Gradient heat flux measurement in study of heat transfer during subcooled water boiling at sphere

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Abstract. The new method for study of film boiling of subcooled water is proposed. Applying the heterogeneous gradient heat flux sensors (HGHFS) allows first the experimental determination of heat flux and heat transfer coefficient (HTC) when subcooled water is boiling at the spherical surface preheated up to 673 K. Maximum of the heat flux was fixed when the sphere contacted with subcooled water (ΔT = 80 K). Incessant and synchronous measurement of heat flux, surface temperature, and observation of vapor film were implemented. Traditional boiling curve was also obtained. Functionality of HGHFS under the complicated conditions of experiment was confirmed.

1. Introduction

The film boiling of subcooled liquid is of grand practical importance for it is used in many branches of industry and power engineering. For example, this process allows cooling the external surface of PWR vessel during beyond-the-design basic accident, removing extreme heat flux with small temperature head for quenching and rapid cooling of metal; it can be used in electronics and computer cooling systems, for extinguishing fires, etc.

Film boiling of subcooled liquids has applied significance and causes fundamental interest. There is a great need of complete theory for this phenomenon, with analytical description and numerical investigation, based on the experimental data. Different researchers investigated this phenomenon for a long time. Various scientific groups in Russia tried to describe the subcooled water boiling (Yagov, V. [1], Zeigarnik, Yu. [2]). Those experiments used thermocouples and high-speed camera to determine the regime of boiling and heat flux per unit area. Heat flux per unit area and HTC were determined based on solving the inverse heat conduction problems or thermal balance according to thermometry data. Results are inaccurate because they used some predicates. Local values of heat flux cannot be calculated. Foreign researchers also used those methods. For example, Sher et al. [3] researched boiling at the spherical surfaces from aluminum, copper and steel. They founded a “golf-ball” boiling period at preheated spheres in subcooled water. Also, they discovered the dependence between quenching temperature and subcooling degree. Besides, Dogan [4] observed the influence at the spherical metal surfaces of nanofluids from alumina, titania, copper oxide. Gylys et al. [5] carried out the experimental investigation of the cooling process preheating steel, copper and aluminum spherical bodies in subcooled water.
The development and implementation of a new gradient heat flux measurement method allows us to determine local heat flux and calculate HTC according to indications of unique heterogeneous gradient heat flow sensors (HGHFS). They are successfully used in the study of convective heat transfer in a single-phase fluid [6], in steam condensation [7], in study of complex heat transfer in the combustion chamber of a diesel engine [8] and in a number of other applications. In our work gradient heat flux measurement data are supplemented with high-speed imagery frames. The pilot experiments of subcooled water boiling at the cylinder are described in [9].

2. Methods
Heterogeneous gradient heat flux sensors based on anisotropic thermoelements (figure 1), which were created, were tested and calibrated at Peter the Great St. Petersburg Polytechnic University [10].

Due to anisotropy of thermal and electric conductivity and thermoelectromotive force (thermo-EMF) there are the temperature gradients in two directions: along and across the heat flux vector (transverse Seebeck effect). This leads to appearance of thermo-EMF which is proportional to heat flux value.

![Figure 1. Scheme and principle of the work of the HGHFS.](image1.png)

The HGHFS signal is proportional to volt-watt sensitivity of HGHFS and its area. The three-wire circuit with chromel and two alumel wires is used to control the temperature of HGHFS because sensitivity depends on temperature. A radiation component contributes significantly to the total heat flux at a high temperature. The surface of HGHFS is a grey body; thus it is possible to determine integral HTC without separating it into components, when measuring the heat flux at film boiling.

A unique feature of HGHFS is their time constant, amounting to 1 ... 10 ns. This feature makes HGHFS virtually inertial measuring means for the most heat exchange problems. In the experimental setup, HGHFS made from the steel 12Cr18Ni10Ti + nickel. Calibration of sensor is described in [9]. The error of calibration is 7...12%.

![Figure 2. Experimental setup.](image2.png)
3. Experiment
The experimental setup consists of the vertical furnace, National Instruments (NI) with PXI-1303, high-speed camera Evercame 1000-4-C and water tank with a flat wall (figure 2).

The test sphere of brass L68 (68% of cooper) of 25-mm diameter was used. To mount the HGHFS, the groove (0.8 mm deep) was done by the milling machine. A special compound holds the sensor at the mica layer in the groove. Also at the surface near HGHFS the thermocouple (k-type) was installed (figure 3a). Wires were lead out through the sphere in the ceramic tubes.

The sphere was preheated up to 673 K and submerged in water (298 K). The temperature of water was practically constant during the experiment. Signals from HGHFS and thermocouples were recorded by NI and processed by Origin Pro. Experiment data supplemented frame from high-speed camera.

4. Result
The obtained experimental dependences are presented in figure 4. The results do not fly in the face of well-known data. The oxide film springs at the spherical surface and damages it (figure 3b). Moreover, the oxide film damages the compound, and HGHFS separates from the spherical surfaces. Further experiments will be carried out on the surface of more corrosion resistant material.

The negative heat flux per unit area is explained by separation of the oxide film, fixed by a high-speed camera. Further fluctuations of heat flux per unit area behind the cooling sphere are explained by separation of HGHFS from the sphere and staying in a water layer. However, the maximum of heat flux per unit area increases the critical heat flux for saturated water. Application of heat flux measurement to study film boiling of subcooled water opens up new possibilities, which are reduced to the following.

1. One can determinate integral value of heat flux per unit area for boiling, which includes both convective and radiant components.
2. Time constant of the HGHFS allows the record of heat flux pulsations. It is possible to determine the time of contact of liquid with hot surface. It may be helpful in experimental investigation of a wide range of phenomena associated with boiling on pattern surfaces, under the conditions of steam explosion, etc.
3. Synchronization of optical methods, thermometry and heat flux measurement in study of film boiling is implemented.
4. Implementation of high value of heat flux gives new possibilities in design of heat exchangers and power units at large.
5. Conclusion
The obtained original experimental data showed that gradient heat flux measurement using HGHFS yields right results. That is a promising method for studying film pool boiling of subcooled liquid. The experiments confirm the results of other scientific groups in this field, what gives the prospect for the development of gradient heat flux measurement.

The obtained pilot results will be used in the study of more complex and diverse cases of boiling of various liquids under different conditions of subcooling and geometry and material of surfaces.

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