Gradient heatmetry in the study of boiling on spherical surface

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Abstract. The combination of methods of gradient heatmetry and high-speed visualization made it possible to compare the distribution of the local heat flux and the hydrodynamics of the process during boiling of subcooled water on the surface of the sphere. The results are compared with the works of other authors and conclusions are drawn about the effect of subcooling of water on the intensity of heat transfer.

1. Introduction
The study of heat transfer during boiling is one of the most promising research topics. The lack of an extensive experimental base and the impossibility of carrying out direct measurements of the local heat flux made it difficult to study boiling until recently. All experiments were carried out by thermometry. Temperature values recorded by thermocouples are converted into indirect values of heat flux by solving the inverse problem of thermal conductivity [1]. The use of gradient heatmetry in the study of heat transfer during boiling 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,

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

where \( E_0 \) – thermoEMF, mV; \( S_0 \) – volt-watt sensitivity of GHFS, mV/W; \( A \) – area of GHFS, m²; \( q \) – heat flux per unit area, W/ m².
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%, but the uncertainty of the experiment was not estimated due to the large difference in the values of the heat flux density [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 HGHFS 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.

Of greatest interest is design of the experimental model (figure 2). The holder 3 (figure 2) 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 10,12 and HGHFS 11 made it possible to estimate local heat flux per unit area and temperature at various temperature differences and boiling modes.

Figure 1. Gradient heat flux sensor (GHFS): a – action scheme; b – photo.
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 experiment
The first experiments on boiling using gradient heatmeatry are described in [2]. They confirmed the applicability and serviceability of the HGHFS and the model as a whole. However, the results did not fully correspond to the capabilities of the methodology, and some data needed to be adjusted.
The first series of experiments is devoted to boiling on the surface of a ball heated to 300°C and immersed in water brought to saturation (Figure 4, a).

When the ball is immersed in water, there is a significant temperature difference between the poles [1]. According to [4], the second critical heat flux is 0.46 ... 0.63 MW·m⁻². In figure 3, a, the first and largest peak corresponds to this range. Three modes of boiling are distinguished: 1 - contact moment and the appearance of film boiling; 2 - transient mode; 3 - bubble boiling. It can be seen that the heat flux at the south pole of the sphere is higher, and the bubble regime begins earlier. It follows from this that the destruction of the film starts from the south pole.

Figure 3, b, c show high-speed video frames. Figure 3, b shows the moment of contact of the sensor on the ball with the liquid. Microbubble boiling occurs on the submerged part of the ball, preceding the formation of a film. Figure 3, c demonstrates stable film boiling. The time lag between the peaks of the heat flux for the north and south poles of the sphere corresponds to the time the ball is immersed in water. This was captured using high-speed imaging.

The next step was to increase the temperature of the ball and decrease the temperature of the water. Determination of the heat flux during film boiling was considered in [5]. The authors lowered the heated ball into water and measured the thickness of the vapor film, after which the heat flux was calculated. We lowered the ball, heated to 464°C, in water with a temperature of 64°C (subcooled to saturation by 36°C).

In figure 4, a, the red point indicates the moment of contact of the ball with the water surface and the nucleation of a vapor film. After this point, stable film boiling is established. The heat flux measured with the HGHFS corresponds to the results of work [5]. The zone numbering is the same as in figure 3.
In the transient mode (figure 4, b), large bubbles are detached, the film begins to break down, in connection with this, an increase in the heat flux is observed. The bubble boiling regime (figures 4 a, c) has a characteristic peak exceeding the first critical value of the heat flux, which corresponds to the data of S. S. Kutateladze \[6\]. A comparison of our data with these classical results is shown in figure 5. The abscissa shows a dimensionless complex with $c\Delta T r^{-1}$, where $c$ – is the heat capacity of the liquid, J·(kg·K)$^{-1}$; $\Delta T$ – is underheating to saturation temperature, K; $r$ – is latent heat of vaporization, J·kg$^{-1}$.

![Figure 4](image1)

**Figure 4.** Comparison of the heat flow sensor data frames with a high-speed imaging ($T_w = 464^\circ$C; $T_f = 64^\circ$C); a – time dependence of the heat flux; b – transient boiling mode (mode № 2); c – bubble boiling mode (mode № 3).

![Figure 5](image2)

**Figure 5.** Relative changes in the critical heat flux in a subcooled liquid.

5. **Conclusions**

Our results are comparable with the data of [5] obtained under similar conditions for saturated and subcooled water (figure 6,a). Good convergence is seen in the stable film boiling regime. In the
transient and bubble regimes, the hydrodynamics of the process is chaotic and does not give an unambiguous relationship.

In works [7, 1], the average heat flux was determined by solving the inverse problem of heat conduction; high-speed video filming was also carried out (the results of the study are close to our work). We conducted the experiment under conditions close to one of the experiments presented in [1]. The correspondence of the data with those obtained by the method of gradient heatmetry (figure 6,b) shows a similar shape of the curves at an eightfold discrepancy in the level of the maximum heat flux. This confirms the need to estimate the local heat flux and the apparent uncertainty of the data obtained by averaging over the entire surface of the model.

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