Comprehensive study of boiling regimes with use of high-speed imaging and gradient heatmetry

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Abstract. In the study of heat transfer during boiling, optical methods and thermometry are prevailing. The possibilities of experiment are significantly expanded by new technology – gradient heatmetry, in which heterogeneous gradient heat flux sensors with time constant of nanoseconds are used. When studying of boiling of subcooled water in a large volume on the surface of the titanium sphere, preheated up to 300-500 °C, heatmetry was combined with visualization of boiling modes using a high-speed camera Evercam 1000-4-M. It is possible to obtain the distribution of heat flux per unit area along the latitudinal coordinate and to relate the local heat flux per unit area with observed boiling regimes and initial temperatures of water and the model.

1. Introduction
Until recently, the difficulty in determining of the heat flux per unit area (HFPUA) was absence of small-sized and low-inertia heat flux sensors. The great part of studies is carried out by methods of optical imaging and thermometry. Optical methods make it possible to measure the thickness of the vapor film and calculate the average heat flux at the surface of the model [1]. Thermometry allows to calculate the average heat flux, and no more [2]. Gradient heatmetry, being the new method here, allows us to measure local HFPUA, and, if necessary, to obtain its distribution over the surface of the model [3]. High-speed imaging was used to reveal the relationship between local HFPUA and boiling regime.

2. Gradient heatmetry
Gradient heatmetry uses HGHFSs – heterogeneous gradient heat flux sensors (figure 1) [4], whose action is based on transverse Seebeck effect. When a heat flux of $q$ passes through the sensor, it appears proportional to transverse thermoEMF

$$E_0 = S_0 \cdot A \cdot q,$$

where $E_0$ – thermoEMF, mV, $S_0$ – volt-watt sensitivity of HGHFS, mV/W, $A$ – area of HGHFS, m², $q$ – heat flux per unit area, W/m².

3. Experimental setup
The experimental setup (figure 2) includes: channel furnace (2); MCC National Instruments (8); water tank (4) with a volume of 10 litres; high speed Evercam 1000-4-M camera (6).
Figure 1. Heterogeneous gradient heat flux sensor (HGHFS):
(a) – action scheme
(b) – photo.

Figure 2. Experimental setup: 1 – model, 2 – furnace, 3 – holder, 4 – water tank, 5 – Fluke 289 with thermocouple, 6 – high speed Evercam 1000-4-M camera, 7 – illuminant, 8 – MCC NIPXI-1050, 9 – computer, 10 – light emitting diode.
Experimental model (1) is a 34 mm dia sphere made of VT22 titanium. On the surface of the model, the HGHFS with dimensions of 3×3×0.3 mm$^3$ is installed. Temperature of the furnace (2) and homogeneity of temperature field in model (1) were monitored with two thermocouples of iron-constantan and copper-constantan types installed on the surface and in the center of the sphere. Measurement of their thermoEMF was provided by MCC National Instruments (5).

When the required temperature was reached, the holder (3) released the model (1), and it falls into the tank with subcooled water (4) [5]. Temperature of water was measured with the thermocouple connected to Fluke 289 device (5). Synchronization of sensor signal and high-speed imaging was carried out using light emitting diode (10). Computer (9) provided visualization, processing and archiving of obtained results.

4. Results
By synchronizing the data obtained by high-speed imaging and gradient heatmetry, it was possible to establish the boundaries of the boiling regimes (figure 3). Mode 1 corresponds to film boiling, which is confirmed by HFPUA values and high-speed imaging frames. HFPUA pulsations are here associated with fluctuations of thickness of the vapor film. Mode 2 corresponds to destruction of the vapor film and its transition to nucleate boiling. The high-speed imaging shows that the film occupies only the part of surface of the sphere, and the bubbles are forming on the rest of the surface. Mode 3 corresponds to developed nucleate boiling. It is in this region that the HFPUA maximum is observed; the frames of the shooting show individual bubbles coming off the surface. The HFPUA pulsations in this region are associated with the separation of bubbles from the surface of the HGHFS. No boiling occurs on the compound around the HGHFS, but the survey shows that the sensor is in the same conditions as the surface of the model.

![Figure 3](image_url)

**Figure 3.** Dependence of heat flux per unit area on time ($T_w = 464 \, ^{\circ}\text{C}; T_f = 64 \, ^{\circ}\text{C}$).
The complex application of high-speed imaging and gradient heatmetry made it possible to obtain the distribution of HFPUA over the sphere surface (figure 4). When the model is immersed under water, a vapor film forms on it, which prevents the contact of cold liquid with the heated surface of the model. With further immersion, the vapor film is completely destroyed, but due to the underheating of water, developed nucleate boiling is not observed, and only microbubble regime is recorded. The HFPUA peak

Figure 4. Angle heatmetry diagram ($T_w$=450 °C, $T_f$=25 °C).

Figure 5. Angle heatmetry diagram ($T_w$=450 °C, $T_f$=50 °C).
corresponds to immersion of the model under the water surface, during which the vapor film breaks down.

With increase of the water temperature $T_f$, HFPUA peak shifts to latitudes of $75 < \varphi < 90^\circ$ (figure 5), which is associated with increase in the duration of film boiling. High-speed imaging confirms this dependence, and upon further immersion of the model, destruction of the vapour film is observed.

5. Conclusion
The complex use of gradient heatmetry and high-speed imaging provides reliable data in study of heat transfer during the boiling of subcooled water on the surface of the sphere. It is possible to relate the values of the local heat flux per unit area with instantaneous boiling patterns and to fix the boundaries of boiling regimes.

References
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