Gradient heat flux measurement in study of unsteady water film boiling at the surface of the sphere

S Z Sapozhnikov, V Yu Mityakov and V V Subbotina

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, 195251, Politekhnicheskaya, 29, Russia

*E-mail: subbotina.vv@edu.spbstu.ru

Abstract. The new method of study heat transfer is the gradient heat flux measurement. It allows measuring the heat flux per unit area for unsteady film boiling at the spherical surface. For the first time distribution over the surface of heat flux per unit area and heat transfer coefficient were derived. The time dependences for the local heat flux per unit area and heat transfer coefficient were obtained in different angles of the spherical surface. The spherical surface was made of titanium VT 22 with a diameter of 20 mm. High-speed shooting supplemented the experimental curves with a frequency of 1 kHz. The error of heat flux per unit area measurement was not exceeding 12%.

1. Introduction
Unsteady film boiling of subcooled liquid on various surfaces is used in power engineering, metallurgy, electronics, and other fields. The theoretical description models [1] or methods of calculation [2] and obtaining reliable experimental data on heat transfer in this boiling regime [3, 4] were hampered by an absence of the heat flux sensors of the proper level.

Many scientific groups headed by Yu. Zeigarnik [5], V. Yagov [6], and other researchers [7–9] used various method for the study of boiling liquid. Every method has advantages, however the heat flux per unit area was calculated, and describe average value.

Gradient heat flux measurement gives the distribution of the local heat flux per unit area and heat transfer coefficient (HTC) over the heat exchange surface. Method is based on the use of gradient heat flux sensors. Their successful use during film boiling at high-temperature cylindrical surface was described in [10]. We used heterogeneous gradient heat flux sensor (HGHFS). Gradient heat flux measurement data are supplemented with high-speed video frames.

2. Experimental research methods
HGHFS was made of composition steel 12Cr18Ni10Ti and nickel, thermometry used k-type thermocouples and high-speed video was performed using the Evercam 1000-4-C camera.

2.1. Gradient heat flux measurement
Layers of steel 12Cr18Ni10Ti and nickel were connected by diffusion welding and formed anisotropy, thermal and electrical properties. When a heat flux passes through such sensor, it generates transverse thermoEMF proportional heat flux per unit area (Figure 1b).

The calibration of HGHFS in the temperature range of 550 ... 800 K was carried out by the absolute method by the Joule heat flux on the high-temperature test bench. The error of calibration was 7…12%.
HGHFS has unique time constant about 10 ns that allows fast recording of the heat transfer processes. The grey surface of HGHFS allows measuring both convective and radiation components of heat flux.

![Diagram of experimental model](image)

**Figure 1.** Experimental model: a) Installation HGHFS and TC, b) HGHFS.

2.2. Thermometry
Control temperature of the experimental sphere and water were measured by k-type thermocouples (0.2 mm diameter). The thermojunction was embedded in sphere near the surface (Figure 1). Thermocouple was submerged in water tank to control temperature.

2.3. Optical method
The high-speed camera Evercam 1000-4-C allows shooting of 1000 fps at the resolution of 1280×860 px. The camera has own software that allows processing, editing and converting video.

3. Experimental setup
Experimental setup consists of the vertical furnace (maximum temperature is 873 K), the water tank with flat walls and volume of 10 dm³, the Evercam 1000-4-C high-speed camera, the National Instruments with a PXI-1303 for recording, processing and archiving signals of HGHFS and thermocouples.

The sphere was submerged into the tank. The depth of immersion was regulated by a stopper.

4. Experimental sphere models
Sphere was made of titanium VT22. Its thermal conductivity about 8 W/(m²·K) was close to value of HGHFS. The sphere had the diameter of 20 mm. HGHFS of 1.5×2.5×1 mm was placed into the groove at the strip of mica with a thickness of 10 μm. Wires were inferred through the sphere (Figure 1a). The holder was replaced with the dial. The sphere had the starting point for 0° on the south pole.

Experimental model sustains more than 20 tests. The surface was covered with the smooth oxide film, but it did not affect to boiling processes.

5. The results
Rotation sphere around axis (Figure 2) carried out 5 points every 45 degrees. Heat flux per unit area and HTC were obtained and averaged in some test at every point. Distribution of the local heat flux per unit area and HTC over the spherical surface are represented in Figure 2.

Local heat flux per unit area for film boiling of subcooled water at rotation angles of φ > 50° is 2...4 times more than the first critical heat flux per unit area for saturated water. HTC for subcooled water for film boiling is 10 times more than for film boiling of saturated water.

Maximum of local heat flux per unit area was received at angle φ=135°. Time dependence is presented in Figure 3 for the detail study. High-speed video frame completed these curve.
Figure 2. The distribution of the local HTC and heat flux per unit area over the surface of the sphere.

Figure 3. Time dependence of local HTC and heat flux per unit area.

Video frames allow us to track the breakdown of the steam film and the transition to bubble boil. The revealed pulsations of the heat flux per unit area require further investigation.
Conclusion
The first time gradient heat flux measurement gave the distributions of local heat flux per unit area and HTC at the spherical surface of the sphere during film boiling of subcooled water. The high-speed video visualized boiling with reference to time. Heat transfer enhancement in this mode was confirmed and quantified.

In the future, various combinations of initial temperatures of the sphere and the liquid, as well as heat transfer on the surface of models of various shapes, with different surface states, etc., will be investigated.

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