Heat transfer enhancement during condensation of water steam on inclined pipe

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Abstract. This paper presents experimental study of heat transfer during film condensation of saturated water steam on the outer surface of the inclined pipe by gradient heatmetry. Heat flux per unit area was measured by gradient heat flux sensors made of a single-crystal bismuth. The experimental results are presented in the graphs of heat flux per unit area dependence on time and azimuthal angle. The highest average heat transfer coefficient during condensation of α = 6.94 kW/(m² · K) was observed when the pipe was inclined at the angle of ψ = 20 °. This value exceeds one obtained on a vertical pipe by 14.9 %. Heat transfer enhancement during condensation of saturated water steam on inclined pipe is associated with changes in condensate film flow. Another part of experiments was made by simultaneously using of gradient heatmetry and condensate flow visualization. Experimental results confirmed the applicability and high informative content of proposed comprehensive method. Comprehensive study of heat transfer during condensation confirmed that heat flux per unit area pulsations may be explained by the formation of individual drops, their coalescence, and drainage from the sensor surface.

1. Introduction
The most common methods of heat transfer enhancement during condensation of water steam are associated with surface development. Ribbing or irradiation of the surface complicate the design of heat exchanger and increase its cost. One of the simplest and underestimated ways to increase heat transfer coefficient (HTC) during film condensation of saturated water steam is pipe inclination.

On the inclined pipe the condensate film flow breaks up into two zones [1]: the main one and the bottom, which is developed in the lower sector of the pipe. Change in the condensate film thickness occurs both along the length and the circumference of the pipe (figure 1). Because of condensate flow redistribution over the surface, it is necessary to install sensors around the circumference and along the length of the pipe. But installation of many invasive measuring devices is unacceptable due to the distortion of natural flow of condensate film.

Surface-averaged measurements [2] allow to determine the optimal angle of pipe inclination with minimal distortion during the condensate flow, but it turns out to be undescriptive. The use of non-invasive optical research methods [3] makes it possible to obtain information about condensate flow distribution over the pipe surface, but turns out to be inapplicable for industrial experiments.

T. Garrett [4] applied optimal sensors’ mounting method. Thermocouples were installed at the same pipe generatrix, and experimental setup could be inclined and rotated around its own axis.
Since 2015, in Science Education Centre «Energy Thermophysics» of Peter the Great St. Petersburg Polytechnic University, heat transfer during saturated water steam condensation has been studied by gradient heatmetry [5]. Gradient heatmetry is innovative technology based on use of gradient heat flux sensors (GHFSs). GHFS action is based on transverse Seebeck effect: when heat flux passes through a plate with anisotropy of thermal and electrophysical properties, thermoemf occurs with vector of intensity normal to heat flux one [5]. Signal of GHFS $E$ is associated with 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, and $S_0$ is its volt-watt sensitivity.

Gradient heatmetry allows to measure local heat flux per unit area, to calculate local HTCs and to estimate the condensate film flow distribution over heat exchange surface. The main purpose of this study is to assess heat transfer enhancement during saturated water steam condensation on inclined pipe by gradient heatmetry.

2. Gradient heatmetry in study of heat transfer during condensation on inclined pipes

The previous works [6, 7] have confirmed applicability of gradient heatmetry to study of heat transfer during condensation. Capabilities of heatmetry and thermometry were successfully combined to calculate local HTCs.

Experimental setup consists of two coaxial pipes (figure 2, a). The inner one made of stainless steel ($d = 20$ mm, $\delta = 2$ mm, $l = 1000$ mm) is fixed with rubber plugs in the outer (casing) one which is made of reinforced rubber sleeve ($d = 0.065$ m, $\delta = 5$ mm). During the experiments, saturated water steam was fed into annular space from above at atmospheric pressure; its flow rate was of $2.8$ g / s. Cooling water with temperature of $t = 20$ °C and flow rate of $200$ ml / s entered in to the inner pipe. Condensate was discharged into the condensate trap.

5 GHFSs made of single-crystal bismuth with dimensions of $10.5 \times 2.5 \times 0.3$ mm were installed at the same generatrix of the pipe, flush with the outer surface of it (figure 2, b). Surface temperature was controlled by 5 semi-artificial thermocouples made of a stainless steel + copper composition. The measuring section was equipped with devices for inclination in the range of $\psi = 0 \ldots 90$ ° with a step of $10$ ° and rotation in the range of an azimuthal angle of $\phi = 0 \ldots 180$ ° with a step of $15$ °. This design of the setup allows to minimize distortions in condensate film flow.

Figure 3, a, as an example, shows the time heatgram – the dependence of heat flux per unit area on time – when the measuring section is inclined by the angle of $\psi = 20$ ° and rotated by an azimuthal angle of $\phi = 180$ ° (all GHFSs are located on the lower generatrix of the pipe). All sensors register heat flux pulsations, which confirms heat transfer nonstationarity during condensation.
Figure 2. Experimental section: scheme (a) and photo of GHFS installation on the pipe (b).

Figure 3. Experimental results on the pipe inclined at the angle of \( \psi = 20^\circ \): time (a) and angular (b) heatgrams.
According to the signal of GHFS №2 at the distance of \( x = 300 \) mm from the upper cut of the pipe, average heat flux per unit area is of 130 kW / m\(^2\), its pulsations are of 10% of average signal. At the distance of \( x = 700 \) mm, GHFS № 4 registers decreasing of average heat flux per unit area up to 120 kW / m\(^2\) and increasing of pulsation amplitudes up to 35% of the average level. Signal of GHFS № 5 installed at the distance of \( x = 800 \) mm corresponds to average heat flux per unit area of 76 kW / m\(^2\) while pulsations are of 22% of the average level. Large amplitude of heat flux pulsations can be associated either with formation of waves on the condensate film, or with runoff of rivulets or separate condensate drops.

Summarizing of experimental results of our study is carried out in polar coordinates. Figure 3, b, shows distribution of dimensionless local heat flux per unit area: its value measured when the pipe is rotated by the azimuth angle of \( \varphi \), is related to heat flux on the upper generatrix, where \( \varphi = 0 \) °. The signals from GHFSs №4 and №5 indicate an increasing of heat flux per unit area in lower sector in the range of an azimuthal angle of \( \varphi = 150 – 210 \) °. Heat transfer enhancement in the lower sector is associated with changes in condensate film flow.

Temperature measurement at the place of sensor installation allows to calculate local HTCs. Figure 4 shows the dependence of average HTCs on the angle of pipe inclination. Average HTC increases when the pipe is inclined by an angle of \( \psi = 10 \ldots 40 \) °. At \( \psi = 20 \) °, the average HTC is maximal (\( \alpha = 6.94 \text{kW/m} \cdot \text{K} \)) and exceeds the value obtained on a vertical pipe by 14.9%.

![Figure 4. Average HTC for the inclined pipe.](image)

To assess heat transfer enhancement during condensation on inclined pipes, it is necessary to determine the reason for occurrence of heat flux pulsations. Therefore, it is necessary to combine gradient heatmetry with condensate film flow visualization.

3. **Simultaneous using of gradient heatmetry and film flow visualization**

The first experimental series on combining of gradient heatmetry and film flow visualization was performed on the model of a cooled vertical plate. The model is a box-shaped structure with fittings for supplying and removing of cooling water with temperature of \( t = 24 \) °C and flow rate of 40 ml / s. The heterogeneous gradient heat flux sensor (HGHFS) made of a copper + nickel composition with dimensions of \( 10 \times 15 \times 0.2 \) mm was installed on the plate surface (figure 5). The experimental set up was an "open system": steam was supplied from the steam generator from below to a plate installed vertically, therefore, in these experiments flow rates of steam and condensate were not measured.

Figure 6 shows the time heatgram and photographs during saturated water steam condensation on the vertical plate. The photographs confirm that condensate drops are formed on the surface of the HGHFS, as well as on the plate surface. Visualization of the condensation revealed that at low
condensate flow rate, a continuous condensate film does not form. In this case, the HGHFS registers pulsations associated with formation and drainage of condensate drops.

\[ F_{\text{plate}} = 7.54 \cdot 10^{-3} \text{ m}^2 \]

\[ F_{\text{HGHFS}} = 0.15 \cdot 10^{-3} \text{ m}^2 \]

**Figure 5.** Experimental section scheme for combining gradient heatmetry and flow visualization.

**Figure 6.** Time heatgram for condensation of saturated water vapor on a vertical plate.

The average heat flux per unit area was of 12.5 kW / m$^2$ with formation of condensate droplets on the surface of the HGHFS; after the condensate draining from the surface, the value increased up to
18 kW/m². After the condensate drains off, the process of condensate formation is repeated, and heat flux per unit area decreases up to 15.5 kW/m².

To create the effect of dripping condensate, in addition to supplying steam from the bottom, separate water drops with a temperature of about $t = 70$ °C are supplied to the HGHFS surface through the injector (figure 7).

![Figure 7. Time heatmap for condensation of saturated water vapor on a vertical plate.](image)

When water is supplied through the injector, the condensate film forms on the surface of the HGHFS, which indicates the film condensation flow at high condensate flow rate. The HGHFS registers increase of heat flux per unit area up to 45 ... 55 kW/m² when heated drops are supplied, and a reverse decrease up to 10 ... 20 kW/m² when the surface is released from them.

4. Conclusion

Experimental study of heat transfer during condensation on the outer surface of inclined pipe have shown that HTC is intensified on pipe inclined at angle of $\psi = 10 ... 40$ °. At $\psi = 20$ °, the average HTC has maximum of $\alpha = 6.94$ kW/m²·°C and exceeds its average value for vertical pipe by 14.9 %. Series of experiments was performed to combine gradient heatmetry and visualization of condensate film flow on a vertical plate. It was revealed that HGHFS registers formation of condensate drops on all the surface, their coalescence and runoff. Experiments carried out with an artificial supply of water have confirmed that the HGHFS registers condensate drops flowing down from above.

References

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