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INVESTIGATION OF TWO-PHASE PROCESS OF ALUMINUM INGOT COOLING BY MEANS OF INVERSE HEAT TRANSFER PROBLEM APPROACH

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Abstract - The Adaptive Iterative Filter (AIF) has been proposed to use for the investigation of heat transfer between a high temperature surface and the cooling system by means of an Inverse Heat Transfer Problem (IHTP) solution. Inverse problems are ill-posed problems in the sense of existence, uniqueness and stability and, as such; in the general case, they do not have a universal solution. Therefore, on the stage preceding the actual solving of the real inverse problem, the simulating inverse analysis should be performed. This analysis, which includes the solution of a methodical inverse problem, is very desired or, even, sometimes required to obtain stable and precise results with each problem under study. The suitable numerical algorithms of AIF are used for the investigation of the influence of the cooling sprayer properties of the heat transfer coefficient of the two-phase regime during the process of the cooling of an aluminum ingot, all identified as a function of the temperature.

1. INTRODUCTION

In our recent research the AIF has been successfully used for the simultaneous identification of the thermophysical characteristics of super-hard synthetic polycrystalline materials as a function of temperature by means of the internal IHTP solution [21]. The mathematical model and its statistical modification for the AIF approach for the solution of inverse problems have been presented in reference [21]. Detailed analysis of using the AIF method for the solving of internal inverse problems also has been done in that research [21]. In this presentation the AIF is used for solving the external IHTP to investigate the influences of the cooling sprayer properties on the heat transfer of the two-phase regime during the process of the cooling of an aluminum ingot.

2. MATHEMATICAL MODEL AND SOLUTION OF STATED INVERSE HEAT TRANSFER PROBLEM BY MEANS OF ADAPTIVE ITERATIVE FILTER

The final target of the mathematical model presented below is an identification of the heat transfer coefficient of the two-phase regime during the process of cooling of a solid aluminum ingot. The equations of this process that will be utilized as an initial mathematical model for IHTP solution may be written:

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right] = C_V(T)\frac{\partial T}{\partial \tau},$$

$$T(x,\tau=0) = T_0;\quad \left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \tag{1}$$

$$-k(T)\frac{\partial T}{\partial x} = h(Tp,\tau)(Tp - Ta) = q(Tp,\tau),$$

where x is space, $k(T)$ is the thermal conductivity, $C_V(T)$ is the specific heat per unit volume, $h(Tp,\tau)$ is the heat transfer coefficient, Ta is the ambient temperature, Tp is the temperature of boundary surface, T_0 is the initial temperature, $q(Tp,\tau)$ is the heat flux and τ is time.

The model (1) can be written in the finite-difference matrix form:

$$\vec{X}_{k+1} = \Phi_{k+1,k}\,\vec{X}_k + F_{k+1,k}\,\vec{U}_k + G_{k+1,k}\,\vec{W}_{k+1}, \tag{2}$$

where $\vec{X}_k$ is the stochastic state vector, $\vec{U}_k$ is the stochastic vector of boundary conditions or, using control theory terminology, stochastic vector of controlling actions because boundary conditions are the factors that control thermal process and $\vec{W}_k$ is the uncorrelated white noise.

The iterative filter [7, 8, 18], which has been created for the solution of parametric and non-parametric identification problems, was successfully used for solving internal and external IHTP to determine a heat transfer coefficient and heat flux as well as the material thermophysical characteristics [6 - 10, 12]. However, as reported in [18, 19, 21], this iterative modification of optimal dynamic filter always requires the preliminary rearrangement of the initial heat transfer equations (1), which enables the transitional matrix to be obtained for solving the specific inverse problem. Actually, the iterative filter method assumes the linearization of the initial mathematical model (1), and its modification depends on the desired thermal parameters. The model (2) obtained from (1) and written in the finite-difference matrix form allows one to determine the iterative filter transition matrices $\Phi_{k+1,k}$, $F_{k+1,k}$, and $G_{k+1,k}$. Reiterating reference [21], it is necessary to repeat here the most significant advantages of the iterative filter. They are: high accuracy of solutions, the ability to use the number of iterations as a regularizing parameter, and the possibility to adopt the expression $d\vec{Z}/d\tau = \dot{\vec{Z}} = 0$ as an initial equation for the unknown parameters. There are also several significant disadvantages that often prevail all advantages. Firstly, it is difficult to modify the mathematical model in order to include the desired parameters in the augmented state vector $\vec{X}_k$ of estimates that consist of the state vector and vector of unknown parameters. Secondly, the transition matrices of this system should be known with certainty, whereas during the iterative filter calculations, only their estimates, even if refined by iterative process, can be obtained. Thirdly, due to the enormous dimensions of the algorithm vectors and matrices, a great deal of computer memory and speed are required.

In order to take advantage of the iterative filter and minimize the difficulties, the method of AIF, first discussed in the references [13 - 15], has been proposed for the identification of the heat transfer parameters, for solving inverse problems, and for the following thermal system simulation.

This paper focuses on the utilization of the AIF methodology for the identification of the heat transfer coefficient between the cooling media and the metal slab during the process of cooling of the aluminum ingot.

The thermal system mathematical model (1) formalized in the form of a matrix-vector equation could be written as the following stochastic discrete equation [7, 18]:

$$\vec{T}^{\,j+1}_{k+1} = A^{-1}L\left[\vec{T}\right]^{i}_{k} + A^{-1}M\vec{U}^{\,j}_{k+1} + A^{-1}N\vec{W}^{\,j}_{k+1}, \tag{3}$$

where A, L, M, N are the matrices of the coefficients obtained from the spatial-time discretization of mathematical model (1), all matrices are the functions of thermophysical parameters, U is the control vector that includes boundary conditions and $\vec{T}_k$ is a state vector (temperature field).

An augmented state vector $\vec{X}_k$ from equation (2) includes temperature field $\vec{T}_k$ and unknown thermal parameters. That is why equation (3) is a part of the general equation (2). To complete equation (3), the equations of the unknown parameters must be added. This will be the equation $d\vec{Z}/d\tau = \dot{\vec{Z}} = 0$ that has been mentioned above. The latter equation and equation (3) are used in the iterative filter or other dynamic filter modifications that have been created before the iterative filter [5, 7]. AIF method does not require the calculation of transition matrices as well as the additional equation for unknown parameters.

To obtain the matrix-vector formula (3), the usual finite-difference approximation (implicit scheme) of the heat conduction equation and boundary conditions (1) has been used to create the following equation:

$$A\left(\vec{X}_k\right)\vec{T}^{\,j+1}_{k+1} = L\left(\vec{X}_k\right)\vec{T}^{\,i}_{k} + M\left(\vec{X}_k\right)\vec{U}^{\,j}_{k+1} + N_k\vec{W}^{\,j}_{k+1}.$$

Equation (3) can be used for the calculation of the matrix of measurement of AIF for the determination of the boundary conditions h(Tp,τ) or $q(Tp,\tau)$. These variables are supposed to be identified on the basis of temperature measurements.

The fundamental algorithm of AIF [18, 19] can be written as follows:

$$\hat{\hat{Z}}^{(j)}_{k+1/K+1} = \hat{\hat{Z}}^{(j-1)}_{k+1/K+1} + K^{(j)}_{k+1}\left[\tilde{\tilde{Y}}_{k+1} - \hat{H}^{(j)}_{k+1}\hat{\hat{Z}}^{(j-1)}_{k+1}\right]; \tag{4}$$

$$K^{(j)}_{k+1} = P_{k/k}[\hat{H}^{(j)}_{k+1}]^T\{\hat{H}^{(j)}_{k+1}P_{k/k}[\hat{H}^{(j)}_{k+1}]^T + R_{k+1}\}^{-1}; \tag{5}$$

$$P_{k/k} = [I - P^{(i)}_{k}\hat{H}^{(i)}_{k}]P_{k-1/k-1}[I - K^{(i)}_{k}\hat{H}^{(i)}_{k}]^T + K^{(i)}_{k}R_{k}[K^{(i)}_{k}]^T; \tag{6}$$

$$\hat{H}^{(j)}_{k+1} = \left\{\frac{\partial\vec{Y}}{\partial\vec{Z}}\right\}^{(j)}_{k+1}, \tag{7}$$

where $\hat{\hat{Z}}^{(j)}_{k+1/k+1}$ is the unbiased, with minimum dispersion, estimate obtained for the vector of the parameters being defined at the j-th iteration of the $k+1$ time step on the basis of the vector measurements $\tilde{\tilde{Y}}_{k+1}$, $P_{k/k}$ is the covariance matrix of the estimate errors, R_{k+1} is the covariance matrix of the measurement errors, K_{k+1} is the weight matrix and $H^{(j)}_{k+1}$ is the non-stationary artificial matrix of measurements.

The $H^{(j)}_{k+1}$ matrix terms represent the partial derivatives of the measured parameters with respect to the identified parameters. The calculation of the artificial measurement matrix, by the numerical method, requires the solution of the equations of the process under study several times at each iteration, that is solving several times the direct heat transfer problems at each iteration (please see the detailed explanation in [19, 20, 21]).

One can deduce that an AIF method allows the identification of the desired parameters (vector $\hat{\vec{Z}}^{(j)}_{k+1/k+1}$) only instead of the determination of whole augmented state vector $\vec{X}_k$ as it takes place when the iterative filter is used. If the number of temperature measurements is *m* and desired parameters *n*, the matrix of measurement *H* can be written as follows:

$$\hat{H}^{(j)} = \begin{bmatrix} \frac{\partial Y_1}{\partial Z_1} & \frac{\partial Y_1}{\partial Z_2} & \cdots & \frac{\partial Y_1}{\partial Z_n} \\ \frac{\partial Y_2}{\partial Z_1} & \frac{\partial Y_2}{\partial Z_2} & \cdots & \frac{\partial Y_2}{\partial Z_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Y_m}{\partial Z_1} & \cdots & \cdots & \frac{\partial Y_m}{\partial Z_n} \end{bmatrix}. \quad (8)$$

The limitation of the iteration number *"i"* of the AIF algorithm is used as the regularizing factor of the iteration process at each time step. The explanation and proofs of the iterative regularization have been published by the authors of this article as well as by numerous other authors [1 – 3, 6, 7, 15, 16, 18, 20]. This number *"i"* is selected in terms of the agreement of the mean square errors of the measurement with the value of general discrepancy, both over *k* moments of time. In addition, the restoration of the diagonal of the covariance matrices of estimate errors to its initial value, at each time step, is used [15, 18]. This restoration allows us to speed up the convergence of the solutions obtained by the AIF algorithm.

3. SIMULATING AN INVERSE ANALYSIS USING AN ADAPTATIVE ITERATIVE FILTER

It is well known that inverse problems are ill-posed problems in the sense of existence, uniqueness, and stability, and therefore, in a general case, they do not have a universal solution. That is why, as it was reported in [20, 21], at the stage preceding the actual solving of a real inverse problem, simulating inverse analysis should be performed. This analysis, which includes the solution of a methodical inverse problem, is desired or, sometimes, required to be performed for the purpose of obtaining stable and precise results. In this paragraph, we focus on the solution of methodical inverse problems by means of AIF for the investigation of the two-phase process of the cooling of a solid material surface. Actually, the stated and solved methodical external inverse problems relate to the identification of the heat transfer coefficient of the 3rd kind of boundary condition. The initial mathematical model and testing plan were taken in many ways to be similar to the investigation in paper [21] with the only difference being that in reference [21] internal IHTP have been solved whereas in this presentation the problems being investigated are external IHTP. Finite-difference approximation is suggested. The matrix form (3) of the equations of the heat transfer system under study is used as the initial mathematical model. The finite-difference approximation is proposed to obtain the matrix form (3) from equation (1). The exact temperature data that is the result of the direct heat transfer problem solution is disturbed by a random value using the generator of a Gaussian distribution (white noise). The simulating plan includes, but is not limited to, the determination of the influence on the identification results of the following:

- the position and number of measurement devices (thermocouples or other temperature sensors),
- the magnitude of time step of recurrent process,
- the smoothing of temperature measurements,
- the value of the errors of real temperature measurements.

A number of one-dimensional direct problems have been solved to calculate the "measured" temperatures. Actually, the three-dimensional problem was stated. However, the heat transfer between ambient and both main surfaces of a parallelepiped-shape metal ingot under study is symmetric about the mid-section and uniform along the surfaces. Taking into consideration the above-symmetry of the heat transfer, and the fact that the other side surfaces of the object are insulated against heat transfer, the model of the process under investigation may be represented as a rod of one-half length of the width of the initial parallelepiped object (total width of parallelepiped is 0.4 m). This metal rod of 0.2-meters was divided into 20 sections (the total numbers of nodes is 21, from 0 to 20; one-dimensional mesh width is 10 mm). The time step was assumed to be between 0.02 and 0.0625 seconds, and the temperature measurement errors are assumed to be in the range of 0.5% to 10% of the highest measured temperature. On one side of the rod (at the node #0), the trivial boundary conditions of the 2nd kind were considered: $k(T)\frac{\partial T}{\partial x}\Big|_{x=0} = 0$. On the other side (at the node #20) the 3rd kind of boundary condition $-k(T)\frac{\partial T}{\partial x}\Big|_{x=0.2} = h(T,\tau)\cdot(T - T_a)$ was with two-phase regime cooling. The heat transfer coefficient for the solution of direct problems was taken as follows:

*h(T)=0.32*T-120(kW/m². K), $400 \le T \le 500$;*
*h(T)=-0.12*T+100 (kW/m². K), $500 \le T \le 800$.*

The metal's thermophysical characteristics are: thermal conductivity $k(T) = 385 - 0.02*T (W/m.K)$, specific heat per unit volume $C_v(T) = 3450 - 0.05*T (kJ/m^3.K)$.

Influence of the location of temperature sensors. The locations of the sensors are taken, respectively, at the nodes *n=2, 5, 10, 15,* and *19.* The initial temperature distribution is: $T_0 = 850K$, and the measurement errors equal to 1% of T_{max}. The initial approximation of the desired heat transfer coefficient is taken: $h_o = 8000, W/m^2.K$, and covariance matrix of the initial estimate: $P_{0/0} = diag\{8.10^3\}$.

Restoration of the diagonal of the covariance matrices of the estimate errors to their initial values, at each time step, is used. This restoration considerably influences the regular properties of the algorithm as well as the quality of the estimates and the rates of their convergence [15, 18]. This technique is especially important when measurement errors (or value σ_k - sum of mean square errors of temperature measurements over *k* time steps) are large and the diagonal elements of covariance matrices of estimate and measurement errors compare well with each other. The process of the matrix $P_{k/k}$ restoration has to begin after the last iteration at each time step where the violation of the filter convergence condition occurs [18].

The pointwise identification procedure [9, 10, 12, 14, 17, 21] without preliminary approximation of the desired function has been applied. To obtained the *h(T)* function, first the functions $h(\tau)$ and $T_p(\tau)$ were determined. The results of the influence of the position of temperature measurement nodes on the accuracy and stability of the numerical solution are presented in Figure 1, where:

- *h2, h5, h10, h15, h19* are the identified curves of the heat transfer coefficient identified on the basis of the temperature data measured at nodes *n=2, 5, 10, 15,* and *19*, respectively
- The accuracy of the results and stability of the obtained curves are acceptable when the temperature is measured at nodes *10,* or *15,* or *19*. The maximum identification errors over the whole temperature range ($400 \leq T \leq 800$) of parameter *h(T)* are 13%, 6%, and 7%, with respect to measurements at nodes 10, or 15, or 19.

From Figure 1 one can conclude that the accuracy of the identified heat transfer coefficients determined on the basis of measurements taken at nodes close to the heat source *h15* and *h19* (high temperature gradient area) are very precise, whereas the accuracy of the *h5* curve determined based on measurement at node 5 (far from heat source, low temperature gradient area) cannot be accepted. However, it needs to be noticed that the accuracy of curve *h5* is improving while the cooling process continues because the temperature gradient also increases in this area from one time step to another. Curve *h2* is unstable because node 2 is very far from the heat source and the temperature gradient in this area is low throughout the cooling process.

<u>Preliminary conclusions of the required location of temperature measurement:</u>

- The accuracy of the identification of the heat transfer coefficient is acceptable if the thermocouples are mounted in the area of relatively high temperature gradients. Therefore, it is not necessary to take measurements in the highest temperature gradient area.
- When the temperature is measured in the medium temperature gradient area, the resulting accuracy is satisfactory, and the curves are always stable.
- Measurements taken in the low temperature gradient area lead to unacceptable accuracy of the identified parameters and the result is very unstable.

The explanation of this phenomena from the control theory point of view is the following: at the beginning of the intensive two-phase cooling (or heating) process, the temperature near the heat source (the unknown boundary conditions) changes very fast, while on the opposite side, far from the heat source, the temperature changes very slowly and sometimes does not change at all (the thermal inertia problem). As a result of the latter issue, the calculated elements of the covariance matrix of the estimated errors are wrong and the identified parameters are unstable.

Influence of time step. In order to regularize the process and to eliminate the instability when measurements are still taken at low gradient areas, it is possible to apply the so-called natural regularization procedure by time step [1, 5, 7]. One could increase the time step which results in increasing the temperature values of the low temperature gradient area. However, in this case, due to very limited number of temperature measurements, there is the jeopardy of sacrificing accuracy while obtaining stability. In fact, in the stated problem, the identification results will not correctly represent the actual two-phase cooling process curve. As shown in Figure 2, the curves of heat transfer coefficients *h2b* and *h2c* are obtained based on the same temperature measurements in node 2. The time step during measurement process to identify curve *h2b* was 0.05 sec, while determining curve *h2c* the time step was 0.0625 sec. Curve *h2* is the same unstable curve that was presented in Figure 1, the identification process time step for this curve being 0.02 sec. The *h2b* and *h2c* results became stable, but they do not precisely represent the physical phenomena of the two-phase cooling process. This research has confirmed the conclusion of the previous paragraph where it was mentioned that the thermocouple(s) should be located in the relatively high temperature gradient area.

Influence of the smoothing of temperature measurements. The next step was the study of the influence of smoothing temperature measurement data on determining the heat transfer coefficient. The results are presented in Figure 3, where the identified curves *h19a* and *h19b* are respectively obtained based on non-smoothed and smoothed temperature measurement data at node 19. The temperature measurement errors were 10% of T_{max}. The curve *h19b* obtained from the smoothed temperature data at node 19, is stable, however, the accuracy is unacceptable. For example, the very important actual maximum of the heat transfer coefficient at critical temperature $T_{cr} = 500K$ is equal to $h_{max} = 40\ (kW/m^2.K)$, whereas the identified maximum $h_{max} = 28\ (kW/m^2.K)$ relates to $T_{cr} = 428K$. The curve *h19a* obtained on the basis of non -smoothed temperature data at the same node 19 represents the two-phase process much better. This curve is relatively stable around the exact values. The accuracy is also acceptable: the above-mentioned maximum is *h=45.1(KW/m².K)* at $T_{cr}=522K$, relatively close to the theoretical values (bearing in mind that the noise was increased to the unrealistic value of 10% of the maximum of the measured temperatures).

Conclusion:

- It is vital to use a non-smoothed temperature measurement data for the identification in short and intensive thermal processes, specifically, the two-phase cooling process.
- In general, this investigation has confirmed our previous research that, in general, the statistical methods, and, particularly, the AIF and iterative filter methods are highly tolerant to measurement anomalies and are not affected significantly by measurement errors [7, 10, 14, 15, 18, 21]. An increase in the measurement errors enlarges the estimate errors but does not disrupt the stability of the identification process. Moreover, for the investigation of the short and intensive thermal processes, the use of non-smoothing measurement data is not only desired, but, even, required.

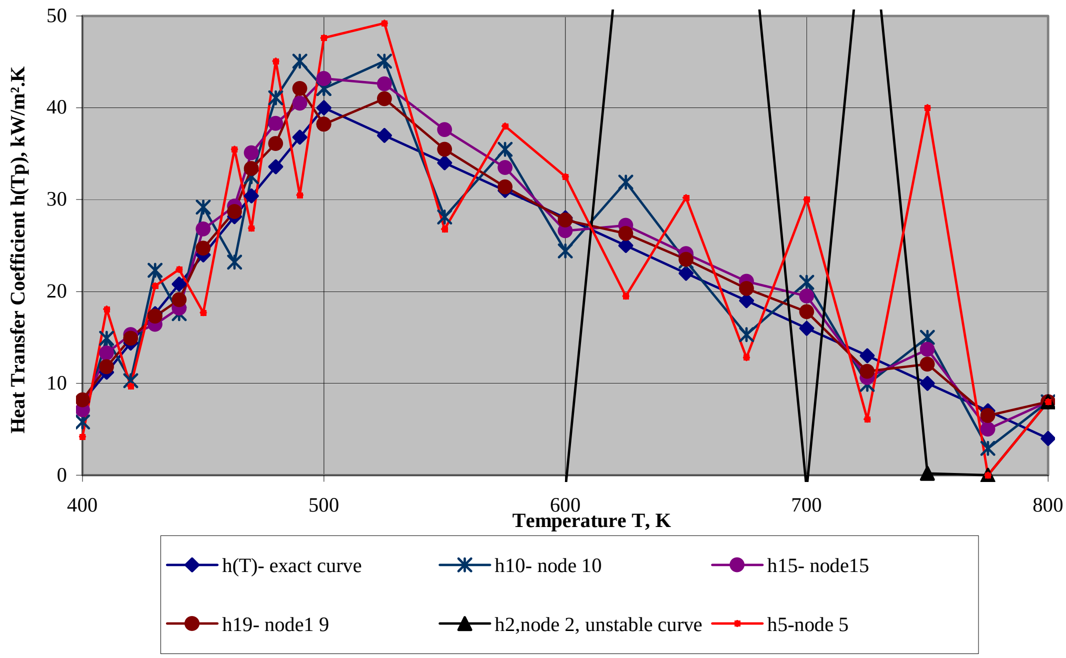

Figure 1: Influence of the Position of Temperature Measurement Nodes on the Identification of Heat Transfer Coefficient

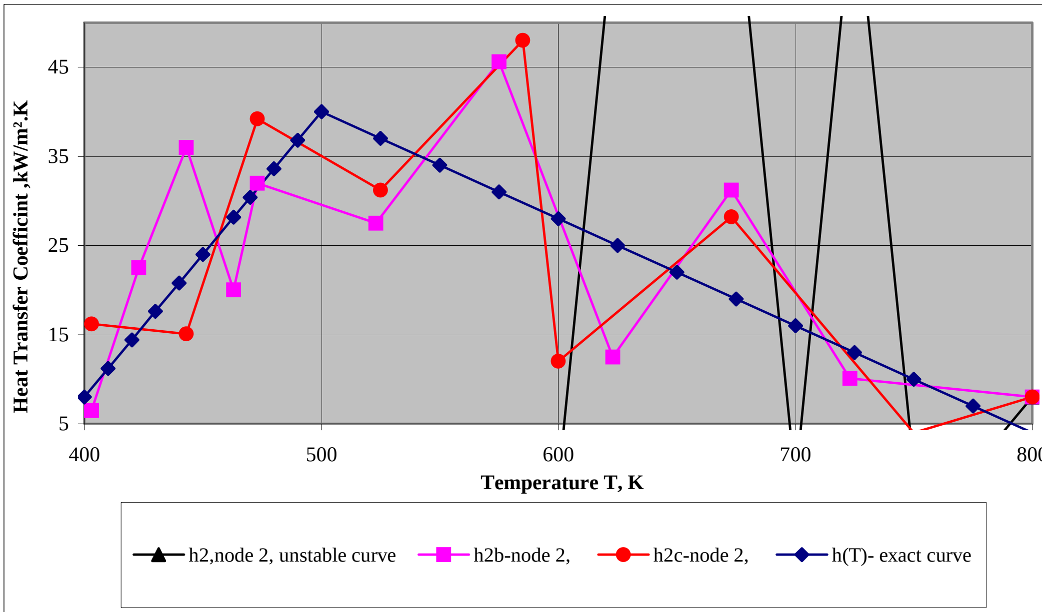

Figure 2: Influence of the Time Step on the Identification of Heat Transfer Coefficient in Two-Phase Regime

Influence of the number of temperature sensors. The results of solution of appropriate inverse problems are presented in Figure 4, where *h(5), h(5,10), h(10,15), h(5,10,15), and h(5,10,15, 19)* are the curves obtained with the measurements taken at nodes (5), (5,10), (5,10,15), and (10,15,19), respectively.

The temperature errors were $0.005*T_{max}$. All the curves are stable enough around the exact curve. The accuracy of the curve *h(5,10)* is better than *h(5)* but worse than the accuracy of the *h(10)* results obtained based on measurements in node 10 only. The same is valid for *h(5,10,15)*: this curve is more accurate than curve *h(5)* but less accurate than curve *h(10)*. The reason for these phenomena is that the node 5, representing the low temperature gradient area, affects the solution accuracy much more significantly even if the number of measurement nodes is increased. This result confirms the importance of choosing temperature measurement nodes in high temperature gradient areas. (Please also keep in mind the above-mentioned note regarding the calculation of elements of the covariance matrix of estimated errors).

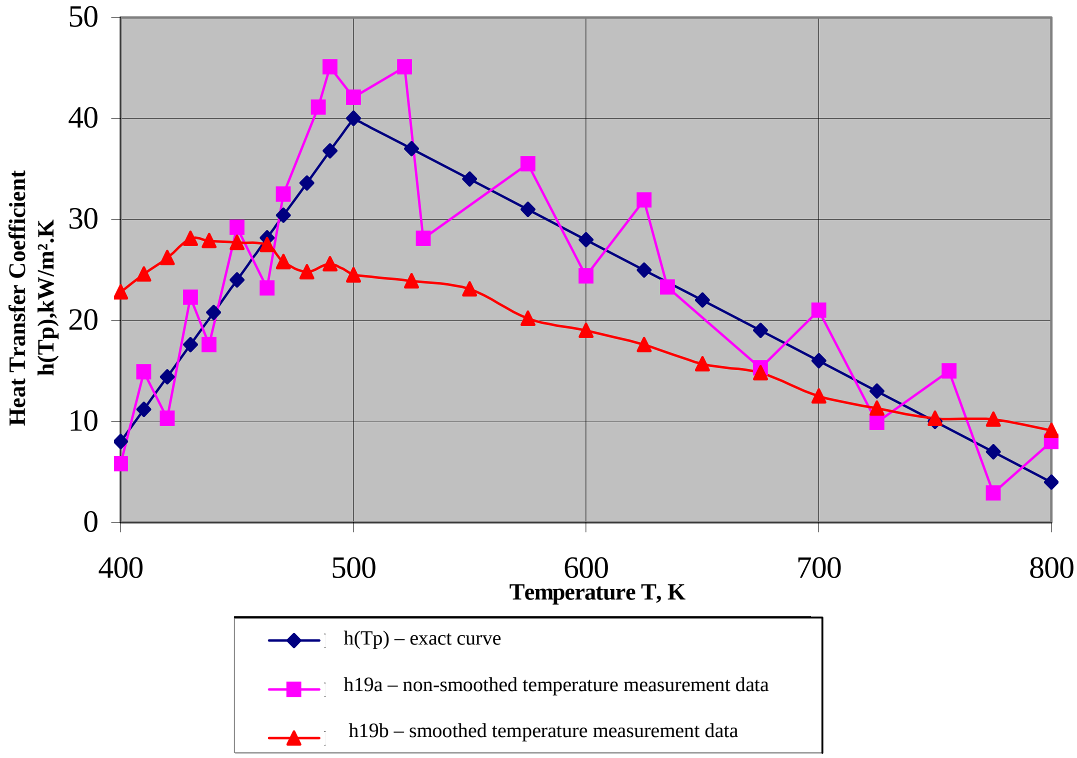

Figure 3: Influence of the Smoothed Temperature Measurement Data on the Investigation of Two-Phase Regime of Intensive Cooling

Concerning the curves *h(10,15)* and *h(10,15,19)* obtained on the basis of the corresponding nodes and representing the medium-high temperature gradient area, their accuracy substantially improved with the increase of the number of nodes, and reached the optimum result with three nodes of temperature measurements. Thus, the number of temperature measurements improves the solution accuracy if the location of thermocouples has been chosen appropriately as it was shown in this section. The optimum number of measurement nodes is three.

4. INVESTIGATION OF TWO-PHASE PROCESS OF ALUMINUM INGOT COOLING

Aluminum is the earth's most abundant metallic element making up approximately eight percent of the planet's crust. Among the common metals aluminum cedes first place only to steel. While aluminum never occurs naturally in its pure form, it is commonly found in the form of oxides and extracted from the bauxite. Aluminum obtained from chemical and electrolytic process is cast into large parallelepiped blocks, and then solidified. The obtained ingot, at a temperature T=873K, is cooled by a flow of disperse cold water.

Heat transfer between the hot aluminum surface and the cooling media depends upon several parameters. The most important is the fluid dispersing coefficient *g* [4], which represents the ratio between the amount of pulverized cooling fluid and the temperature of the cooled surface per unit time.

The experiments were conducted in the specially built test rig described in the same reference [4]. Side and bottom surfaces of the cylindrical aluminum rod are insulated by four screens. As a result, the one-dimensional temperature field that significantly simplifies the process of identification needs to be investigated. A series of tests with various dispersing coefficients ranging from 5.5 to 80 mm^3/mm^2s were conducted. The measurement data are taken every 0.4 sec from three sensors that are mounted, respectively, 5, 15, and 25 mm from the cooled surface.

The aluminum rod being tested was divided into 20 sections with the spacing $\Delta x = 5\ mm$ between nodes. Aluminum thermophysical characteristics are given: $k=160+0.3*T,(W/m.K)$; $C_v=2160+0.79*T,(kJ/m^3.K)$. The maximum error of measurements is estimated to be: $\sigma = 0.02*T_{max}$. The initial temperature of the cooled object is: $T(x,\tau=0)=873K$. The average environment temperature is: $Ta = 294\ K$. The initial value of desired heat transfer coefficient to start the AIF procedure is estimated to be: $h_0 = 8000,\ W/m^2.\ K$. The initial covariance matrix of estimated errors was taken: $P_{0/0}= diag(7.10^3)$. The technique of the restoration of the diagonal of the covariance matrices of the estimate errors to its initial value at each time step is applied.

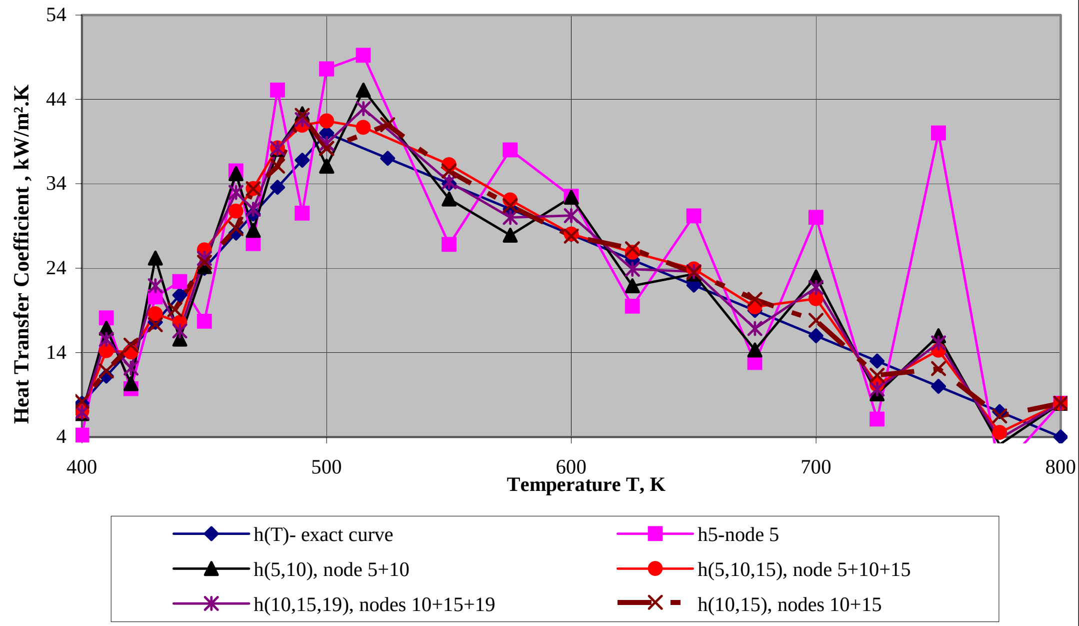

Figure 4: Influence of the Number of Temperature Measurement Nodes on the Accuracy of Identification of Heat Transfer Coefficient

The obtained results are compatible and coincide satisfactory with other research of similar two-phase boiling process [4, 11, 22]. This is illustrated by Figure 5, which shows the relationships between the heat transfer coefficient and the surface temperature for different dispersing coefficients $g = 5.6, 12.8, 32.5, 50$, and $78.8\ mm^3/mm^2s$. The actual change from nucleating boiling regime to film boiling is observed at a mean critical temperature close to: $T_{cr} = 450K$. Maximum values of the desired heat transfer coefficient at this critical temperature are varying between *40 – 65* $kW/m^2.K$. The coincidence of our calculated values with the values by other authors obtained mostly by different measurement methods shows the reliability of the results of identification of cooling process of an aluminum ingot by the flow of disperse cold water.

In order to complete this analysis, the variation of the heat transfer coefficient *h* with respect to the dispersing coefficient *g*, was studied. This analysis has been done on both sides of the cooling process, nucleating boiling regime and film boiling regime (before and after critical temperature).

The curves *h(g)* for a given surface temperature T_p within these two regions ($T_p > T_{cr}$ *and* $T_p < T_{cr}$) have a trend as shown in Figure 6 and 7.

Based on required boundary conditions (heat flux or heat transfer coefficient), geometry of sprayer in use, it is easy to figure out the aluminum surface temperature during the cooling process to predict the heat exchange on a boundary. Another possible scenario of using nomograms in Figures 6 & 7 is a selection of the required sprayer (specific dispersing coefficient) when boundary conditions and required surface temperature are given.

5. CONCLUSIONS

- The obtained results show that the AIF method can be used to create a complete chart of the heat transfer coefficient *h(Tp,g)* as a function of the cooled surface *Tp* and the dispersing coefficient *g*.
- The AIF method has been successfully used for the investigation of the two-phase heat transfer process during the intensive surface cooling by means of dispersed water jet.

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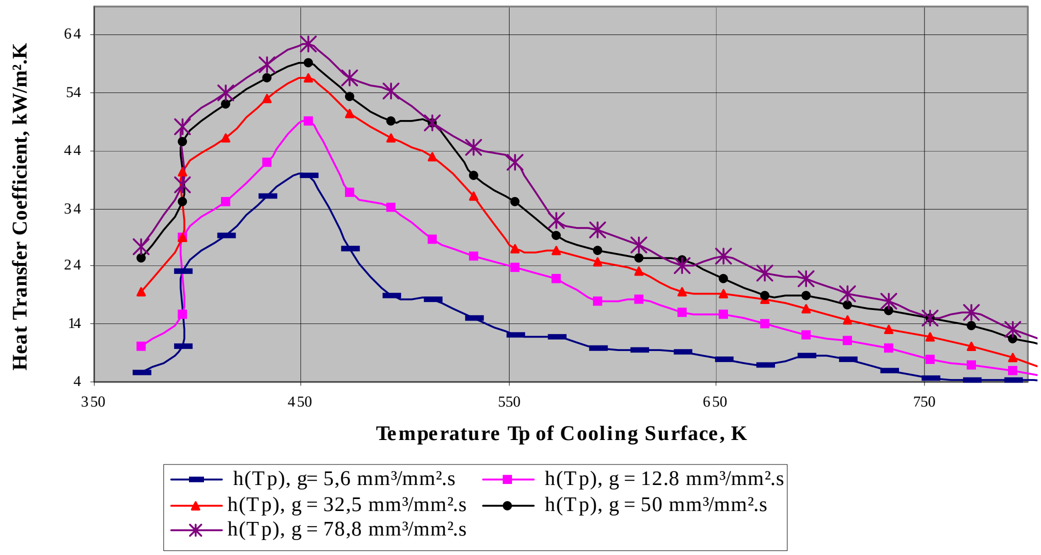

Figure 5: Two-Phase Aluminium Ingot Cooling Process

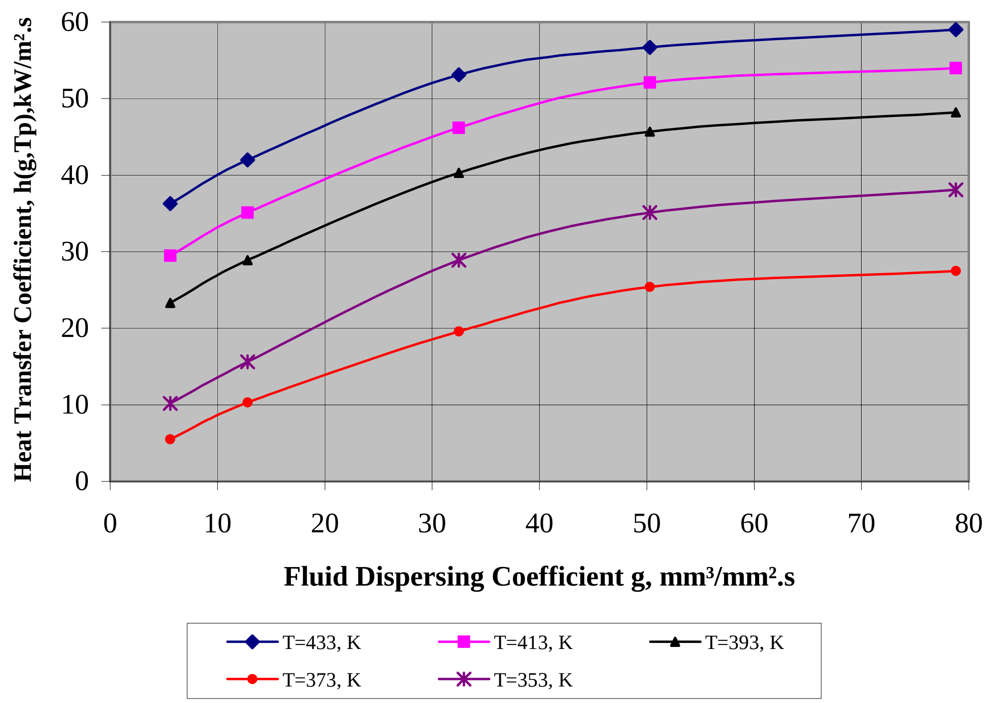

Figure 6: Heat Transfer Coefficient h(g,Tp) at Nucleating Boiling Regime

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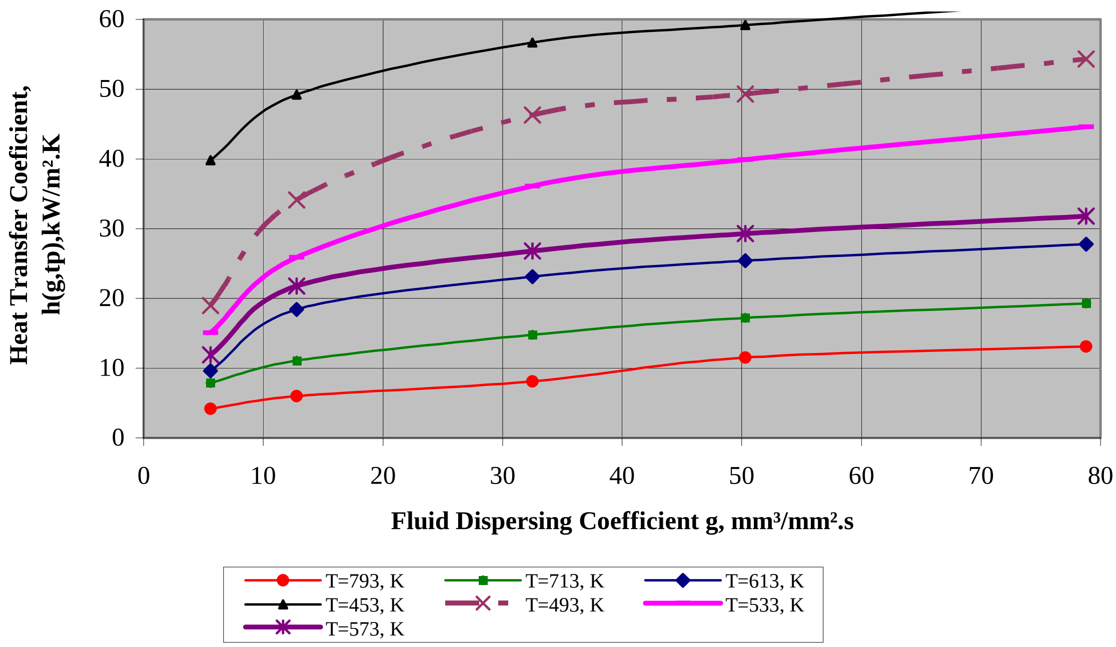

Figure 7: Heat Transfer Coefficient h(g,Tp) at Thin Layer (Film) Boiling Regime

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