Experimental study of the boiling process in a fire-tube boiler with different heat transfer fluids

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Abstract. Currently various boiler modifications differing in the types of heat transfer fluid used and in the heat exchange conditions in the boiler working area are presented on the market. To improve the boiler efficiency, it is necessary to take into account the peculiarities of the heat exchange process during convection or boiling depending on the properties and type of the heat transfer fluid used.

1. Introduction

To date, there is a wide variety of boilers modifications on the market that meet the design engineer's requirements. The choice should be made in favour of high efficient heat sources [1, 2]. A high efficiency boiler is a unit in which deposits are not accumulated on the heat exchange surfaces, has the lowest probability of corrosion on the surfaces and produces high-quality steam. To ensure the reliable and long-term boiler operation, it is necessary to use high-quality chemically purified water as well as to conduct the research aimed at developing the unique design solutions of the heating surfaces enhancement [3, 4]. Examples of modern boilers designs include vacuum boilers and boilers using a waterless coolant.

The given boilers are reliable, have a long service life, operate with minimal risks of deposits and corrosion formation on the heating surfaces. Moreover, in the given boilers, heat and mass transfer processes can be accompanied by the heat transfer fluid boiling. Water, high-temperature fluids and nanofluids can be used as a heat transfer fluid.

The developed boiling is accompanied by the process of steam formation in the working chamber with a heat transfer fluid. The beginning of this process is characterized by increasing the saturation temperature at the constant pressure. There are two main types of boiling [5]. Nucleate boiling is characterized by the vapour bubbles formation at regular intervals, these bubbles subsequently rising and detaching from the surface. If the heat load is further increased, the vapour bubbles join to form a steam film. In this case, the process is called a film boiling. During the film boiling, the heat transfer coefficient decrease results in the heat exchange deterioration [5]. The present paper considers the experimental study issues of the heat exchange during nucleate boiling in order to reveal the thermophysical characteristics determining the efficiency of a fire-tube vacuum boiler.

2. Problem statement

Physical properties of the heat transfer fluid, pressure and heat flux have a direct impact on the hydrodynamics and heat transfer coefficient of the two-phase flow. The enhancement of the boiling process under the vacuum conditions is influenced by the geometric characteristics of the heat exchange surface. During the transition from the atmospheric pressure to vacuum, the boiler efficiency decreases. Conducting an experimental research is necessary to investigate the features of nucleate boiling in vacuum, to identify the factors influencing the heat transfer coefficient, such as the local...
parameters and geometric characteristics of the heat exchange surface under study. To confirm the reliability of the data obtained and to evaluate the local heat exchange parameters, it is necessary to develop a test bench.

3. Theory
Finning in the form of the capillary slotted channels is applied to the test sample of the heat exchange surface. The test bench is designed with the possibility of replacing the studied samples of the heat exchange surface. In the first stage of the study, water is used as a saturated heat transfer fluid. Further on the investigations are expected to be carried out using mineral oils as well as oil with the addition of solid particles. When conducting the experiments on a finned surface with slotted channels at the subatmospheric pressures, it is necessary to take into account a number of features. This requires a constant heat flux to be supplied to the test area base and to the side surfaces of the test bench. During the experiment, the temperature and operating pressure are measured on both smooth and finned surfaces.

4. Experimental results
To study the features and intensity of the boiling process on various heat exchange surfaces and to confirm the calculated dependences allowing to change the local operating parameters during the experiment, the test bench shown in figure 1 has been developed.

![Figure 1. The test bench diagram.](image-url)

Figure 1 shows the test bench diagram which consists of a sealed container made of stainless steel (1), a capacitor (5), a vacuum pump (6) to maintain the subatmospheric pressure as well as control and measuring instruments: a flow gauge (FE), thermocouples (TE), a pressure gauge (PE). There is a manhole in the boiler housing. A pressure gauge is mounted on the housing cover. The container is filled with water. The power supply system includes two different systems: one is for the supply and discharge of the working fluid (water) to the capacitor and another is a power source PS. In the working area (4), where the test samples of the heat exchange surface are located, the main heater (2) which provides heat supply to the working area and auxiliary heaters (3) are installed. When conducting the experimental studies at the atmospheric pressure, the installation of a hypsometer is included. The test sample is cylindrical in shape with finning and is made of an aluminum alloy. To define the fin base temperature, a thermocouple is mounted. The type of the test sample is shown in figure 2.
The test sample of the heat exchange finned surface has the following geometric parameters: the number of fins is 30, the fin thickness is 1.5 mm, the slot gap size is 1.5 mm, the fin height is 4 mm. The first experimental studies were carried out on the unfinned cylindrical sample, while all the subsequent experiments were conducted on the finned surface.

The stages of the experimental studies include the following:
- the power calculation;
- the calculation of the heat flux supplied to the working area;
- the calculation of the specific heat flux passing through the fin base.

The fin base temperature is calculated by the following formula:

$$t_w = t_{w1} - \frac{\delta q_b}{\lambda_w}$$

where $t_w$ is the fin base temperature, $t_{w1}$ is the wall temperature at the depth of the thermal element installation, $\delta$ is the depth of the thermal element installation.

The reduced heat transfer coefficient of the boiling liquid is calculated by the formula:

$$\alpha_{sm} = \frac{q_b}{t_w - t_s}$$

where $q_b$ is the heat flux density at the fin base.

In each series of experiments, the system power and pressure were changed. Before the start of each experiment, the working fluid temperature was ambient. To confirm the data obtained during the experimental study, each experiment was conducted at least three times.

As a result of experiments, numerical values of the following parameters were obtained: the heaters power, the cold water flow rate, the water temperature in the capacitor, the saturation temperature, the working area temperature, the system pressure.

To verify the previously conducted studies, the heat transfer coefficients values obtained during the numerical simulation were compared with the values defined while testing, the value of the heat flow being equal to $q=50000$ W/m$^2$. Figure 3 shows the comparison of the data obtained during the experimental study with the results of the numerical simulation using the RPI model in ANSYS CFX.

Water is used as a heat transfer fluid, while a mineral-oil based nanofluid with the addition of small solid particles (aluminum oxides, titanium dioxide, carbon nanotubes and others) which size does not exceed $10^{-9}$ m is planned to be considered as a promising heat transfer fluid in the future studies.
Figure 3. The dependences of the reduced heat transfer coefficient on the finned surface pressure.

Figure 3 shows the results of the numerical study depicted by the solid line and the results of the experimental studies represented by the points. A decrease in the working pressure leads to a decrease in the heat transfer coefficient, which does not contradict the fundamental principles of the heat exchange.

The maximum discrepancy between the experimental and numerical data is 13.7%. The minimum discrepancy of 10.3% corresponds to the pressure of 101.15 kPa.

The obtained calculated dependences characterize the heat exchange process during the nucleate boiling of liquid (water) in the capillary slotted channels at the subatmospheric pressure. The numerical simulation results obtained using the RPI model in ANSYS CFX can be used for further calculations of the heat exchange during liquid boiling in boilers at the atmospheric pressure and in vacuum.

5. Conclusions
The following conclusions are proposed based on the research results:
1. A methodology of conducting the experimental study has been developed to study the heat exchange peculiarities during the liquid boiling in the capillary slotted channels at the subatmospheric pressure.
2. A test bench has been developed.
3. The numerical studies results obtained using the RPI model in ANSYS CFX were experimentally confirmed. The maximum variation between the calculation and experiment include the following:
   - the heat transfer coefficient on the finned heat exchange surface is 13.7%;
   - the fin efficiency is 13.1%.

6. References
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