Searching of the optimum tilt of the pipe at condensation by using gradient heatmetry

S Z Sapozhnikov, V Yu Mityakov, A V Mityakov, A Yu Babich, E R Zainullina and A V Pavlov
Peter the Great St. Petersburg Polytechnic University, Russia, 195251 St. Petersburg, Politeknicheskaya, 29
zaynullinaelza@gmail.com

Abstract. The aim of the study is to determine optimum tilt of the pipe at film condensation by using gradient heatmetry. Dependence of heat flux per unit area on time and azimuthal angle are presented for vertical, horizontal and inclined pipe. Maximal heat transfer coefficients for experimental conditions are observed for the angle 20° from vertical. The gradient heatmetry gives high informational content, which opens up new possibilities for studies of heat transfer during condensation.

1. Introduction
The study of film condensation is important for many branches of industry. Reliable information about distributions of heat flux per unit area, heat transfer coefficient (HTC) and character of the condensate film flow must help to improve heat exchangers and increase their efficiency. It is impossible to use surface intensifiers in some types of heat exchangers due to their design features. Analysis of literature shows that in some studies, condensation heat transfer enhancement was achieved by inclination of the single tube [1 – 2] or tube bundle [3]. Nowadays thermometry is the most used method of experimental investigations in this field. Thermocouples and resistance thermometers confirmed the temperature variation at the surface of these tubes. Therefore, heat flux and the HTC values are determined by calculation. Pulsations of heat flux cannot be detected by thermocouples because of their inertia.

In this work, heat flux during film condensation on the outer surface of an inclined pipe was studied by gradient heatmetry [4]. The aim of experiments was to find out by gradient heat flux sensors (GHFS) dependence of the HTCs on the angle of the pipe inclination.

2. Experiment technique
2.1. Gradient heatmetry and thermometry
Action of GHFS is based on transverse Seebeck effect (figure 1, a): when a heat flux passes through media with anisotropy of thermal and electrophysical properties, thermoEMF occurs with vector of intensity normal to the heat flux one [4].

The signal of GHFS $E$ is associated with the heat flux per unit area $q$, W/m², passing through the section of the sensor, as

$$E = q \cdot F \cdot S_0, \text{ mV},$$

where $F$ – GHFS' area, m²,
$S_0$ – volt-watt sensitivity of GHFS, mV/W.
Members of the scientific group of Science Education Centre «Energy Thermophysics» create and produce GHFSs from natural anisotropic materials (primarily from single-crystal bismuth), and from cross-fibred composites with artificial anisotropy as well. Composite GHFSs are known as heterogeneous gradient heat flux sensors (HGHFSs) [4].

In previous experiments [5], the condensation heat flux per unit area was measured by HGHFS from nickel + stainless steel composition. The large width of the HGHFS (10 mm) and their insufficient volt-watt sensitivity forced us to use GHFS from single-crystal bismuth, which are successfully used in studies of convective heat transfer [6]. In our new setup, 5 GHFS with dimensions of $2.3 \times 10.5$ mm and a thickness of 0.3 mm were installed flush with the surface on the pipe (figure 1, b).

![Diagram](image1.png)

**Figure 1.** GHFS: scheme (a) and photo of its installation on the pipe (b): 1 – anisotropic thermoelement, 2 – mica paper, 3 – soldering joint, 4 – wires, 5 – dacron spacer.

To determine HTCs it is necessary to know the wall temperature at the place of the sensors installation. The GHFSs and semi-artificial thermocouples are installed at the same generatrix. Use of semi-artificial thermocouples allows 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. GHFSs and thermocouples are mounted in 0.32 mm depth dimples flush with the outer surface of the pipe.

2.2. Experimental setup

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

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 diameter of 3 mm are passed along the pipe, to which wires from GHFSs and thermocouples are diverted (figure 2, c).

The experiments were carried out with a countercurrent: saturated water steam with temperature close to 100 °C and feed rate of 10 kg/h was fed into the annular space from above, and cooling water with temperature of 22 °C and consumption of 200 ml/s was fed into the pipe from below. The condensate was discharged through the holes in the lower stopper.

The experimental setup was equipped with devices for tilting ($\psi = 0…90^\circ$) and rotating around its own axis ($\phi = 0…180^\circ$) of this construction (figure 3) made it possible to study heat transfer in vertical, horizontal and inclined pipe positions.
Figure 2. Experimental section: construction (a); the upper rubber stopper (b); guide rods (c).

Figure 3. Experimental setup: rotation (1) and tilt (2) devices.
In our experiments, GHFSs generate microvolt-level signals, which make it difficult to use modern digital converters. For recording the signal of the GHFSs the measuring instrument based on a light-beam oscilloscope (figure 4) 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.

3. The results

3.1. Vertical pipe
Figure 5 shows the dependence of heat flux per unit area on time (heatgram), obtained by condensation of water steam on a vertical pipe. The signals of three sensors are presented: GHFS №2 ($x = 300$ mm – distance from the upper cut of pipe), GHFS №4 ($x = 700$ mm) and GHFS №5 ($x = 800$ mm).

Heatgram confirms the instability of heat transfer on the outer surface of the vertical pipe. All GHFSs detected pulsations of heat flux. The pulsations intensify with distance from the upper cut of the pipe.
the experimental section, it is noticeable by comparing the signals of GHFS №2 and GHFS №4. Most part of steam condenses at the upper end of the pipe, therefore, GHFS №5 detects the lack of a condensate film, it corresponds to sections of the heatgram with constant heat flux per unit area.

As result, the average over the length of a vertical pipe heat flux per unit area was of $\overline{q}_{\text{vert}} = 133.4$ kW / m$^2$, wall temperature of $T_{\text{vert}} = 78$ °C. The average over the length of a vertical pipe HTC was of $\overline{\alpha}_{\text{vert}} = 6.06$ kW / (m$^2$ · K), which is close to the calculated according to W. Nusselt formula value, equal to 6.1 kW / (m$^2$ · K).

3.2. Horizontal pipe
When the pipe is inclined from 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 6, the local heat flux per unit area, measured when the pipe is rotated by the azimuth angle of $\varphi = \psi$, is related to the value of $q(0)$ on the upper generatrix, where $\varphi = 0$ °. Dimensionless local heat flux per unit area is determined as

$$\tilde{q} = q(\varphi)/q(0).$$

![Figure 6](image)

Figure 6. The dependence of dimensionless heat flux per unit area on azimuth angle for condensation on a horizontal pipe.

The decrease in heat flux is observed in the range of $\varphi = 120 − 240$ °, where condensate film forms a bottom zone. HTC averaged over the surface of the horizontal pipe was of $\overline{\alpha}_{\text{hor}} = 5.54$ kW / (m$^2$ · K), the result differs from the calculated according to W. Nusselt formula value, equal to 9.81 kW / (m$^2$ · K). This difference may be explained by the experimental conditions: saturated water steam completely condensed on the pipe, the distribution of the condensate film and temperatures along the length of the horizontal pipe were not uniform. The study of condensation heat transfer on a horizontal pipe requires additional research at high steam flow rates.

3.3. Inclined pipe
The study of heat transfer on an inclined pipe requires information on the distribution of heat flux around the perimeter of the pipe. The tilt of the pipe varied in the range of $\psi = 0..90$ °. The dependence of dimensionless heat flux per unit area on azimuth angle are constructed for three
sections according to signals from GHFS №2, GHFS №4 and GHFS №5. The angular distribution of the heat flux per unit area presented in a dimensionless form.

Figure 7 shows the dependence of dimensionless heat flux per unit area on azimuth angle when the pipe is tilted at angles of $\psi = 30, 60, 80^\circ$ from the vertical.

![Graph](image)

**Figure 7.** The dependence of dimensionless heat flux per unit area on azimuth angle for condensation on an inclined pipe: (a) $\psi = 30^\circ$; (b) $\psi = 60^\circ$; (c) $\psi = 80^\circ$.

GHFS readings provide information about the bottom zone, which character depends on the angle of inclination. Heat transfer during condensation on an inclined pipe was investigated at angles of $\psi = 0 – 90^\circ$ with a step of 10°. Dependence of HTC on the angle of inclination is shown in figure 8. At $\psi = 20^\circ$, the average HTC is maximal and exceeds the average value obtained on a vertical pipe by 14.9%.

![Graph](image)

**Figure 8.** Average HTC for the inclined pipe.
The relative uncertainty of measured heat flux per unit area, calculated according to ISO / IEC Guide 98-1: 2009, does not exceed of 7.5%, and for HTC it does not exceed of 8.4%.

4. Conclusion

Application of gradient heatmetry to study of condensation made it possible to measure heat flux per unit area on vertical, horizontal and inclined pipe. Combination of gradient heatmetry with thermometry provided the determination of HTCs. Use of GHFSs provides new priority information. As a result, optimum tilt of the pipe at condensation ($\psi = 20^\circ$) was determined under experimental conditions. The results must be confirmed with other operational parameters.

5. References

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