Gradient heat flux measurement in study of heat transfer during steam condensation inside pipes

A Y Babich, E R Zainullina, and S Z Sapozhnikov,

Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya st.,
Saint-Petersburg, 195251, Russia

a.y.babich@mail.ru

Abstract. The article is about the application of the gradient heat flux measurement in the study of heat transfer during steam condensation at the inner surface of the pipe during different directions of water and steam supply. The installed gradient heat flux sensors (GHFS) and thermocouples did not disturb the condensate film flow on the pipe surface. Heat flux per unit areas and temperatures were measured along the length of the pipe. The obtained results confirmed the high informative of gradient heat flux measurement, as well as the capability of GHFS operating under experimental conditions.

1. Introduction
Condensers with pipes are common in power engineering, refrigeration, and chemical technology. Their improvement, optimization, switching to new working fluids is a challenge that is associated with the deep study of condensate flow, and heat transfer during condensation.

Almost all papers and works about heat transfer during condensation on the tube surfaces are based on the Nusselt model proposed in 1916 [1]. But the Nusselt model includes several assumptions. The flowing steam in a pipe causes waves on condensate film that improves heat transfer.

In 1948, Kapitsa theorized the increasing average condensate film conductivity by 21% due to wave formation [2]. A year later, he showed that the increasing condensate film conductivity and the heat transfer coefficient (HTC) depends on the dimensionless complex Re Ka [3]. In 1957, Labuncov has proposed his correlation in the form of power dependence of the Nusselt number on the Reynolds number [4]. Roshenow studied the condensate film inertia forces and derived the correlation number [5].

In 1935 Icob studied condensation at the inner surface of the brass tubes, this is one of the earliest condensation experiments [6]. Over time, experiments about the study of condensation do not lose their significance. Experimental installations became more complex and tasks are more specific. Also, there are a lot of works about condensation with noncondensable gases [7].

Moreover, the problem of condensation inside pipes occurs at the geothermal power plants. That is why the works of Russian scientists on condensation inside large-diameter pipes were published [8].

A literature review showed that only thermocouples were used to measure the heat flux and determine the heat transfer coefficients. This indicates a lack of measuring tools for heat flux measurement. There are a lot of methods were used to measure the condensate film thickness such as optical [9] and laser [10], needle probe [11], and capacitive sensor [12]. However, these methods are
complex and their applicability is limited. Against this, the gradient heat flux measurement is more useful [13]. The gradient heat flux measurement has been already used in different studies of heat and mass transfer [14-15].

2. Gradient heat flux sensors
Gradient heat flux sensors (GHFS) are the artificial thermal elements with anisotropic structure. Gradient heat flux sensors generate a signal proportional to the heat flux due to the anisotropy of the thermal and electrophysical properties of the sensor [13].

The GHFS signal is:

$$E = S_0 \cdot F \cdot q$$  \hspace{1cm} (1)

Here, $E$ is the electromotive force, $S_0$ is the GHFS sensitivity, $F$ is GHFS area, $q$ is heat flux per unit area.

![Figure 1. GHFS schematic representation](image1)

![Figure 2. GHFS photo](image2)

The heterogeneous gradient heat flux sensors (HGHFS) of steel+nickel composite were used. Their response time was about $10^{-8}...10^{-9}$ s [13]. Sensors were individually calibrated by the absolute method.

3. Experimental setup
The experimental section was made of a stainless steel pipe, surrounded by a plastic pipe. Saturated steam was supplied inside the stainless steel pipe, and tap water was supplied in the intertube space at a temperature of 22 °C. With the help of the electrospark machine, four segments were cut in the pipe at a distance of 300 mm from the upper edge and 200 mm from each other.

There are beds for GHFSs and holes for the wires and thermocouples in the segment. The segment was soldered into the pipe after installing sensors and thermocouples (figure 3).

Moreover, the installation can rotate the experimental section relative to the vertical axis and around the axis of the pipe. This feature will be used in the next series of experiments.

The overall view of the experimental setup is shown in figure 4.
4. Results and Discussion
Experiments were performed when steam was supplied from the upper edge of the pipe. With a decrease in the power of the steam generator from 12 to 7 kW, the heat flux and the total heat power at the experimental site change slightly. At a power of 5 kW, the complete condensation of steam was observed, which was confirmed by measuring the condensate flow and the last GHFS signal.

The averaged local HTC depending on the Reynolds number are shown in figure 5. The calculated curves are also shown.
The time dependence of heat flux per unit area is shown in figure 6.

Figure 5. Experiment results

The fluctuations of the heat flux density at GHFS 3 and 4 are visible, which corresponds to the wavy condensate film flow. The pulsation analysis is performed in figure 7.

Figure 6. The time dependence of heat flux per unit area ($N=12\ kW, G=0.05\ kg/s$)

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Power spectrum density graphs (PSD) for GHFS 3 at different steam generator power and cooling water flow rate of 0.05 kg/s and 0.033 kg/s are presented. Peak frequencies are highlighted in the graphs. By the analogy with [9-12], the forms of the PSD and peak frequencies are the same, which indicates the non-randomness of pulsations. Peak frequency values are in the range from 2 to 17 Hz, which corresponds to the traditional works.
5. Conclusions
An experimental setup for gradient heat flux measurement during condensation has been created. Showed that the gradient heat flux measurement allows building the distributions of the local heat flux and local HTC along the length of the pipe. The results correspond to different models. Power spectrum density graphs were built. The gradient heat flux measurement is promising in the design and improvement of the condenser.

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