Gradient heat flux measurement in condensation study at inner and outer surfaces of the pipe

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Gradient heat flux measurement in condensation study at inner and outer surfaces of the pipe

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Abstract. Gradient heat flux measurement is used in study of heat transfer during condensation of water steam at inner and outer surfaces of the pipe. Experimental setups allow producing experiments with minimal distortion of condensate film flow. Experiments were carried out for different directions of steam and cooling water and for different angles of pipe inclination relative to the vertical. Heat transfer coefficients and their change along the length and perimeter of the pipe were measured. The obtained data allow studying formation of the condensate film and parameters of film motion. The results of these experiments correspond to classical ideas.

1. Introduction
Information about heat transfer during condensation is necessary for the calculation of heat exchangers at nuclear and thermal power plants. Routine method of experimental study is based on thermometry. Our review of papers has confirmed the popularity of this method and revealed its significant drawbacks, such as invasiveness, persistence, the necessity for precision installation of thermojunctions, and significant uncertainty of the results. Our group offers unique approach for study of heat transfer during the condensation, namely gradient heat flux measurement which is based on using gradient heat flux sensors (GHFS) [1].

2. Gradient heat flux sensors
GHFS is an artificial thermal element with anisotropic structure. The operation principle of GHFS is based on transverse Seebeck effect, which comes out of the anisotropy of thermal and electrophysical properties of matter.

Gradient heat flux measurement allows determining heat flux value "in direct way", which significantly reduces uncertainty of experiment at large. The GHFS’s indications are proportional to heat flux per unit area:

\[ E = S_0 \cdot F \cdot q \]  (1)

Here, \( E \) is the electromotive force, \( S_0 \) is the GHFS sensitivity, \( F \) is GHFS area, \( q \) is heat flux per unit area.
So called heterogeneous gradient heat flux sensors (HGHFS) of steel+nickel composite were used. Their sizes were of $10 \times 10 \times 0.2$ mm, and their time constant was of $10^{-8}...10^{-9}$ s. Individual calibration of all sensors by absolute method was carried out.

3. Condensation at inner surface

The main task in the experimental setup design was to reduce distortion of condensate film flow. Four segments along the length of the pipe were cut off by an electrospark machine (figure 1, a) and then installed back flush with the inner surface of the pipe (figure 1, b). Wires and thermocouples were pulled through the special holes.

Due to the low electrospark cut thickness, the inner surface has no gaps. The pipe with installed segments was placed in a plastic cover and fastened by two rubber plugs. All the wires were removed through the upper rubber plug that ensured the tightness of the installation. HGHFS were located at distances of 300, 500, 700 and 900 mm from the upper edge of the pipe. The overall view of the experimental setup is shown at figure 1, c.

Pilot experiments were produced when steam was supplied from the upper edge of the pipe. The time dependence of heat flux per unit area is shown in figure 2, a. The heat flux value increases along the length of the pipe, which does not correspond to the Nusselt model. This occurs because of water was supplied from the bottom and heated while moving up. Observed pulsations of heat flux near the third and fourth HGHFS were due to waviness of the condensate film [2].

The following experiments were carried out at steam supply from the bottom. Regime of reflux condensation occurs at the maximal power of the steam generator equal to 12 kW. During reflux condensation phenomena, one part of condensate film was running down the wall, while another part was driven upward by the steam flow (figure 2, b).
Figure 2. Heat flux diagram during steam supply from above (a) and from the bottom (b).

Figure 3. Heat flux diagram during steam supply from the bottom. Steam generator power is (a) 7 kW, (b) 5 kW.

The water plug occurs in the pipe when the power of the steam generator was reduced to 7 kW (figure 3, a). In figure 3, it is seen that the heat flux at the upper HGHFS is equal to zero, because water plug blocks the steam flow. When the plug is moving up, all sensors react one by one, which confirms their high performance. Reflux condensation regime occurs after ejection of the plug.

While reducing the power of the steam generator down to 5 kW, water plug stops moving upwards but it falls down under the action of gravity, which is shown at figure 4, b. The heat flux at the upper HGHFS was equal to zero throughout the entire experiment. The frequency of pulsations of heat flux at the third and fourth HGHFS was revealed. The plug fluctuated with a frequency of about 0.1 Hz.

4. Condensation at the outside surface
The experimental setup consists of two coaxially arranged pipes (figure 4). The inner one is made of stainless steel ($d = 0.025$ m, $\delta = 2.5$ mm), the outer one is made of rubber reinforced hose ($d = 0.065$ m).

The slope of the pipe was carried out by rotation of two separating discs within the range of $\psi = 0 \ldots 90^\circ$ (figure 4). Rotation of the experimental section relative to the pipe axis by an angle from 0 to 180° was provided for estimation of heat flux per unit area along the pipe perimeter.
Steam with a pressure close to atmospheric one and temperature of about 100 °C was fed from the steam generator with power of 12 kW into the annular gap between the pipes from the top. The cooling water was fed into the inner pipe from the bottom. Condensate was formed at the outer surface of the inner pipe and then discharged into the condensate collector.

HGHFS were installed in the prepared places flush with the outside surface of the pipe to reduce distortion in condensate flow. Three-wire circuit were used, which allows measuring heat flux and sensor’s temperature simultaneously. Four HGHFS were placed at the same generatrix of the pipe outer surface. Four thermocouples of T type were installed diametrically opposite to the HGHFS.

The upper HGHFS signals were not considered because they were out of order. The angular graph was based on the readings of three other sensors. The heat flux per unit area was represented in dimensionless form. The pipe rotates relative to its axis at an angle of $\phi$, which is counted off from the upper point. The dimensionless heat flux was calculated respectively by the heat flux at the angle of $\phi = 0^\circ$:

$$
\tilde{q} = \frac{q_\phi}{q_0}. \tag{2}
$$

For instance, in figure 5, a the angular graph of variation in dimensionless heat flux is shown when the pipe is tilting at an angle of 30° to the vertical. Experimental points were obtained by averaging of the readings.

Similar experiments were made in study of heat transfer from a horizontal pipe. Figure 5, b shows the distribution of heat flux along the perimeter of the horizontal pipe. The average heat flux in all three sections is almost the same.
Figure 5. Variation in dimensionless heat flux with respect to angle: (a) the inclination angle of $30^\circ$, (b) horizontal pipe.

Figure 6. Variation in dimensionless heat flux with respect to angle $\psi$.

The inclination angle relative to the vertical with the maximal average heat flux along the pipe was found. The heat flux at an inclination angle of $30^\circ$ was greater by 12.6% than the average heat flux at the vertical pipe (figure 6). The average heat flux at the inclination angles of $10^\circ$...$60^\circ$ was higher than that at the vertical position.
Thus, heat transfer enhancement for the pipe inclined at an inclination angle of 30 ° from the vertical is caused by changing of condensate film flow.

5. Conclusions
The results of our experiments correspond to the classical ideas. The graphs show pulsations of heat flux, which indicates the non-stationarity of heat transfer during condensation. On average, the experimental results differ from the values calculated by the Nusselt formula by 15%, with a standard uncertainty of not more than 10%.

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