat Conduction [in Russian], Naukova Dumka, Kiev (1982).
3. Yu. M. Matsevityi, A. V. Multanovskii, and I. A. Nemirovskii, "Solution of the external inverse problem of heat conduction under conditions of contact of cooled elements of the metallurgical equipment with molten ferrous and nonferrous metals," Promyshlennaya Teplotekh., 5, No. 5, 16-20 (1983).
4. O. T. Il'chenko, Calculation of the Thermal State of Structures [in Russian], Vyshcha Shkola, Kharkov (1979).
5. V. N. Yurenev and P. D. Lebedev (eds.), Handbook of Heat Engineering [in Russian], Vol. 2, Énergiya, Moscow (1976).