Method of restoring boundary conditions on the high-temperature sphere surface during its cooling

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Abstract. The paper describes the method of restoring heat flux values on the surface of high-temperature nickel ball 45 mm in diameter at process of its intensive cooling by water in 1D and 2D formulation.

1. Introduction

The task of restoring temperature and heat flux fields in solid bodies by results of inner temperature measuring reduces to solution of inverse heat conduction problem (IHCP). This problem is closely related to study of thermal strength characteristics of materials and constructions, and consequently the reproduction of required temperature gradients in models at experimental conditions. Usually it is not possible to equip models with multiple temperature sensors due to technological, constructional and methodological reasons. Therefore, the initial information of such experiments is usually limited, and it is often determined only by indirect temperature measurements at sufficiently large distance from an external surface. At study of various heat exchange processes in systems «solid-liquid», the non-steady heat transfer problem is of great importance. In many practically important cases, the main method of such a research is still the experiment. It requires not only qualitative execution of the experiment, but also search for an effective way of obtained data processing.

Little is known about any accurate thermophysical studies of film boiling of a subcooled liquid. In the late 1980s several works of famous English researchers G.F. Hewitt, D.B.R. Kenning and their post-graduate students were published [1, 2]. In these articles the unique experimental data on pool film boiling of subcooled water on the copper balls surface were presented. The authors have firstly described the regime, named as «microbubble boiling», that was obtained at film boiling of water at subcooling degree over 22 °C. The regime was detected at ball surface temperatures over 400 °C, when a direct contact between liquid and hot wall is impossible. Heat transfer coefficient (HTC) at such a regime was unusually high for stable film boiling of saturated water: over 10 kW/(m²K).

In the article by Prof. K. Suzuki [3] a process, similar to one studied in works of English colleagues, was discussed. Emission of microbubbles close to heated surface was obtained at pool boiling of water-ethanol mixtures at subcooling degree of about 40 °C. The difference from Hewitt and Kenning investigation is that such a process was obtained when wall superheat was not over 50°C at transient boiling.

Unfortunately, papers described above does not contain any theory of the discovered process.

2. Experimental facility and the methods of results treatment

Based on the results of our previous studies [7-14], we planned to investigate an influence of material, tested sample size, and coolant properties on the quenching process regularities. Sphere is a convenient shape that provides 1D conditions in a limiting case. Therefore, in all our experiments spheres 30-51 mm in diameter are used as the tested samples. Rather large size of a tested sample allows studying a possible deviation of the temperature field from spherical symmetry. That is why
measuring temperature in several points of a metallic sphere is required; usually four or five thermocouples are imbedded in a sample. Several thermocouples located at surface of ball at several points of its surface on cooling time. At high intensity of heat transfer, the temperature field in the sphere is not uniform and not spherically symmetric. Under such conditions, one has to solve an inverse heat conduction problem in order to calculate heat flux density at the sphere surface. It is well known that the solution of ill-posed (inverse) problems cannot be rigorous. In fact, estimation of unknown boundary conditions is realized. In this study, an actual numerical solution of direct unsteady heat conduction problem has been found to recover boundary conditions at the surface of the cooled sphere.

Assuming axial symmetry of the temperature field in a sphere, one can use 2D unsteady heat conduction equation:

$$\rho c \frac{dT}{dt} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( \lambda r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \lambda \sin \theta \frac{\partial T}{\partial \theta} \right)$$  \hspace{1cm} (1)

Actually, an analytical approximation of the experimental thermograms for the surface thermocouples readings is used as a boundary condition. Solution of Eq. (1) gives a temperature field at any time moment. Comparison of a calculated time dependence of temperature of the sphere central point with the corresponding experimental data allows us to estimate a reliability of the obtained solution.

The problem simplifies, when a cooling process is spherically symmetric; this occurs mainly at film boiling of saturated or weakly subcooled water ($\Delta T_{sub} \leq 20 ^\circ C$). This approximation is also used for rather small spheres even at high intensity of heat transfer at the sphere surface. In this case the second term in right hand part of Eq. (1) vanishes, and the boundary conditions become as follows:

$$t = 0, 0 \leq r \leq R_{ball} : T = T_w = T_0;$$
$$r = 0 : \frac{\partial T}{\partial r} = 0;$$
$$r = R_{ball} : T = T(t, \theta)$$  \hspace{1cm} (2)

Properties with index «0» correspond to the initial temperature, index «w» correspond to the wall temperature.

The solution is an iterative one. At each time step some value of heat transfer coefficient (HTC) is initially given and the simplified (1D) equation (1) is solved numerically using the program «Rteta» (developed at the Department of Engineering Thermophysics of MPEI). The calculated values of the surface temperature are compared with the measured ones. By means of a proper HTC choice in interactive regime, coincidence of the measured and calculated values of temperature is provided. Then, the temperature field found at the previous time step is used as the initial one for the following time step. In this way, the HTC is determined for the entire cooling process. This method gives good results while spherical symmetry of temperature field is obeyed.

3. Results and discussion
Starting work with any new sample, the experiments with saturated or weakly subcooled ($\Delta T_{sub} \leq 10 K$) water have been carried out at first. Their results are quite similar to those obtained in previous studies. At stable film boiling, the heat transfer intensity is rather low, HTC is about 200 W/(m$^2$K). Cooling duration in saturated water from the initial temperature $T_0 = 500-700 ^\circ C$ is 70-170 s, in dependence on a size and material of a sphere and a value of $T_0$. Under these conditions, the heat transfer regimes can be considered as the regular convection modes of cooling; for limited time intervals heat flux at the sphere surface is calculated with reasonable accuracy according to an approximate method of lumped capacity, as follows:
The measured values of HTC in these regimes agree well with calculations on the widely known predicting correlations (see, for example, [4]). These preliminary experiments confirmed a reliability of the experimental methods; the examples of such results were given in [5, 6].

Experimental thermograms of cooling 45 mm nickel ball in 50°C water were selected as a source of boundary condition. The thermogram shown in Fig. 1 demonstrates that the mode of rapid cooling process is moving with a shift. The experimental thermograms shown in Fig. 1 were approximated by an axially symmetrical function of time and polar angle. For the region \( \pi/8 \leq \theta \leq \pi \) we selected a function similar to hyperbolic tangent of the Fourier number (\( \text{Fo} = at/R^2 \)) and polar angle \( \theta \):

\[
F1(\text{Fo}, \theta) = \frac{1}{\exp \left( 2 \cdot Y_{11}(\theta) (\text{Fo} - Y_1(\theta) \cdot \cos \left( \frac{\theta}{\pi} \right)) \right) + 1}
\]

(4)

This function provides adequate initial and final limits. However, when processing this thermogram it was found that the use of zero excess temperature at the upper point improved the agreement of the experimental and calculated temperature in the center of the ball. It is logical to assume the presence of a zone with a saturation temperature near the upper pole of the sphere. Therefore, all data with this hypothesis was processed. After this condition and procedure of linearization, the function looked like this:

\[
F(\text{Fo}, \theta) = \begin{cases} 
0, & \text{at } \theta \leq \frac{\pi}{16} \\
\text{LIN}(\text{Fo}, \theta), & \frac{\pi}{16} < \theta \leq \frac{\pi}{8} \quad \text{if } \text{LIN}(\text{Fo}, \theta) > 0 \\
F1(\text{Fo}, \theta), & \theta > \frac{\pi}{8} 
\end{cases}
\]

(5)

Comparison of experimental thermograms with calculation of the proposed function for particular polar angles is presented in Fig. 1.

Figure 1. Comparison of experimental data with calculation for particular polar angles for sphere cooling in 50°C water.

Dimensionless temperature was determined as:

\[
\theta = \frac{t - t_s}{t_0 - t_s}
\]

(6)
Properties with index «s» correspond to the saturate temperature of liquid.

Numerical solution of eq. (1) allows us to obtain temperature fields and calculate density of heat flux on sample surface (Fig. 2).

As a result, heat flux densities variation in time at the surface was calculated; values of $q = 3-6$ MW/m² at the lower part of the sphere surface were obtained for the first 3-4 s from intensive cooling incipience. During this period, the surface temperature remained essentially higher than the attainable limiting temperature of water.

As can be seen from the above material, the choice of a function to describe the temperature distribution over the surface of a cooled sphere as a function of time and the polar angle is a very nontrivial task. However, the results achieved allow us to reliably estimate the heat transfer coefficient and the heat flux to the surface of the sphere.

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