Gradient heat flux measurement in study of heat transfer for condensation of water vapour on pipes

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Abstract. Heat transfer during condensation of saturated water steam on the outer surface of a pipe has been investigated by the method of gradient heat flux measurement. Heat flux per unit area and heat transfer coefficients obtained for vertical, horizontal and inclined pipe are presented. The optimum angle of inclination of the pipe ($\psi = 30^\circ$) was experimentally determined. High informational content of gradient heat flux measurement has been revealed, which opens up new possibilities for studies of heat transfer during condensation.

1. Introduction
A great part of experiments on study of heat transfer in film condensation is performed by thermometry [1-3]. The advantages of this method include: simplicity of design and installation, accessibility; its disadvantages are invasiveness, persistence and high uncertainty when calculating heat transfer coefficients (HTCs). We have developed a new method for the study of heat transfer during film condensation, using gradient heat flux sensors (GHFSs).

2. Gradient heat flux measurement
Any GHFS is a battery of anisotropic thermoelements connected in series (figure 1, a). Its action is based on transverse Seebeck effect: when a heat flux passes through a plate with anisotropy of thermal and electrophysical properties, thermoEMF occurs with a vector of intensity normal to the heat flux one [1]. The signal of GHFS $E$ is associated with the heat flux per unit area $q$ passing through the section of the sensor, as

$$E = q \cdot F \cdot S_0,$$

where $F$ is GHFS area, $S_0$ is volt-watt sensitivity of GHFS.

In study of heat transfer during film condensation of saturated water steam on the outer surface of the pipe, we used GHFSs made of single-crystal bismuth with dimensions of 10.5×3×0.3 mm (figure 1). Volt-watt sensitivity of these GHFSs is $S_0 = 0.32$ mV / W; this value is practically temperature independent [4].

3. Experimental setup
The experimental section (figure 2, a) consists of two coaxial pipes: the inner one is made of stainless steel ($d = 0.02$ m, $\delta = 2$ mm), the outer (casing) is made of a reinforced rubber sleeve ($d = 0.065$ m,
$\delta = 5\text{ mm})$. The inner pipe is fixed in the casing with the help of two rubber stoppers; through the upper one the wires from the GHFSs and thermocouples are pulled out.

**Figure 1.** GHFS: scheme (a) and photo of its installation on the pipe (b):
1 – anisotropic thermoelement, 2 – soldering joint, 3 – wires, 4 – dacron spacer.

**Figure 2.** Experimental section without a casing (a) and general view of the setup (b):
1 – GHFS; 2 – rods; 3 – rubber stopper; 4 – tilt device; 5 – rotation device.
In three sections along the length of the pipe, removed at 400, 600 and 800 mm from the upper end of the working part, the GHFSs and semi-artificial thermocouples are installed at the same generatrix. The use of semi-artificial thermocouples allows us to reduce the number of wires, since hot junctions represent the contacts of the copper wires and the pipe surface, and the mutual cold one represents the contact of the copper wire with the pipe material (steel) located at air media with ambient temperature. The gradient heat flux sensors and thermocouples are mounted in 0.32 mm depth dimples flush with the outer surface of the pipe. In study of film condensation, it is important to keep the surface of the pipe free from any measuring tools and wires. To do this, at a distance of 7 mm two rods with a dia of 3 mm are passed along the pipe, to which the wires from the GHFSs and thermocouples are diverted (figure 2, a).

The experiments were carried out with a countercurrent: saturated water steam with a temperature close to 100°C was fed into the annular space from above, and cooling water with a temperature of 22 °C was fed into the pipe from below. The condensate was discharged through the hole in the lower stopper.

The possibility of tilting the experimental section from vertical at an angle $\psi = 0 – 90^\circ$ and turning it at an angle $\varphi = 0 – 180^\circ$ made it possible to study heat transfer in vertical, horizontal and inclined pipe positions (figure 2, b).

In our experiments, the GHFSs generate microvolt-level signals, which make it difficult to use modern digital converters. The measuring instrument based on a light-beam oscilloscope for recording the signal of the GHFSs has been developed. The light sources were replaced by laser modules, the rays of which were directed to the mirrors of galvanometers. Reflected rays were projected onto a remote scale. The modified unit made it possible to record signals of GHFSs without electromagnetic noise and to increase measurement accuracy due to the far remote long scale.

4. The results

Figure 3 shows the dependence of heat flux per unit area on time, obtained by condensation of steam on a vertical pipe. Pulsations of the heat flux on the curves can be attributed to the flow of rivulets and wave formation on the film surface.

![Graph](image)

**Figure 3.** The dependence of heat flux per unit area on time for a vertical pipe.

As result, the average over the length of a vertical pipe HTC was of 6.06 kW / (m$^2$ · K), which is very close to the calculated according to W. Nusselt formula value, equal to 6.1 kW / (m$^2$ · K).
When the pipe is inclined from the vertical, condensation is not axisymmetric. It is necessary to investigate distribution of heat flux per unit area along the perimeter of the pipe. In figure 4, the local heat flux per unit area, measured when the pipe is rotated by the azimuth angle $\phi$, is related to the value of this parameter on the upper generatrix, where $\phi = 0^\circ$.

![Figure 4. Dimensionless heat flux per unit area.](image)

Figure 5 shows dimensionless heat flux per unit area for condensation on a horizontal pipe averaged over indications of all GHFSs. The decrease in heat flux is observed in the range of $\phi = 120 - 240^\circ$, where the condensate film forms a bottom zone [5].

![Figure 5. The dependence of dimensionless heat flux per unit area on azimuth angle for condensation on a horizontal pipe.](image)

Heat transfer during condensation on an inclined pipe was investigated at angles $\psi = 0 - 90^\circ$ with a step of $10^\circ$. The dependence of HTC on the angle of inclination is shown in figure 6. At $\psi = 30^\circ$, the average HTC is maximum and exceeds the average value obtained on a vertical pipe by 12.6%.

The relative uncertainty of measured heat flux per unit area, calculated according to ISO / IEC Guide 98-1: 2009, does not exceed 9%, and for HTC it does not exceed 12%.
5. Conclusion
Applicability of gradient heat flux measurement in study of heat transfer during condensation on differently oriented pipes is confirmed. Combination of gradient heat flux measurement and thermometry reduces uncertainty in calculation of HTC. Received data are helpful for optimizing the heat exchangers: information about location of the bottom zone will determine the best places for intensifiers.

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