Gradient heatmetry for boiling of underheated water on spherical surface

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Abstract: The method of gradient heatmetry made it possible to obtain the distribution of local heat flux per unit area for boiling of subcooled water on the surface of the ball.

1. Introduction
Today, the study of heat transfer during boiling is one of the promising objects of investigation. This is due to the lack of necessary experimental base, which allows to rate heat exchangers with phase transitions with high accuracy. Until recently, thermocouples were the only available primary sensors for studying phase transitions. Using a thermocouple, temperature values are recorded on the surface and in the center of the model, after which, by solving the inverse heat conduction problem, heat flux is indirectly estimated [1]. The use of gradient heatmetry in the study of heat transfer in phase transitions allows direct measurements of heat flux [2].

2. Gradient heatmetry
The method is based on the use of gradient heat flow sensors (GHFS) that implement transverse Seebeck effect in media with anisotropy of thermal conductivity, electrical conductivity, and coefficient of thermoEMF. In anisotropic media through which heat flux is transmitted (Figure 1a), the transverse component of its vector appears, which is proportional to heat flux,

\[ E_0 = S_0 \cdot A \cdot q \]  

(1)

where \( E_0 \) – thermoEMF, mV; \( S_0 \) – volt-watt sensitivity of GHFS, mV/W; \( A \) – area of GHFS, m\(^2\); \( q \) – heat flux per unit area, W/m\(^2\).

![Gradient heat flux sensor (GHFS): a – action scheme; b – photo](image)

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At Peter the Great St. Petersburg Polytechnic University, heterogeneous gradient heat flux sensors (HGHFSs) were created, heat resistance of which exceeds 1500 K [3]. Compositions of two different metals were used to create the sensors. The modification made of composition of copper+nickel (Figure 1, b), was used in our work. The graduation of the HGHFSs was carried out at a special setup. The relative uncertainty of calibration was of 4% [3].

3. Experimental setup
The experimental setup is shown in Figure 2. The test sample 1 is placed in the furnace 2 and fixed in it using the holder 3. Temperature of the sample and the uniformity of heating are monitored by two thermocouples installed in it, the readings from which are displayed on the measuring and calculating complex (MCC) 8. When the required temperature is reached, the holder 3 releases the sample 1, and it falls through the furnace 2 into the water tank 4; recording of the thermocouples and HGHFS signals on the MCC 8 and the boiling pattern on the high speed camera 6 begins. Temperature in the water tank 4 was controlled with Fluke 289 instrument with thermocouple 5, and the required temperature level was maintained by the electric heater. Recording from a video camera 6, data from the GHFS and thermocouples were placed on the computer's hard drive. The video recording frequency was of 1000 frames/s, and the data from the HGHFS and thermocouples were recorded at a frequency of 5000 measurements/s.

Fig. 2 Experimental setup
1 – research model; 2 – furnace; 3 – holder; 4 – water tank; 5 – Fluke 289 with thermocouple; 6 – high speed camera; 7 – illuminant; 8 – MCC NIPXI-1050; 9 – computer
Of greatest interest is design of the experimental model (Figure 3). The holder (Figure 3) allowed not only to move the model vertically, but also to rotate it around the equatorial axis; the measurement zone moved to an arbitrary latitude from the south pole to the north. Thus, a single set of thermocouples and HGHFS made it possible to estimate local heat flux per unit area and temperature at various temperature differences and boiling modes.

![Fig.3 – The experimental model](image)

The experimental model is a titanium VT22 sphere; the HGHFS from a copper+nickel composition with dimensions of 3×3×0.3 mm is installed on the surface of the model. Temperature was controlled by two thermocouples: one junction was located near HGHFS (type G), the other one in the center of the sphere. The layer of mica installed under the sensor provided electrical isolation of it from the model. The high-temperature compound was used to fix HGHFS. The surface of the sphere was polished, and the working surface of the sensor was flush with the surface of the model. Thermal imaging control did not reveal significant temperature distortions at the installation site.

4. The results of the experiment

The experiment was repeated for 12 times in each series, and the rotation of the measuring area between experiments was of 15 degrees. The heatmetry graph (Figure 4) shows the result of experiments for temperature of the sphere of 350°C and temperature of water of 25°C. In this mode, there were no conditions for occurrence of film boiling on the surface. Maximal heat flux per unit area was fixed at the south pole (0). At this point the model touches the water surface, and there arises the largest temperature difference. With further immersion of the sphere in water, heat flux per unit area decreases in 5 times.
In next series of experiments, temperature of water remained of the same 25 °C, and temperature of sphere was of 450°C. Heatmetry angular graph (Fig. 5) shows that heat flux has become higher than in the previous mode, and its maximum has shifted to the latitude of φ = 45°. This is due to the occurrence of vapor layer in contact with water, but film boiling did not occur due to a significant subcooling of water. With further immersion, the sphere cools down and vapor layer is destroyed after passing of 45 degrees. A transition to bubble boiling occurs, which is accompanied by a sharp increase in heat flux.

Fig. 4 Heatmetry angular graph (T_w=350 °C, T_f=25 °C)

Fig. 5 Heatmetry angular graph (T_w=450 °C, T_f=25 °C)
In the next mode, the subcooling of the water was of 50°C and temperature of the sphere was of 350°C. Nature of the results has changed significantly (Fig. 6). Maximal heat flux became blurred, and average heat flux increased.

When the sphere is heated to temperature of 450°C and water is subcooled up to 50°C, a pronounced peak of heat flux is observed at $\phi = 90^\circ$ (Fig. 7). In the northern hemisphere, nature of the curves coincides with the regime in Fig. 5.
The vapor layer lasts longer at a temperature of subcooling of water of $T_f = 50^\circ C$ and after this developed bubble boiling is observed. The sphere was cooled much faster at water temperature of $T_f = 25^\circ C$ and active bubble boiling does not occur.

5. Conclusion
The average values of heat flux per unit area are given in table 1.

| Regime                  | Temperature difference, $\Delta T = T_w - T_f, ^\circ C$ | Average heat flux htr unit area, $q$, MW/m$^2$ |
|-------------------------|----------------------------------------------------------|-------------------------------------------------|
| $T_w=450 ^\circ C, T_f=50 ^\circ C$ | 400                                                       | 9,3321                                           |
| $T_w=450 ^\circ C, T_f=25 ^\circ C$ | 425                                                       | 3,929                                            |
| $T_w=350 ^\circ C, T_f=50 ^\circ C$ | 300                                                       | 0,9297                                           |
| $T_w=350 ^\circ C, T_f=25 ^\circ C$ | 325                                                       | 0,2404                                           |

It can be seen that temperature difference of $(T_w - T_f)$ does not determine the level of heat removal. The magnitude of this important parameter depends mainly on the subcooling of water – which gives reason to choose the parameters of the coolant in various technical applications.

References
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