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EXPERIMENTAL STUDY OF UNDEVELOPED NUCLEATE BOILING ON THE HORIZONTAL TUBE HEATED BY CONDENSING STEAM

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Abstract

The experimental study of undeveloped nucleate boiling on the horizontal tube heated by condensing steam has been carried out in the Institute for Physics and Power Engineering. The feature of the processes investigated was a presence of natural circulation in primary circuit of the facility. The experiments were carried out at heating steam pressure P_{s1} = 0.35 MPa. On the base of the results of these experiments the empirical correlations for prediction of heat transfer coefficient was obtained. This correlation can be used for the substantiation of work of VVER steam generator in the condensation mode.

Introduction

The NPP-2006 project of nuclear power plant with water-moderated water-cooled power reactor (VVER) provides for use of passive safety systems (Figure 1). They involve second-stage hydro-accumulators (HA-2 system) and passive heat removal system (PHRS). In the event of an accident with rapture of primary pipelines and loss of electric power supply sources, these systems are utilized to remove residual heat from the reactor core.

PHRS ensures the transition of horizontal steam generators (SG) to the mode of condensation of primary circuit steam, coming into the SG pipelines from the reactor. The condensate from steam generators is directed into the core, ensuring its additional cooling [1].

As a result of condensation of primary steam in SG pipelines, the heating of secondary water up to the saturation temperature with forming of steam takes place. Due to natural circulation in steam-condensate circuit of PHRS, this steam comes into the aerial heat-exchangers, mounted on the external surface of containment in special airways. Steam is condensed, giving its energy to air. The formed condensate comes back, by gravity, into the intertubular space of SG. Thus, the heat transferring facility designed for operation under forced circulation of coolants in both circuits and high value of saturation pressure in the second circuit is converted in operation regime of multi-row horizontal steam-pipe evaporator under natural circulation in both circuits and low values of P_{s2}. Such sharp change in operation regime on heat transferring facility will change considerably the heat transfer between circuits and, hence, the thermal load q on the heat-transferring surface.

The steam generator off-design condensation mode has the following features: undeveloped nucleate boiling on the horizontal tubes heated by condensing steam; natural circulation processes in the both steam generator circuits; low heat fluxes and temperature differences.

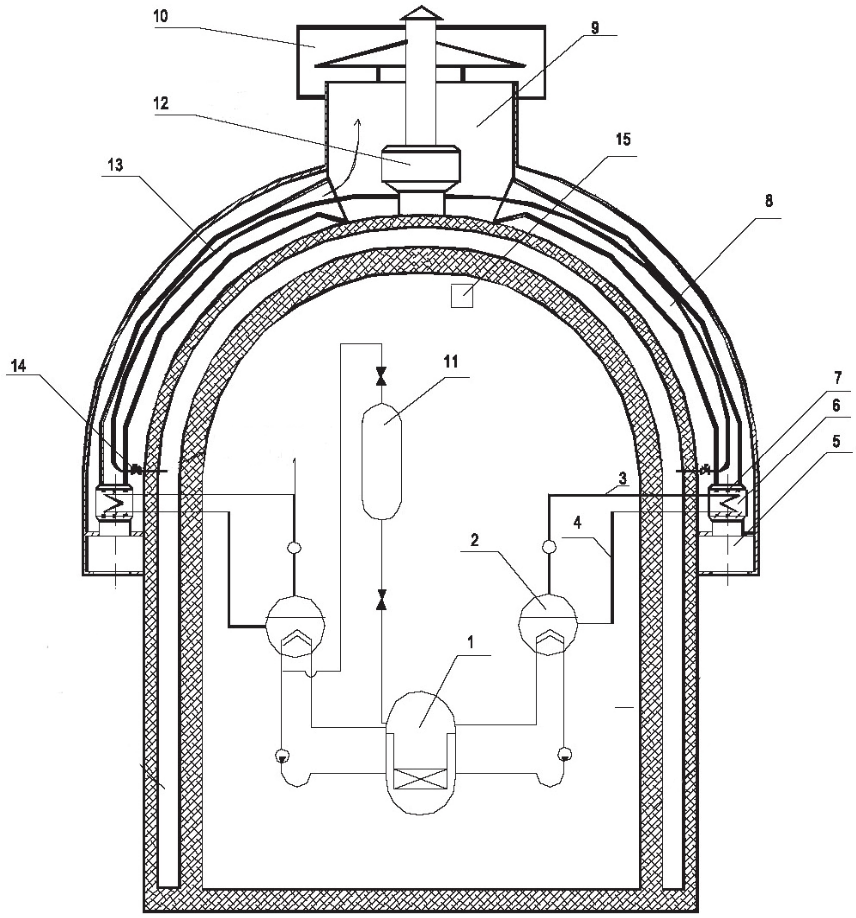

Figure 1 "NPP-2006" Passive Safety Systems.1 – reactor; 2 – SG; 3 – PHRS steam path; 4 – PHRS condensation path; 5 – inlet header; 6 – PHRS heat exchanger; 7 – slide valve; 8 – draught stack; 9 – output header; 10 – deflector; 11 – HA-2; 12 – filter; 13 – heat- exchanging channel; 14 – valve; 15 – hydrogen recombiner

During last years both in Russia and abroad, the experimental investigations of heat transfer between steam condensing in horizontal tubes and cooling water circulating in secondary circuit were carried out [2-4]. Such experiments were carried out either on multi-raw heat-transferring pipes, or on single tubes with heat removal in secondary circuit by cooling water under force convection. Therefore, the phenomena investigated in these experiments considerably differ from the processes of heat transfer at double phase transition (condensation of the first circuit steam and undeveloped nucleate boiling of the second circuit water) and natural circulation.

Because of the considerable complexity and insufficient knowledge of the mechanism of the process itself, there is still no reliable generalized criterion or empiric correlations for heat transfer prediction in such heat transferring facilities. To calculate analytically the heat transfer between circuits under double phase transition and undeveloped nucleate boiling on horizontal tube heated by condensing steam is rather difficult. So, the reliable thermal characteristics of such specific heat-exchanger can be obtained only experimentally.

1. Experimental equipment and test procedure

1.1 Test facility

The purpose of the experiments was to determine the characteristics of heat transfer between condensing steam and boiling water under natural convection in single horizontal tube. The experimental study of undeveloped nucleate boiling on the horizontal tube heated by condensing steam has been carried out on the GROT test facility, consisting of two circuits (Figure 2).

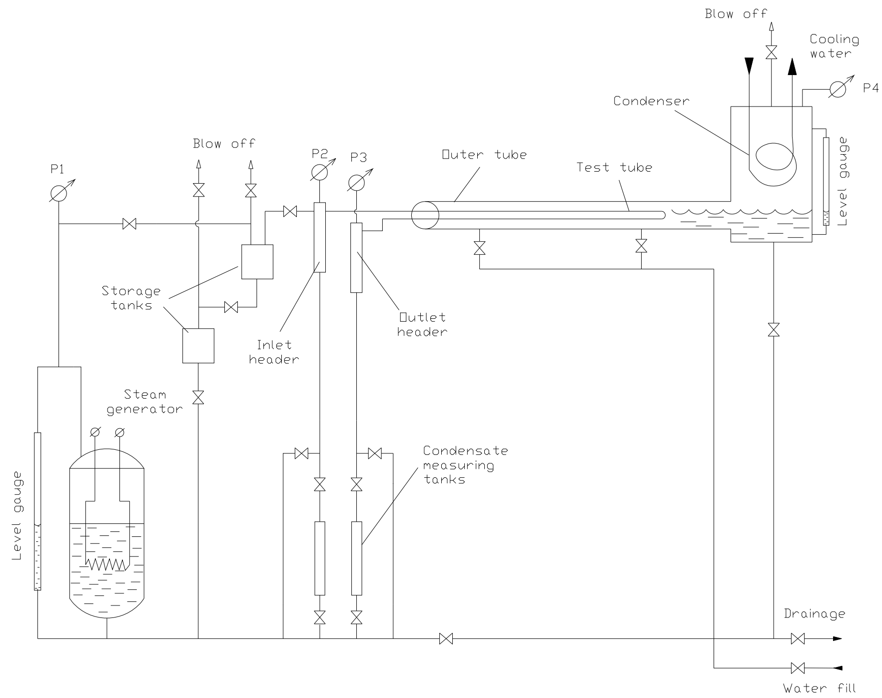

Figure 2 Schematic diagram of the GROT test facility.

The first circuit incorporates a steam generator of a volume of 0.3 m^3 with an internal 12 kW electrical heater, 0.1 m^3 storage tanks and processing lines with check valves. The heart of the test facility is the single VVER steam generator tube (length l=10.2 m, outer diameter d=16 mm, wall thickness δ=1.5 mm). The tube is fabricated of the original stainless steel material. The length and geometry of the test tube corresponded to that of real steam generator. The test tube is coupled with headers at the beginning and the end. These headers are used for connection with the steam supply. They agree in principle with the original headers, but they serve essentially as separators for the absorption of condensate. For drainage of condensate from the test tube to be secured, the branches are made with some slope relative to the headers with altitude difference of 20 mm, as on real VVER steam generator.

The second circuit includes the outer tube filled with steam and boiling water (length l=6.5 m, inner diameter d=160 mm) and the coiled condenser inserted to the steam volume intended to regulate the pressure of the second circuit's medium. Both circuits connected by processing lines with a common system for filling with distilled water and drainage. The processing equipment and pipelines are thermally insulated and equipped with the controlled nickel-chromium electrical heaters.

1.2 Instrumentation

The GROT facility is intensively equipped with measurement systems for the acquisition of the thermohydraulic process parameters such as pressure, temperatures, and water levels at the primary and secondary sides (Figure 3). The control over the pressure of medium at the test facility was provided by four reference pressure gauges; in addition, the thermocouples were used to measure temperature within the steam generator, storage tanks and steam lines.

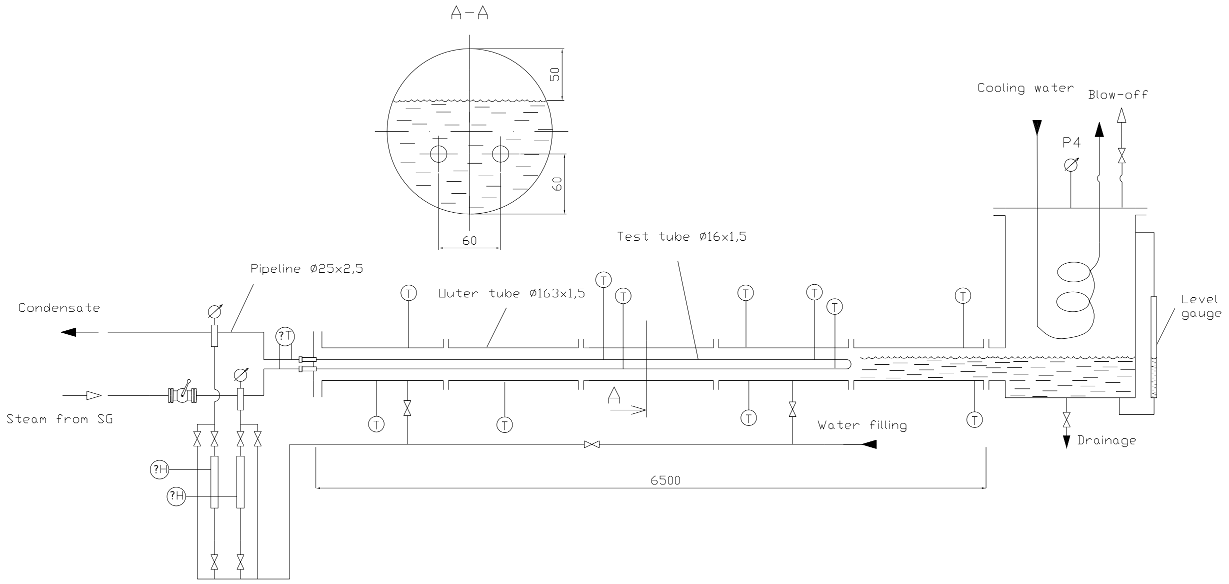

Figure 3 Scheme of instrumentation layout of the GROT test facility.

The steam flow coming from the steam generator to the test tube was evaluated by direct measurements of condensate amount formed in the tube using the condensate measuring tanks. The condensate collection system consists of two measuring tanks equipped with a level meters based on of Metran-100-DD type gauge, valves for collecting condensate from inlet and outlet headers and drain valves. During the experiments, after steady-state condition being achieved, the condensate amount was measured by filling the measuring tanks and registering the level with subsequent draining through the drainage line.

The pressure along the facility circuit was measured by piezoresistive pressure transducers METRAN-100-DI. The water levels were measured by hydrostatic method using pressure difference transducers METRAN-100-DD. Chromel-copel thermocouples with a diameter of 1.0 mm were used to measure temperature. The sampling of measuring channels of the data acquisition system was implemented with a frequency of 1 Hz.

The reduced error of temperature measuring channels as a sum of amplifier module error (0.8%) and thermocouple calibration characteristic error (0.1%) was estimated as 0.81%. The reduced error of pressure and level measuring channels is made up of the current signal amplifier error (0.1%) and the METRAN-100 sensor error (0.25%), i.e. it is 0.3%.

1.3 Test procedure

The experiments on a study of undeveloped nucleate boiling on the horizontal tube heated by condensing steam were carried at the pressure 0.35 MPa, what corresponds to that in VVER reactor in the case of beyond design basis accident with the rapture of main circulation line [1].

The experiments on the GROT test facility were carried out according to the following procedure. First, the given pressure was set in the steam generator and the storage tanks by means of electrical heaters. For each test the isothermal condition was preliminarily established by means of electrical heaters along the steam line, headers and in the measuring tanks at which thermal losses were completely compensated.

The heating of the facility equipment took place up to the establishment of stationary parameters of mediums (pressure and temperature) in both facility circuits. The determining indication of sufficient facility warming up was the uniformity of thermal field along the length of water in outer tube and stability of pressure in primary and secondary facility circuits. Simultaneously, the air was blown off by opening the corresponding valves to prevent the presence of steam-air mixture in the circuits. To prevent the heat exchanging pipe dry out, the level of water in the outer tube in experiments was supported at 0.05–0.07 m above the test tube.

Then, the required values of pressure in the secondary circuit were established by increasing the cooling water flow-rate through the condenser, i.e. the pressure (temperature) difference between circuits was rose. After the necessary pressure difference has been achieved, the monitoring of pressure and temperatures in the circuits was produced, and the test facility was transferred into new stationary state. After a new steady-state regime had been achieved, the parameters were recorded by the computer controlled data acquisition system.

A constancy of pressure in the facility equipment during the experiments carrying out was secured by the auxiliary system of pressure control, which allowed supporting the pressure in the primary circuit, within an accuracy of 0.01 MPa, independently upon the changes of steam flow rate to the test tube.

2. Results of Experimental Study

The experiments at the test facility were carried out at steam pressure in primary circuit P_{s1} = 0.35 MPa. The experiments were carried out at constant pressure P_{s1} and various values of P_{s2}, i.e. at change of pressure difference ΔP between primary and secondary circuits. The range of pressure differences investigated was about 30–60 kPa. Change of pressure P_{s2} was realized by adjustment of cooling water flow-rate through a condenser.

While carrying out the experiments, special attention was paid to maintenance of stable parameters of primary and secondary circuits' media. Because of presence of natural circulation processes, it was of great importance to maintain the constancy of heating steam pressure in a primary circuit. The system of pressure maintenance used at the facility allowed supporting steam pressure during experiments within an accuracy of ±10 kPa. As an example, the values of pressure in both circuits for one of experiments are presented in Figure 4.

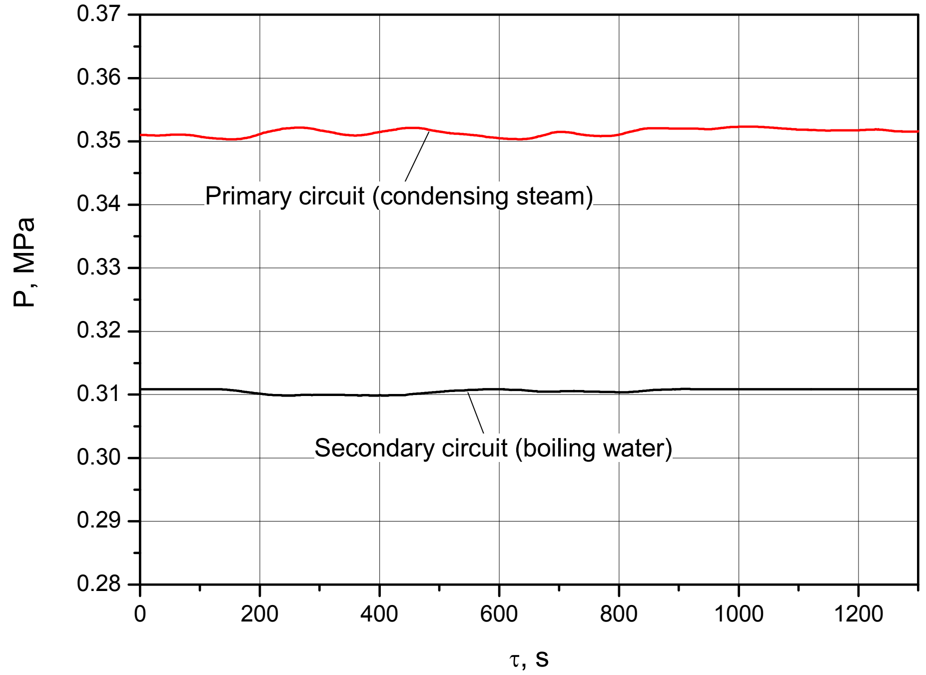

Figure 4 Steam pressure in primary and secondary circuits in experiment.

The system of condensate collection of the GROT facility enabled measuring of condensed steam from both inlet and outlet headers to be carried out. As an example, relative flow rate of condensate in two branches of test tube in some experiments are shown in Figure 5. It is seen from this figure, that about 90% of condensate flows in outlet line, while only 10% is fed into the zone of inlet header.

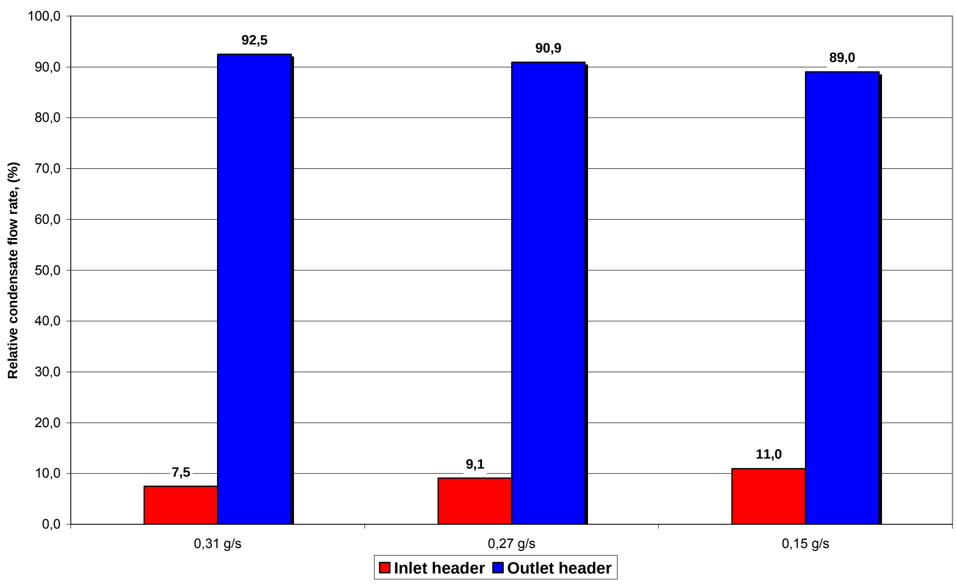

Figure 5 Relative flow rate of condensate in experiments.

The experimental data concerning the study of processes of heat transfer from steam being condensed to boiling water obtained were summarized in the form of the dependence of heat transfer coefficient upon heat flux density and pressure in primary circuit: $k = f(q, P)$. Heat transfer coefficient can be calculated from balance relationship:

$$Q = \frac{kF\Delta T}{r\rho_1'} \quad (1)$$

where: Q – flow-rate of steam, condensing in a horizontal test tube, m^3/s; F – area of the test tube's heat-transfer surface, m^2; ΔT – temperature head between circuits, K, r – specific heat of vaporization, J/kg, ρ_1' - density of the first circuit steam, kg/m3.

Using the values of steam flow-rate and temperature head, measured experimentally, the dependence of heat flux density upon the heat transfer coefficient was obtained which is shown in Figure 6.

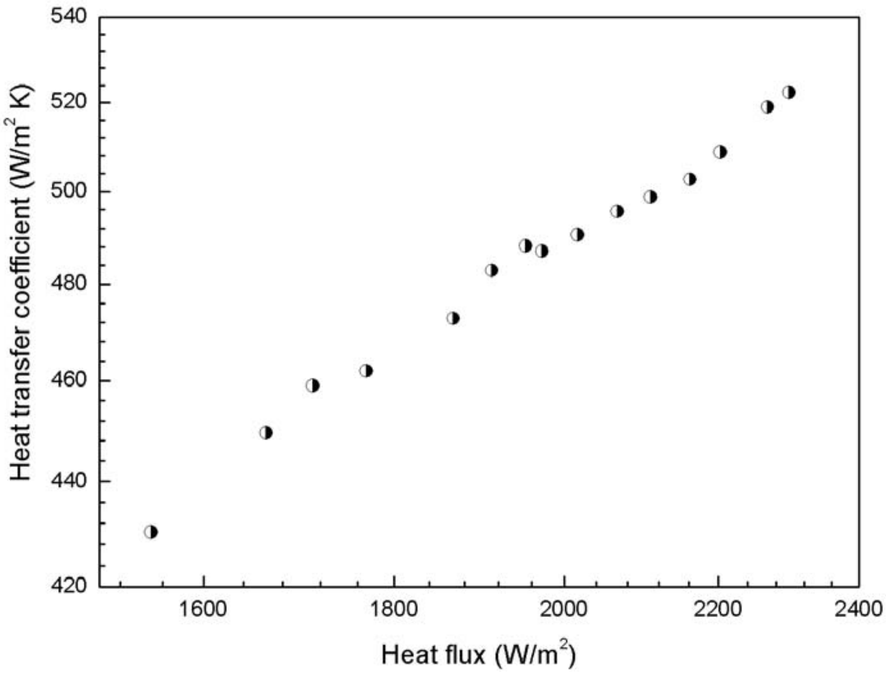

Figure 6 Correlation between heat transfer coefficient and heat flux.

It is seen from these figures, that the value of heat flux under boiling condition does not exceed 2400 W/m^2 and the value of heat transfer coefficient is less then 530 $W/(m^2 \cdot K)$.

On the base of the experimental data treatment, the empirical correlation for the heat exchange coefficient was obtained for undeveloped nucleate boiling on the single horizontal tube under natural circulation of heating steam, applied at the pressure 0.35±0.01 MPa:

$$k = 10{,}9 q^{0,5}, \quad (2)$$

where: k – heat transfer coefficient, $W/(m^2 \cdot K)$;
q – heat flux, W/m^2.

The character of this correlation allows making a conclusion about features of heat transfer processes taking place in SG model. The dependence of heat transfer coefficient upon the heat flux in the power of 0.5 shows, that the regime studied is an intermediate one between single-phase convection ($k \sim q^{0.33}$) and developed nucleate boiling ($k \sim q^{0.7}$).

The comparison between experimental and calculated (using Equation 2) heat transfer coefficients is shown in Figure 7. It is seen from this figure, that the discrepancy between values does not exceed 3%.

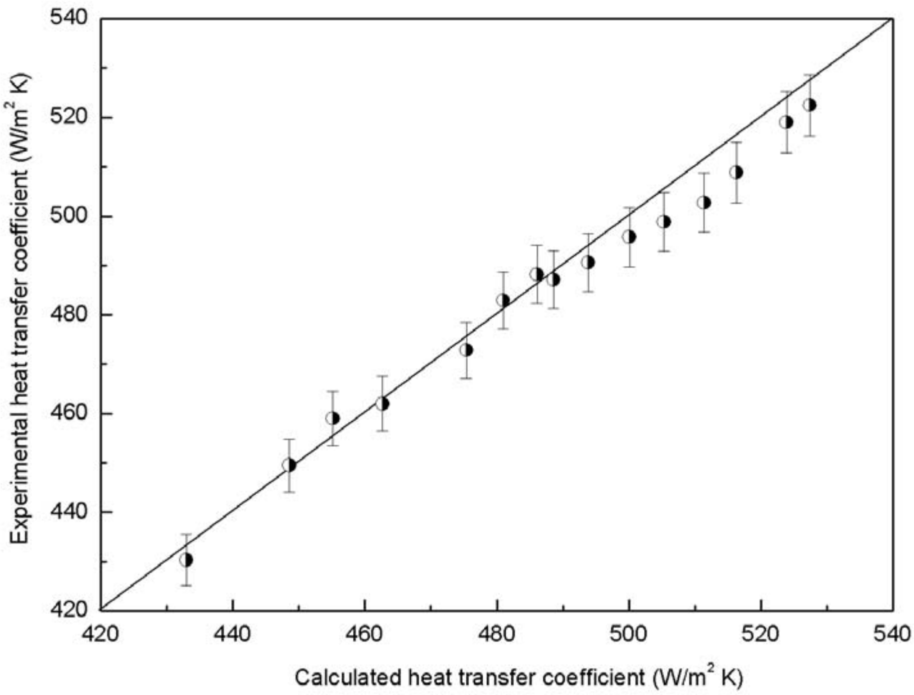

Figure 7 Experimental vs. calculated heat transfer coefficient.

3. Conclusion

The experimental study of undeveloped nucleate boiling on the horizontal tube heated by condensing steam has been carried out in the Institute for Physics and Power Engineering. The experiments have been carried out on the GROT test facility. The feature of the processes investigated was a presence of natural circulation in primary circuit of the facility. The stainless steel heat-transfer tube has the following characteristics: length l=10.2 m, outer diameter d=16 mm, wall thickness δ=1.5 mm. The length and geometry of the heat transferring tube corresponded to that of VVER steam generator. The experiments were carried out at heating steam pressures P_{s1} = 0.35 MPa. On the base of the results of these experiments the empirical correlation for prediction of heat transfer coefficient was obtained. This correlation can be used for the substantiation of work of VVER steam generator in the condensation mode, and also can be applied to the verification of computer codes.

4. References

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