Gradient heat flux measurement while researching of saturated water steam condensation

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Abstract. The heat flux measurement is used for research of heat transfer during condensation of saturated water steam at the surface of the tube made of stainless steel. A number of produced experimental setups allowed us to set different directions of movement of steam and cooling water, to change the space orientation of the tube, and also rotate the tube around its axis. In addition, the places of installation of the gradient heat flux sensors at internal and external surfaces of the tube were ranged. In the experiments we determined the local heat transfer coefficients, and their change along the length of the tube and for different values of the azimuthal angle. The obtained data allow to study in detail the formation of the film of condensate on the inside and outside surfaces of the tube and the heat transfer. The experimental results is in accordance with the classical ideas. The graphs show the pulsations of heat flux, which enable us to investigate non-stationary parameters of heat transfer during condensation. Experimental results differ from those calculated according to the Nusselt’s formula for 15% with standard uncertainty lower than 10%.

1. Introduction
Heat transfer during condensation on internal and external surfaces of pipes is of main interest in most of thermal power plants. Until recently, experiments were carried out with using thermometry. The values of heat flux and heat transfer coefficients (local and average) were determined by calculation. This approach eliminates any attempts to describe the unsteady heat transfer and the formation of waves on the condensate film. The using of the high-speed Heterogeneous Gradient Heat Flux Sensors (HGHFS) [1] provides new opportunities. The orientation of pipes and the different flow directions of coolant are studied.

2. Gradient heat flux sensors
HGHFS are artificially anisotropic thermoelements (figure 1). HGHFS was designed and tested in Peter the Great St. Petersburg Polytechnic University [1,2].

In HGHFS temperature gradient occurs in two directions – collinear and normal to vector of heat flux – due to anisotropy of heat conductivity and thermoelectric coefficients. Transverse Seebeck effect leads to the appearance of the thermopower proportional to heat flux.
Signal of the HGHFS:

\[ E = S_0 \cdot A \cdot q, \]

where \( S_0 \) is volt-watt sensitivity of the HGHFS, \( A \) is the sensor surface, \( q \) is heat flux.

Signal polarity depends on direction of heat flow. HGHFS made of nickel+stainless steel composition were used in the experimental setup.

Their characteristics are:
- Working temperature is up to 1300 K.
- Sensitivity is \( S_0 = 0.2...0.8 \text{ mV/W} \).
- Time constant is about \( 10^{-9} \text{ s} \).

GHGFS do not disturb the temperature field in the measurement zone due to their small sizes (5×5×0.2 mm).

3. Calibration of HGHFS

GHGFS are required to calibrate in situ because of technique of their installation. HGHFS calibration was made according to the Joule law. The nichrome wire located along the axis of the tube is powered from the regulator. In this case, an axial electric heater generates heat flux. Output power was controlled by a voltmeter and amperometre. HGHFS signal were measured by the digital multimeter (see figure 2).

Combined standard uncertainty of HGHFS volt-watt sensitivity was about 9%.
4. Condensation at the inner surface of the tube for counterflow of saturated steam and condensate film

The heat transfer at the inner surface of tubes, for the counterflow of steam and condensate was investigated. More common name of this process is reflux condensation phenomena. The obtained results will increase the effectiveness of the passive systems of heat removal from the active zone of the nuclear power reactor [3].

The experiments were conducted in the vertical tube, made of stainless steel, with inner diameter of 20 mm with wall thickness of 0.5 mm. The tube was surrounded by a cooling jacket. Steam was generated by the steam generator which was located under the test section (see figure 3).

![Diagram](image)

**Figure 3.** Scheme of the experimental setup (a) and it’s appearance (b).

The experiments showed that HGHFS is available for investigation of condensation. The pictures of the heat flux pulsations during the reflux condensation phenomena were made, that demonstrated high performance of the HGHFS [4].

Figure 4 shows two areas: heating and reflux condensation phenomena. Reflux condensation is accompanied with the pulsations of heat flux, which demonstrates the unsteady heat transfer process.

![Graph](image)

**Figure 4.** Pulsation of heat flux while condensation.
Heat flux at the distance of 75, 150 and 225 mm from the top edge of the tube was also measured (figure 5).

![Figure 5. Heat flux value at the different distance from the top tube edge of the tube.](image)

The heat flux decreases towards the bottom of the tube, due to increase of thermal resistance of the condensate film.

5. **Condensation at the external surface of the tube**

The experimental setup imitates the tube of typical heat exchanger. The test tube (see figure 6) made of stainless steel has inner diameter of 20 mm, length of 1200 mm, with wall thickness of 2.5 mm. The tube is surrounded by a jacket made of rubber sleeve. Water inside the tube was flowing with temperature of 22 °C. Saturated steam was supplied to the jacket from the steam generator with temperature close to 100 °C. Four HGHFS were installed at the external surface of the tube.

![Figure 6. Scheme of the experimental setup.](image)

Several experiments were made for different regimes of water and steam flow. Some of them are represented below (see figure 7 and figure 8).
Figure 7. Heat flux for steam and water counterflow at the distance of 500 mm from the tube edge.

Figure 8. Heat flux for steam and water uniflow at the distance of 500 mm from the tube edge.

It is obvious that the heat flux is accomplished with the pulsations during the condensation at the external surface of the tube.

The average experimental results differ from ones calculated by the Nusselt solution by 15%.

The results show that the heat transfer becomes more intense for counterflow of steam and water.

6. Conclusion

The experiments showed possibilities of the using the HGHFS. The graphs show pulsations of heat flow, which indicates nonstationary nature of heat transfer during condensation. Experimental results differ from those calculated by Nusselt solution by 15%, when standard uncertainty is no more than 10%.

In the near future impact of sensors on measured heat flux will be investigated, technique of sensors mounting, upgraded the processing and archiving of signals will be improved.

Reference

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