Gradient heat flux measurement in study of condensation at inner surface of the tube

S Z Sapozhnikov 1, V Y Mityakov 1, A Y Babich 1 and E R Zainullina 1

1 Peter the Great St.Petersburg Polytechnic University (SPbPU) 
Russia, 195251, St. Petersburg, Politekhnicheskaya, 29

babich1994@mail.ru

Abstract. To study heat transfer during water steam condensation in the pipe, experiments were carried out with a steam supply from the top pipe edge with the gradient heatmetry. The results which allowed us to apply the new method for non-classical problem have shown compliance with literature data. When the pipe is inclined, the distribution of heat flux per unit area on the inner surface becomes asymmetric, that’s why it is necessary to measure local heat flux in some points there. The distribution of local heat transfer coefficients on the inner surface of the pipe at different angles of inclination is obtained. The heat flux decreases in the lower part of the pipe section, which corresponds to increasing of the condensate film thickness in this area.

1. Introduction
The presented paper is a continuation of the investigation described in the article [1]. In previous experiments, the applicability of gradient heat flux sensors (GHFSs) for heatmetry during condensation on the inner surface of the pipe was proved. For this purpose, classical and well-studied area of condensation on the inner surface of a vertical pipe was chosen. Many analytic models [2 – 5] and experimental data [6 – 8] allowed us to evaluate the advantages of GHFSs. One of them is their unique time constant, which allows to measure not only the average heat flux, but also its pulsations, and therefore the pulsations of the condensate film thickness.

Gradient heatmetry has already used in different spheres of heat and mass transfer [9,10].

2. Investigation method
Gradient heat flux sensors are artificial thermal elements with anisotropic structure (figure 1). The GHFS generate signal proportional to the heat flux due the anisotropy of thermal and electrophysical properties of the sensor [11].

The GHFS’ signal is:

\[ E = S_0 \cdot F \cdot q \]  

(1)

Here, \( E \) is the electromotive force, \( S_0 \) is the GHFS sensitivity, \( F \) is GHFS area, \( q \) is heat flux per unit area.
3. Experimental setup

In previous investigations were studied heat transfer during condensation inside the vertical pipe. That’s why the test tube was designed to stand in one position (figure 3) [1].

Heterogeneous gradient heat flux sensors (HGHFS) of steel+nickel composite were used in the experiments (figure 2). Their time constant was about $10^{-8}...10^{-9}$ s. Sensors were individually calibrated by the absolute method.
The results of investigation of heat transfer during steam condensation inside inclined pipes are presented now. For this purpose, the experimental setup was upgraded. Firstly, the test tube was attached to the rotating device with a dividing disk, which deflects the pipe at fixed angles $\psi$ of inclination to the horizontal. Secondly, since the distribution of the heat flux along the inner surface of the pipe is not symmetrical, the test tube was installed on another rotating device that allowed the pipe to rotate the pipe around its axis at fixed angles $\phi$ (figure 4). This allowed to use only one sensor and one thermocouple for measurement the heat flux and temperature along the inner perimeter of the pipe.

Four heterogeneous GHFS were installed at the measuring segments and soldered back into the pipe. A detailed description of the sensor installation is described in the article [1]. In addition to the measuring segments, thermocouples are installed on the outer surface of the pipe for the heat flux measurement by temperature difference. Also, thermocouples were installed at the inlet and outlet of the water supply to check the thermal balance of the setup.

4. Results and discussion

The experimental results are presented for inclination angles $\psi$ from 0 to 60 because when the angle is increased to 90 degrees, heat transfer coefficient (HTC) distribution became symmetrical. The results for the vertical pipe are described in the article [1]. All results are presented at a 4.4 g/s steam flow rate.

Figure 5. Relative local heat transfer coefficient along the inner diameter of the pipe.
The automatic data collection system collected readings from GHFSs and thermocouples and then calculated HTC at each point. Further, the HTC were related to the HTC at the top of the pipe. Figure 5 shows the relative HTC. The charts show HTC decrease at the bottom area of the pipe, where condensate flow down in this part, where heat transfer between steam and surface decreases.

Figure 6 shows the relative average heat fluxes for the pipe. The results show that maximal heat flux is achieved at the inclination angle of 30 degrees to horizontal, which corresponds with literature data [12].

![Figure 6. Relative average heat flux of the pipe.](image)

5. Conclusions
An experimental installation for the study of condensation using heterogeneous gradient heat flux sensors was developed, manufactured, tested, and used.

Local heat transfer coefficients in different sections of the pipe and for its different angles of inclination were measured in our experiments. The results show distribution of heat flux per unit area on the inner surface of the pipe. Relative graphs of distribution of heat transfer coefficients show presence of heat transfer decrease zone.

6. References
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