The study of heat transfer during condensation on inclined pipes by gradient heatmetry

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Abstract. The paper presents results of studying of heat transfer during condensation on the outer surface of inclined pipe by using gradient heatmetry. The proposed approach made it possible to estimate distribution of local heat flux per unit area in several sections along the pipe’s length. Combination of gradient heatmetry and thermometry allows us to show dependence of heat transfer coefficient from the angle of pipe inclination. Under experimental conditions the maximal average heat transfer coefficient, \( \alpha = 6.94 \text{ kW/} (\text{m}^2 \cdot \text{K}) \), was observed when the pipe was tilted at the angle of \( \psi = 20^\circ \) from vertical. The relative uncertainty of measured heat flux per unit area was of 7.5 %, and for heat transfer coefficient it does not exceed the level of 8.4%. The use of gradient heatmetry in this study provides us information about films thickness distribution over the pipe surface without optical visualization, which is especially important in experiments at industrial heat exchangers.

1. Introduction
Analysis of the literature revealed several experimental studies of heat transfer during condensation on the outer surface of an inclined pipe [1-4]. In these works, heat flux per unit area and heat transfer coefficients (HTC) were calculated from thermocouples readings, this approach increased the uncertainty of experiments. Direct measurement of heat flux per unit area by using heat flux sensors (HFS) increases accuracy and information content of experiments. In study of heat transfer during condensation inside an inclined pipe by using HFS of Omega Company dependence of HTC from pipe inclination was obtained [5]. The relative uncertainty of HTC was estimated by authors as ±8%. But the large size of these HFSs (28.5 mm × 35.1 mm) and small inner diameter of the pipe (\( d = 4.8 \text{ mm} \)) do not allow us to consider measurements and calculations as local ones.

The research group of Science Education Centre «Energy Thermophysics» of SPbPU previously conducted research of heat transfer during film condensation on a vertical pipe by using gradient heat flux sensors (GHFSs) [6]. GHFSs have confirmed their applicability to condensation studies and high information content. The purpose of this study is to apply GHFS to investigation of heat transfer during condensation on the outer surface of inclined pipe.

2. Experiment technique

2.1. Measuring technique
Heat flux per unit area during condensation was measured by gradient heatmetry method [7] developed at Science Education Centre «Energy Thermophysics» SPbPU. Our experiments were carried out by using GHFSs from single-crystal bismuth. The size of GHFSs (figure 1) were as
following: width – 2.3 mm, length – 10.5 mm, thickness – 0.3 mm. Volt-watt sensitivity of these GHFSs were about 1.3 mV/W in temperature range of 70…100°C.

Determination of local HTCs requires temperature measurement at the GHFSs location. To reduce the number of wires, temperature was measured by using semi-artificial thermocouples [8], which are widely used in thermophysics of metalwork. Sensitivity of these thermocouples at a temperature difference between their cold and hot junction of 100 °C was about 0.3 mV / °C.

2.2. Experimental setup
The experimental section of our setup consists of two coaxial pipes (figure 2): the inner one is made of stainless steel ($d_{in} = 0.02$ m, $\delta_{in} = 2$ mm), the outer one (casing) is made of reinforced rubber ($d_{out} = 0.065$ m, $\delta_{out} = 5$ mm).

**Figure 1.** Photo of GHFSs installation on the pipe surface.

**Figure 2.** Scheme and sizes of experimental section.
The inner tube is fixed in the casing with rubber plugs. The experiments were carried out with a counterflow: 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 inner pipe from below. Along the length of the stainless steel pipe, 5 pairs of GHFSs and semi-artificial thermocouples were installed flush (figure 3) with the pipe surface on the same generatrix.

The test bench allows to tilt the measuring section in the range of $\psi = 0 \ldots 90^\circ$ from vertical and to turn it around its axis in the range of $\phi = 0 \ldots 180^\circ$.

3. The results

Detailed results of gradient heatmetry application to the study of heat transfer during condensation on a vertical pipe can be found in the forthcoming articles [9-10]. We only point out that the average heat flux per unit area was of 133.4 kW/m², and the average HTC was of 6.06 kW/(m² · K), which is close to the calculated according to W. Nusselt formula value, equal to 6.1 kW / (m² · K).

When condensation occurs on an inclined pipe, the condensate film flow can be conditionally divided into the main and bottom zones [11]. The study requires measuring (with GHFSs) of heat flux per unit area over the entire surface of the pipe in the range of azimuthal angle of $\phi = 0 \ldots 180^\circ$ with a step of 15°.

Figure 3 shows the distribution of heat flux per unit area according to the signals from GHFS №2, №4 and №5. The results are presented in dimensionless form for pipe inclinations of $\psi = 40$, 60 and 80° from vertical. Dimensionless local heat flux per unit area

$$\tilde{q} = q(\phi)/q(0),$$

where $q(\phi)$ – local heat flux per unit area, measured when the pipe is rotated at the azimuth angle of $\phi$; $q(0)$ – local heat flux per unit area on the upper generatrix, where $\phi = 0^\circ$.

![Figure 3](image)

**Figure 3.** Dependence of dimensionless heat flux per unit area on azimuth angle for condensation on an inclined pipe for: (a) $\psi = 30^\circ$; (b) $\psi = 70^\circ$; (c) $\psi = 80^\circ$.

The signals from the GHFSs can be used to determine the distribution of the condensate film thickness over the outer surface of an inclined pipe. The experimental results show that for a pipe
inclined at $\psi = 80^\circ$ (figure 3, c), condensate accumulates in the lower sector of the pipe in the area of $\varphi = 150\ldots210^\circ$ and it is most effective to install surface intensifiers in this area.

Combination of gradient heatmetry and thermometry made it possible to estimate distribution of local HTC. Figure 4 shows the distribution of the dimensionless local HTC over the pipe inclined at $\psi = 20, 50$ and 70°.

**Figure 4.** Dependence of dimensionless HTC on azimuth angle for condensation on an inclined pipe for: (a) $\psi = 20^\circ$; (b) $\psi = 50^\circ$; (c) $\psi = 70^\circ$.

**Figure 5.** Average HTC for the inclined pipe.

Dimensionless local HTC is determined as

$$\tilde{\alpha} = \alpha(\varphi)/\alpha(0),$$

(2)
where $\alpha(\varphi)$ – local heat flux per unit area, measured when the pipe is rotated by the azimuth angle of $\varphi$; $\alpha(0)$ – local heat flux per unit area on the upper generatrix, where $\varphi = 0^\circ$.

Heat transfer during condensation on an inclined pipe was investigated at angles of $\psi = 0^\circ$ – $90^\circ$ with a step of 10°. Dependence of HTC on the angle of inclination is shown in figure 5. For $\psi = 20^\circ$, the average HTC is maximal and exceeds the average value obtained on vertical pipe by 14.9%.

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
The use of GHFSs in study of heat transfer during condensation on an inclined pipe made it possible to estimate the distribution of heat flux per unit area and to identify the area of condensate accumulation. Combination of capabilities of gradient heatmetry and thermometry provided information about the optimal pipe inclination of $\psi = 20^\circ$. Experimental results show that heat transfer during condensation can be intensified by pipe tilting. The intensification is associated with the restructuring of the flow of condensate film. It is necessary to carry out a series of experiments with other operating parameters to confirm the assumption.

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