METHODOLOGY OF EVALUATION OF HEAT TRANSFER EXPERIMENT ON ALUMINUM SAMPLE

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Abstract

Cooling is one of the critical points during aluminum casting. Improper cooling leads to a structure which isn't homogenous, full of internal and surface defects. It is necessary to know the boundary conditions (heat transfer coefficient or heat flux) for cooling optimization. The boundary conditions for different types of cooling are obtained from experiments.

This article is focused on the cooling of vertical surfaces of aluminum by flat water jets. The sample initial temperature was close to the liquid state. The sample was cooled while in a vertical position by a flat water jet which hit the upper part of the cooling surface, and then the water flow down along the surface. The temperatures were recorded during the experiment by a set of thermocouples which were installed inside the sample. Thermocouples were placed closed to the cooled surface at different heights. The moving horizontal Leidenfrost front between nucleate and film boiling could be observed during the experiment. This front moved downward along the sample surface.

The aim of this work is to evaluate the boundary conditions for described measurements. The evaluation held due to the solution of the 2D inverse task, similar to Beck's sequential methods. The computation procedure was modified to be able to deal with the moving Leidenfrost front between low and height cooling intensities. Results are presented in a form of heat transfer coefficients as a function of position and temperature.

Keywords: Aluminum casting, 2D inverse task, heat transfer coefficients, sequential approach

1. INTRODUCTION

Controlling the temperature field history inside a material is important for many industrial applications, including casting. In some applications, the temperature history (especially temperature gradients) determinates the final material structure. In other applications temperature inhomogeneity leads to defects due to internal tension.

The temperature field inside a material can by simulated numerically if the boundary conditions are known. The Heat Transfer Coefficient (HTC) is frequently used as a form of boundary condition. The HTC can by calculated by an empirical formula (from textbooks [1, 2]) for simple geometry, short temperature range and a special type of cooling. However, in most cases the boundary conditions are obtained from measurement by solving the Inverse Heat Conduction Problems (IHCP).

This article deals with the 2D IHCP for a highly heat-conductive sample made from aluminum. The sample was cooled using a flat water jet in the impact area and by water flowing along the surface below. Solving the IHCP is made more difficult by the Leidenfrost effect combined with a special type of cooling conditions.

2. DESCRIPTION OF THE EXPERIMENTS

2.1. Experiment description

The test sample was a small aluminum board (slab). The sample was placed in the vertical position during the experiment. A set of thermocouples were placed inside the sample close to the cooled surface at different heights along its length (see cross section of **Fig. 1**).

Cooling is caused by flat water jets which impact the upper part of the cooling surface (impingement zone), and by the water flow down along the surface (see **Fig. 1**).

Two different cooling regimes can be observed during the experiment. First type is intensive cooling from the beginning (even at high temperature) in area close to the impingement zone. Second type is low cooling from the beginning until the Leidenfrost temperature is reach. The second type is occurs at the rest of cooling surface.

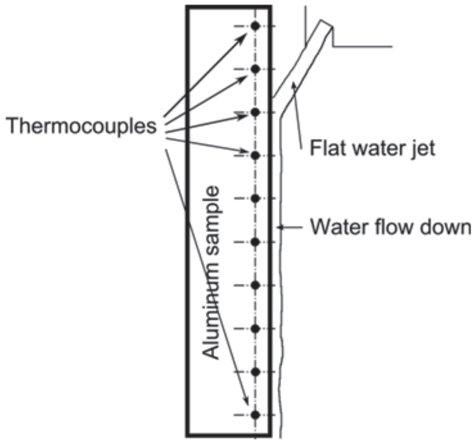

Fig. 1 Cross section of aluminum sample

2.2. Leidenfrost effect

The Leidenfrost effect (LF effect) creates a situation where the heat flux does not monotonically increase as a function of the temperature difference between the surface and the surrounding temperature. The temperature for which the heat function reaches the local minimum is called the Leidenfrost temperature. This point is located between the transition and film boiling regimes; see **Fig. 2** [1].

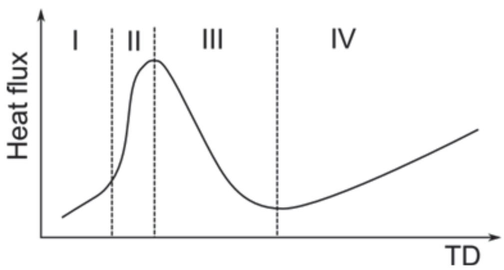

Fig. 2 Typical boiling curves for water at 0.1 MPa, **I** - Convection, **II** - Nucleate boiling, **III** - Transient boiling, **IV** - Film boiling

3. INVERSE HEAT CONDUCTION PROBLEM

3.1. Direct versus Inverse problem

Tasks to find effects from known causes are called direct tasks, while tasks for observed (known) effects but unknown causes are called inverse tasks [3].

Specifically, for the heat conduction problem:

- Causes - initial temperature and boundary conditions
- Effects - temperature distribution over time

Some simple direct problems can be solved analytically. For other, more complex direct problems(for example, temperature-dependent material properties), numerical methods FDM [4], FVM [5], FEM [6] can be used.

Inverse heat conduction problems are usually referred to as ill-posed. Even a small change in input data can lead to significant differences in results. Solving such a problem much more complicated than solving direct tasks. If the inverse heat conduction problem is linear, then the full domain method [3], Tikhonov's regularization [7], etc. can be used. A sequence method is preferable to use for temperature-dependent material properties or large amounts of data. The basics of Beck's sequential method [3] are described in the next chapter.

3.2. Beck's sequential method for 1D problems

The basic idea of the sequential approach is to solve the entire task step by step in time. In each time step t_n there is N_f the measured temperature at an interior point at time t_n, t_{n+1},..,t_{n+Nf} to obtain the heat flux Q_n at the boundary at time t_n. Q_n is determined from the solution of a minimization problem:

$$\min_{Q_n} \sum_{i=1}^{N_f} \left(Y_{n+i} - T_{n+i}\big|_{Q_n} \right)^2, \tag{1}$$

where Y_i are measured temperatures, $T_i|_{Qn}$ are temperatures calculated using a direct calculation for constant heat flux $Q_i = Q_n$.

Formula (2) can be used in a linear case.

$$Q_{t_n} = \frac{\sum_{i=1}^{N_f} \left(Y_{n+i} - T_{n+i}\big|_{Q=0} \right) \Phi_i}{\sum_{i}^{N_f} \Phi_{n+i}^2}, \tag{2}$$

where Ti are temperatures calculated for zero heat flux and Φ_i are sensitivity coefficients.

In other cases, a different standard minimization method can be used. For example Brent's optimization method (which was used in this article) [8].

N_f is the number of forward time steps and operates as a regularization parameter. These methods are unstable for small values of N_f and results become too smoothed for large values [9]. The optimal number of forward time steps is usually searched manually or is obtained by some criteria.

3.3. 2D problem with M thermocouple along the surface

With some modification, the method which was described previously can be used to solve a 2D problem. The boundary conditions on the cooling surface are represented by the M functions. Each heat flux function corresponds to one temperature sensor. Values from i-th heat flux function $Q_i(t)$ are used as a boundary condition on the part of the surface which is closest to the center of the i-th temperature sensor in the direct problem (see **Fig. 3**)

The error term (2) is extended by temperature difference contributions from all temperature sensors. The new minimization task at time step t_n is to find the N value for $Q_1(t_n)$, $Q_2(t_n)$, ..., $Q_M(t_n)$.

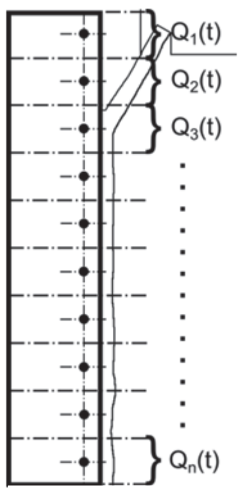

Fig. 3 Heat flux function allocation to the surface area

3.4. Modification for solving task with a moving Leidenfrost front

The heat flux as a function of only time (not vertical position), was assumed in the previous chapter. This assumption is correct if the real heat flux is almost homogeneous at the interval where it is approximated by the calculated heat flux function. Unfortunately, this is not true for experiments described earlier in this text, because the heat transfer coefficient is strongly dependent on temperature and surface temperatures are inhomogeneous in the vertical direction, as well. In other words, a small temperature inhomogeneity (near the LF temperature) in the vertical direction can cause large heat flux inhomogeneity which can be seen in the typical HTC function of temperature in **Fig. 4**.

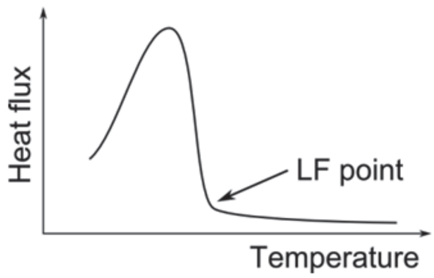

Fig. 4 Typical shape of the HTC function

The consequences of this imprecision can be seen in the smooth shape of the HTC function around the LF point (**Fig. 6**) or even in small differences between measured and calculated temperatures (**Fig. 7**).

Inhomogeneity in the vertical direction can be theoretically suppressed by reducing the spacing between thermocouples. In practice, a minimal distance between thermocouples is used, because each thermocouple slightly distorts the temperature field in the surrounding material.

The sample is undercooled (under the LF temperature) in the area where the water jet strikes the surface at the beginning of the experiment. Then, the undercooled area begins expanding downward along the surface due to heat conduction inside the material. Surfaces with a higher temperature than the LF temperature are almost uncooled by water flow. Consequently, only the positions of points where the surface temperature is equal to the LF temperature are critical for the inverse calculation. The aforementioned points lie on a horizontal line which can be called the Leidenfrost front (LFF).

The inverse calculation method is modified so that the mowing LFF always lies on a border between areas on the surface which corresponding to the functions HTC_i and HTC_{i+1}. This is performed by shifting the borders during calculation (see **Fig. 5**). The speed of LFF motion can be observed in the experiment optically or can be determined by solving a two-stage optimization problem; the first stage is part of the IHCP, the second is a velocity determination based on residual errors from the first stage).

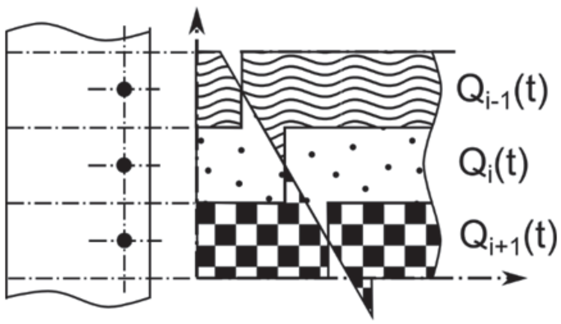

Fig. 5 Region corresponding to Q_{i-1}, Q_i, Q_{i+1} with shifting borders at time

4. DISCUSSION

This method was tested on temperature records from measurement. Comparison of the measured and calculated temperature for both methods is shown on **Fig. 6**. Evaluated HTC by both methods are similarly in first cooling regime (near to impingement zone). Different value form second zone are shown in **Fig. 7** exemplified by three HTC functions.

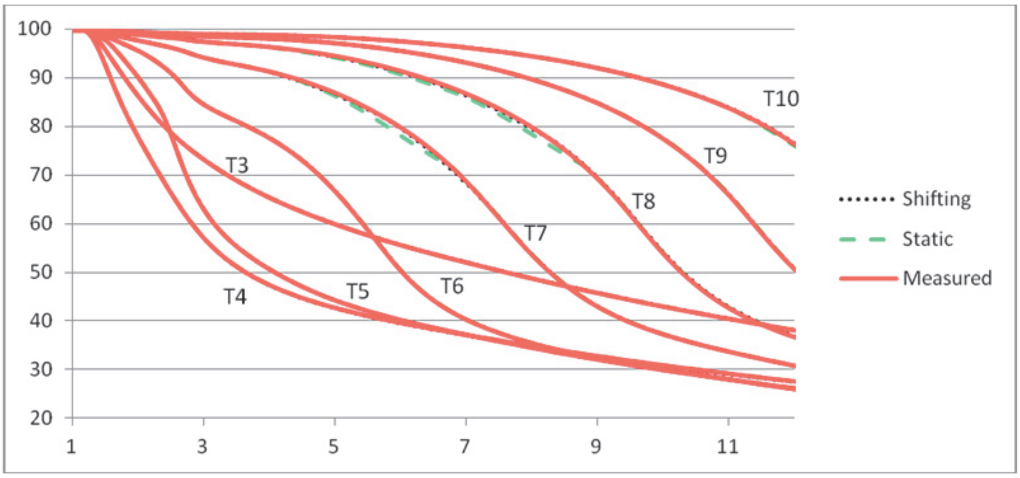

Fig. 6 Comparison of measured temperature with calculated temperature

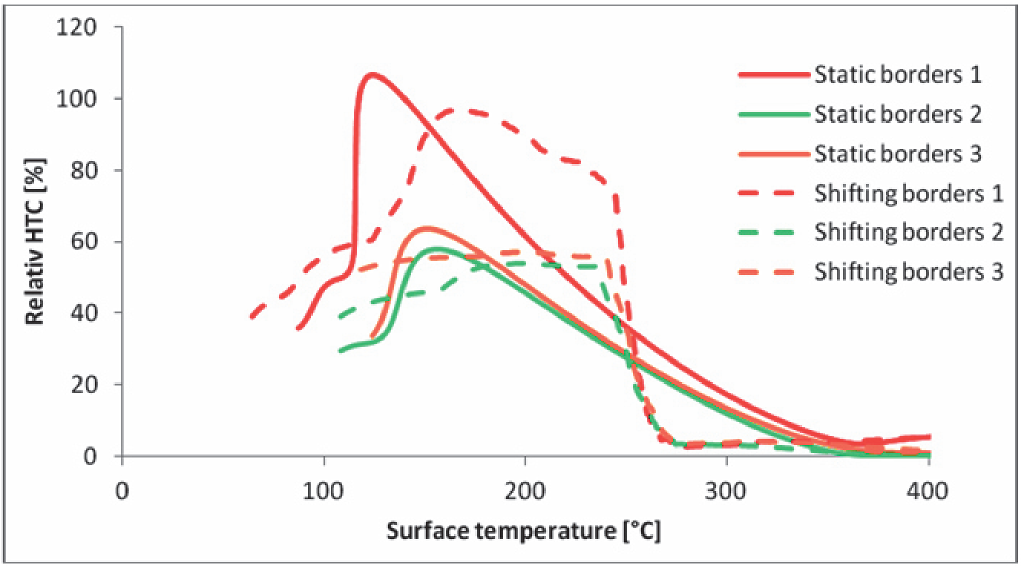

Fig. 7 Comparison of relative HTC function with and without shifting of borders

5. CONCLUSION

Cooling experiments with an aluminum sample were done. Boundary conditions were obtained by solving the 2D inverse heat conduction problem (with and without shifting boundary modification). A comparison of these two methods (**Figs. 6, 7**) shows that despite the fact that the temperature difference is not very large; the differences in heat flux are substantial.

ACKNOWLEDGEMENTS

This work is an output of research and scientific activities of this project LO1202 with financial support from the MEYS under the program NPU I

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