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Temperature regimes of evaporator pipes at partial loading of power units

Abstract. *The results of the study of the temperature regimes of the evaporator tubes in the area around the critical pressure of one-phase and two-phase are given in the paper. The studies carried out in the field of single-phase critical pressure environment can be classified into two groups according to their physical nature: 1) heat exchange process at large values of not heating the liquid up to the pseudocritical temperature at the inlet of the evaporator pipe; 2) heat exchange process at small values of at the pipe entrance. It is appropriate to use the proposed method in order to precalculate the temperature of the screen tubes in partial load modes of steam generators. With the help of this method, we can determine the reliability of the steam generator in this mode by checking the probability of occurrence of a deteriorated mode in the evaporator tubes in a given mode; The change of the temperature regime of the pipes in the area around the two-phase critical pressure is subject to a general regularity; Equations are proposed to calculate the temperature of the pipe wall in the degraded regime and the enthalpy of the fluid at the boundary of the degraded regime.*

Streszczenie. *W artykule podano wyniki badań reżimów temperaturowych rur parownika w obszarze wokół ciśnienia krytycznego jednofazowego i dwufazowego. Badania prowadzone w zakresie jednofazowego środowiska ciśnienia krytycznego można podzielić na dwie grupy ze względu na ich charakter fizyczny:1) proces wymiany ciepła przy dużych wartościach nieogrzewania cieczy do temperatury pseudokrytycznej na wlocie rury parownika; 2) proces wymiany ciepła przy małych wartościach na wejściu rury. Zaproponowaną metodę celowe jest zastosowanie do wstępnego obliczenia temperatury rur sitowych w stanach częściowego obciążenia wytwornic pary. Za pomocą tej metody można określić niezawodność wytwornicy pary w tym trybie, sprawdzając prawdopodobieństwo wystąpienia stanu pogorszonego w rurach parownika w danym trybie; Zmiana reżimu temperaturowego rur w obszarze wokół dwufazowego ciśnienia krytycznego podlega ogólnej prawidłowości; Zaproponowano równania umożliwiające obliczenie temperatury ścianki rury w reżimie zdegradowanym oraz entalpii płynu na granicy reżimu zdegradowanego.* (***Reżimy temperaturowe przewodów parownika przy częściowym obciążeniu bloków energetycznych***)

Keywords: temperature regime, single-phase, two-phase, critical pressure, deteriorated regime, boiling.
Słowa kluczowe: reżim temperaturowy, jednofazowy, dwufazowy, ciśnienie krytyczne, wrzenie.

1. Introduction

The need to ensure high indicators of economic efficiency of electricity production, reliability and safety criteria impose strict requirements on the quality and completeness of design developments, on the level of operation of power plants.

The dynamics of power plants in general and steam generators in particular are important for solving a wide range of problems, covering almost all stages from pre-design development of these plants to their current operation. Problems facing the energy industry in increasing the maneuverability of equipment; improving the reliability of its operation under unsteady conditions; automation of control over a wide range of load changes, covering start-up processes; warning and localization of emergency situations; for their solution, they require the presence of a reliable mathematical description of non-stationary processes in a wide range [1].

The need to ensure high indicators of economic efficiency of electricity production, reliability and safety criteria impose strict requirements on the quality and completeness of design developments, the reliability of the information used and the level of operation of power plants. The current level of development of energy production, the importance of the task of organizing a reliable energy supply, the complexity of the engineering problems being solved, the increased complexity in managing the main technological processes, as well as the ever-decreasing percentage of accidents and failures due to the fault of personnel in the industry require the improvement of the system for ensuring the reliable operation of operational equipment. person, maintaining his qualifications. The dynamics of power plants in general and steam generators in particular are important for solving a wide range of problems, covering almost all stages from predesign development of these plants to their current operation. Problems facing the energy industry in increasing the maneuverability of equipment; improving the reliability of its operation under unsteady conditions; automation of control over a wide range of load changes, covering start-up processes; warning and localization of emergency situations; assessment of reliability and durability indicators; advanced training of personnel using computer simulators requires for their solution the presence of a reliable mathematical description of non-stationary processes in a wide range of changes in operating parameters of power plants.

In this regard, the urgent problem is to develop effective methods for mathematical modeling of dynamic processes and their verification based on the results of dynamic experiments on special physical installations. Taking into account the variety of tasks that impose different requirements on the coverage of the number of modeled parameters, the detail of process descriptions, the accuracy of calculations, speed, etc., there is a need to develop coordinated systems of dynamic models of power plants and their elements that meet specific formulations of research and operational tasks. Moreover, these models, due to the complexity of the processes of non-stationary heat and mass transfer and hydrodynamics during steam generation in power plants, should be based on a combination of the theoretical principles of these disciplines with the results of physical experiments.

A comprehensive methodology for mathematical modeling and experimental study of the dynamics of power plant processes has been created, based on the theory of solving complex algebraic - differential systems of equations, a numerical-analytical method for calculating the dynamics of heat exchangers and their systems, a method for identifying dynamic systems and the use of physical experiment to test and adjust mathematical models and obtain new information about unsteady conditions in heated channels with coolant.

The following new scientific results were obtained in this work. A methodology for constructing all-mode dynamic real-time models of power plants using fossil fuels for simulators of operators of thermomechanical equipment of thermal power plants has been developed and tested in practice, based on a combination of the theory of hydraulic circuits, methods for solving complex algebraic-differential systems of equations and the use of nonlinear integral models of heat exchangers and their systems. Analytical expressions for pulse transient functions of single-phase and boiling heat exchangers, as well as their convolution integrals, are determined, which are used to construct linear and nonlinear integral models of the dynamics of a steam-generating system as an object with distributed parameters.

An exact analytical solution to the problem of nonlinear dynamics of a heat exchanger with a weakly compressible coolant was found, which was an important link in the substantiation of the theoretical approach developed by the author to the construction of nonlinear integral dynamic models of heat exchangers and their systems.

Linear and nonlinear integral models of individual heat exchangers and the steam generating system as a whole have been developed, based on the analytical expressions of the corresponding convolution integrals obtained in the work. Using the linear case as an example, the boundary value problem of dynamics is reduced to a system of Volterra integral equations of the second kind. The necessary quadrature formulas are derived and an algorithm for the iteration-free solution of this system is constructed [1].

Over the past 20 years, in various countries around the world there has been an increased interest in steam turbine units (STU) with organic working bodies (OWB). This is due to the use of low-grade heat to produce electricity, as well as the use of OWB as a working bodies in an autonomous power plant (space, underwater).

When designing and operating heating installations, it is necessary to know the temperature conditions of the walls of heat exchangers. Therefore, there is a need to study the regularities of the temperature regime of the wall and create reasonable methods for calculating local heat transfer coefficients.

Discussing steam generator designs, their wide variety is noted. The presence of spacer devices of different designs, features of the supply of coolant to the annulus and a number of other factors make the flow in the annulus very complex. In real structures, the velocity field is not uniform across the cross section of the tube bundle; the relative angle between the velocity vector and the heat transfer tubes also changes. As a consequence, the temperature field of the heating coolant is also uneven. Unevenness of speed and temperature in a steam generator is undesirable, since it reduces the efficiency of heat exchangers and leads to the appearance of temperature stresses in structural elements. In practice, special measures are taken to level out unevenness. By installing distribution grids, the velocity field is leveled; with the help of partitions, multiple transverse flows around the pipes are carried out, leveling the temperature field. Thanks to these measures, idealized ideas about the identity of all heat exchange pipes according to the conditions of coolant flow around them can be used for many structures. Checking for unevenness is always advisable, although it requires complex calculations.

For structures in which compensation for thermal elongations of heat transfer pipes relative to each other is not ensured, such a check is simply necessary. There are two known approaches to solving the problem of velocity and temperature distributions. The so-called "channel-by-channel calculation" consists of solving a system of conservation equations for n interacting elementary channels into which the entire flow section of the heat exchanger is divided. The second approach is based on the idea of a heat exchanger as an anisotropic porous body and consists in solving a system of equations of motion, energy and continuity, written in the appropriate form. Both approaches require knowledge of a number of closing coefficients for specific implementation: interchannel exchange, friction, heat transfer [2-4].

When energy equipment is operated in partial load modes, the number of accidents increases compared to the normal mode. That is, in these modes, the hydraulic and temperature regimes on the heating surfaces of the steam generator are violated, and as a result, accidents occur in the boiler. This process is observed both in blocks operating at pressures higher than the crankcase and in drum power plants [5].

The analysis of the operating modes of power units shows that during the transition of the power unit from one mode to another, not only the conditions of operation and operating mode of the unit change, but also its usefulness changes. Thus, as a result of the increase in losses in the elements of the turbogenerator unit (in the steam distribution system and the starter pump), the specific fuel consumption also increases. In these modes, due to the increase of throttle angles in the control valves of the steam turbine, the relative internal efficiency of the turbine decreases, and as a result, the efficiency of the turbogenerator unit also decreases.

Operational experience shows that the efficiency of units with a capacity of 300MVt decreases to 11% in partial load mode. That is, the specific consumption of conventional fuel increases significantly. As a result of research, it is known that the practical application of two main options for increasing the economic efficiency of power units operating in partial load modes is of particular importance:

- Moving the block to the sliding starting pressure;
- Optimal distribution of load between blocks in partial load modes. Thus, when power units are operated at powers lower than the nominal powers, their usefulness deteriorates and the specific consumption of conventional fuel for the production of power increases. At the same time, the reliability of the steam generator decreases, and as a result, the probability of failures and accidents in power plants increases. In order to increase the economic efficiency of energy blocks, it is suggested to move the block to a sliding connection pressure or to optimally distribute the load between the blocks [6].

Approximately 85-90% of the electricity produced in our country is produced in thermal power plants, for which millions of tons of organic fuel are consumed annually. As you can see, in order to reduce the cost of electricity produced in the energy system of our country, the main task is to improve the operational performance of thermal power plants. Thus, the share of fuel in the cost of produced electricity is approximately 85%. In recent years, as in other countries of the world, large powerful energy blocks are used in the process of load regulation in the energy system of our country. Thus, large powerful blocks designed to work at base loads in the power system participate in load regulation in the system, and at this time the blocks are operated in partial load modes. In partial load mode, the economic efficiency of power plants, as well as their reliability, decreases considerably. Operational experience shows that the efficiency of Ne=300MVt units decreases by 11% in partial load mode. In other words, the specific consumption of conventional fuel increases significantly. On the other hand, in partial load modes, the hydraulic and temperature regimes on the heating surfaces of the steam generator are disturbed, and as a result, accidents occur in the boiler [5].

In order to switch the steam generators to the sliding starting pressure, the temperature regime of the evaporator tubes was studied experimentally.

As mentioned, one of the main ways to increase the utility of power units in partial load modes is to switch the power equipment to a sliding starting pressure. However, one of the main problems in switching power plants to a sliding starting pressure is ensuring reliable temperature regimes of the evaporator tubes. This, in turn, requires a more detailed study of the heat exchange process in the subcritical area.

2. Experimental part

The results of the study of the temperature regimes of the evaporator tubes in the area around the critical pressure of one-phase and two-phase are presented in the paper. The studies carried out in the field of single-phase critical pressure environment can be classified into two groups according to their physical nature:

- heat exchange process at large values of non-heating of liquid to pseudocritical temperature (t_{pm}) at the inlet of the evaporator tube $\left(\Delta t_{gir} = t_{pm} - t_{gir}\right)$;

- heat exchange process at small values of □t_{gir} at the pipe entrance.

A comparative analysis of the results of experiments conducted with water shows that the initial boundary of the deteriorated mode of heat transfer depends on two main factors:

- from the value of q/□u in evaporator tubes;
- from the value of non-heating of the liquid at the inlet of the evaporator pipe $\left(\Delta t_{gir} = t_{pm} - t_{m,gir}\right)$.

Due to the influence of these two factors mentioned above, the starting boundary of the deteriorated heat transfer regime also changes depending on the nature of the dynamics of temperature and velocity profiles in the boundary layer of the evaporator tube. Figure 1 shows the variation of the temperature of the pipe wall depending on the enthalpy in experiments conducted with water in a vertical pipe with an inner diameter d_{dax}=8.0 mm. As can be seen from the presented dependence, the value of the enthalpy of the working body at the initial boundary of the local increase in the temperature of the pipe wall is equal to i_x=1600kC/kg. In other words, at the border point, i_x/i_{pm}≈0.72.

Summarizing the above, it can be concluded that, regardless of the type of the working body, at small values of Δt_{gir} and the corresponding conditions of the mode parameters, the heat exchange process in the single-phase subcritical area is observed in a degraded mode. The deteriorated regime occurs mainly at the outlet of the pipe, and usually the enthalpy of the liquid at its initial boundary is equal to $i_{ser} \approx (0.82 \div 0.85) i_{pm}$. In other words, the degraded mode is observed in the maximum heat capacity $\left(t_{pm}\right)$ zone. Therefore, it is important to consider this factor when switching steam generators to sliding start pressure.

The generation of a heating-deteriorated regime is a hydrodynamic problem by its very nature. During the forced movement of liquid in a heated pipe, the formation of a degraded regime is caused by the comparative effect of thermal and hydrodynamic processes. Due to their influence, the profiles of temperature and velocity in the boundary layer of the pipe wall are changed, and as a result, a deteriorated regime of the heat transfer process is created. Prof. F.I. Kalbaliyev proposed the following equation to determine the dimensionless value of speed *(U_{or})* and temperature *(T_{or})* [7].

(1) $$U_{or}^{+} T_{or}^{+} = \frac{u}{q / \rho_d \cdot \overline{C_p} \cdot (t_d - t_m)} = \frac{u}{W_g}$$

In the presented equation (1), the velocity of the fraction determines the hydrodynamic effect of the flow (the linear velocity of the liquid in the pipe, u, m/sec), and the denominator of the fraction determines the effect of the heat flux density (Wg – introduced velocity). The presented equation (1) can be written as follows by making a simple transformation:

(2) $$U_{or}^{+} T_{or}^{+} = \frac{u}{W_g} = \frac{1}{\dfrac{q}{\rho_d \cdot \overline{C_p} \cdot (t_d - t_m) u}} = \frac{1}{\dfrac{q}{\rho_d \cdot u \cdot \overline{C_p} (t_d - t_m)} \cdot \dfrac{\rho_m}{\rho_m}} = \frac{1}{K_1} \cdot \frac{\rho_d}{\rho_m}$$

Here:

(3) $$K_1 = \frac{q}{\rho_m \cdot u \cdot \overline{C_p} (t_d - t_m)}$$

The above analyzes once again confirm that the intensity of the heat exchange process in the pipe is determined based on the following parameters:

- the heating intensity of the tube (q);

- from the mass velocity of the liquid flowing through the pipe $\left(\rho_m u\right)$;

- from the price of non-heating of the liquid at the entrance of the pipe *(t_{gir})*.

Taking these factors into account, the dependence $K_1 = f(K_2)$ was used to determine the beginning of the boundary of the deteriorated regime in the pipe. Here the dimensionless complex K_2

(4) $$K_2 = \frac{q}{\rho_m U \Delta i_m}$$

In the presented expression (4), the value of Δi_m is calculated as follows depending on the temperature of the liquid in the section under consideration:

$$\begin{cases} \Delta i_m = i_{pm} - i_m, \;\; i_{pm} > i_m \;\; \text{when thereis;} \\ \Delta i_m = i_m - i_{pm}, \;\; i_{pm} < i_m \;\; \text{when thereis} \end{cases}$$

For water experiments, the following empirical equation can be used to report the degraded regime using the generalized $K_1 = f(K_2)$ dependence (Figure 1b) [8].

The enthalpy of the fluid at the initial boundary of the degraded regime and the boundary heat load corresponding to this regime can be calculated as follows:

(5) $$i_m^s = i_{pm} - 700 \frac{q}{\rho_m U}$$

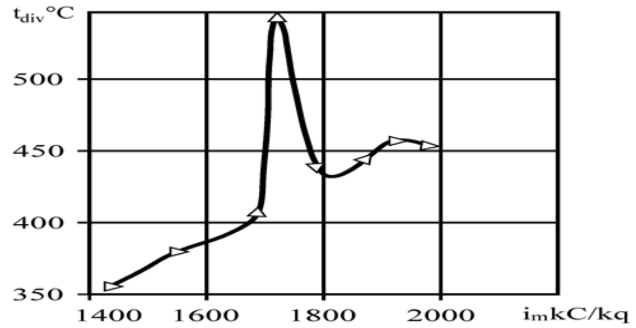
(6) $$q_{pis} = i_m + 1.5 \cdot 10^{-3} \cdot \rho_m U (i_{pm} - i_m)$$

The temperature of the pipe wall in the deteriorated regime can be calculated from the enthalpy:

(7) $$i_d = i_{pm} + 1500 \frac{q}{\rho_m U}$$

As mentioned, when the power units are transferred to the sliding starting pressure in the partial load mode, the heating surfaces of the steam generator are likely to work in the two-phase subcritical area. This mode is a non-reporting mode for flat-flow steam generators, and during the operation of the units in this mode, a violation of the temperature regime of the heating surfaces may occur. It is necessary to know the probability of occurrence of this situation in advance and, if it occurs, to what extent the value of the maximum temperature of the pipe wall will change.

a)



b)

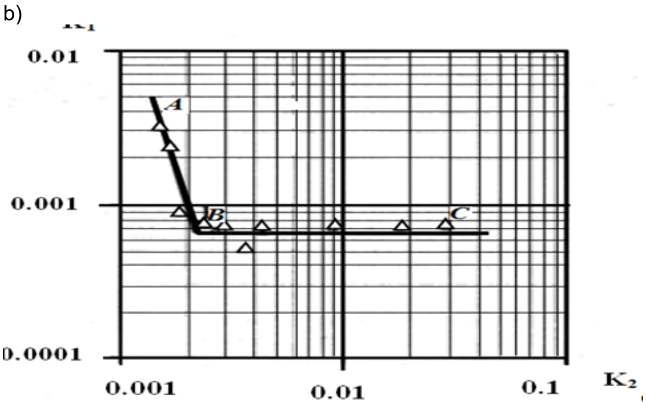


Fig 1. a) $t_{div} = f(i_m)$ addiction; b) $K_1 = f(K_2)$ addiction [8] Working substance: water; P/P_{kr}=1.02; ρu=430 kq/m^2·sec; l= 300 m; d_{dax}=8.0 mm; q=0.33·10^5 Vt/m^2; q/ρu=0.77 kC/kq.

For this purpose, it is necessary to study the temperature regime of the pipe wall in the two-phase subcritical area. For this purpose, numerous experimental results given in the literature and carried out with water were collected, systematized and analyzed.

As a result of the analysis, it was determined that the conducted experiments can be grouped according to their characteristics as follows:

- according to the pressure of the liquid;
- due to the price of not heating the liquid to the saturation temperature at the entrance of the test tube $\left(\Delta t_{gir} = t_d - t_{gir}\right)$.

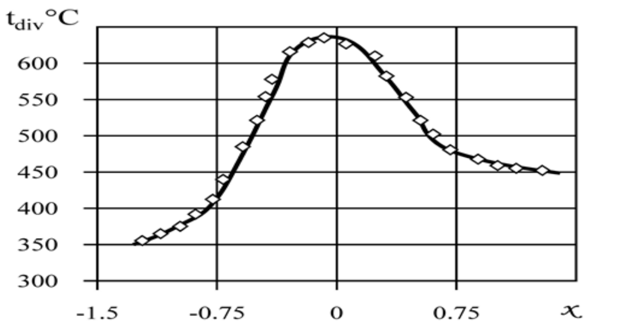
In order to characterize the deteriorated regime in the two-phase critical pressure environment, it is necessary to calculate Δi_m in equation (4) as follows.

$$\begin{cases} \Delta i_m = i' - i_m, \ x > 0 \ \text{when there is;} \\ \Delta i_m = i_m - i', \ \ x < 0 \ \text{when there is} \end{cases}$$

Figure 2 presents the results of the experiments conducted with water using the proposed method.

The obtained results show that the analyzes performed by the proposed method are justified as in the single-phase critical pressure area. In the dependence $K_1 = f(K_2)$ presented in Figure 2, the line AB characterizes the bubbling boiling process, and the horizontal line BC characterizes the deteriorated mode (stratified boiling process). The transition to the stratified boiling regime is characterized by the intersection of lines AB and BC. K_2≈2·10^{-3} is obtained for water in this transition region [9].

a)



b)

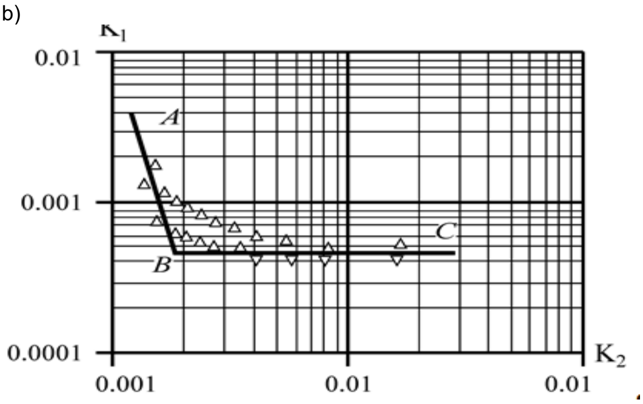


Fig 2. a) $t_{div} = f(x)$ addiction; b) $K_1 = f(K_2)$ addiction $(\Delta - x > 0;\ \Delta - x < 0)$ [9]. Working substance: water; P/P_{kr}=0.93; ρu=700 kq/m^2·sec; l=1200 m; d_{dax}=5.0 mm; q=0.58·10^6 Vt/m^2.

Based on experiments with water, the following equations are proposed to calculate the temperature of the pipe wall in the degraded regime of the two-phase critical pressure environment and the enthalpy of the liquid at the boundary of the degraded regime.

$$i_{div} = i_m + 2000 \frac{q}{\rho u} \tag{8}$$

$$i_m^s = i' - 500 \frac{q}{\rho u} \tag{9}$$

3. The result

Thus, summarizing the above, the following conclusions can be noted:

- It is appropriate to use the proposed method in order to precalculate the temperature of the screen tubes in partial load modes of steam generators. With the help of this method, we can determine the reliability of the steam generator in this mode by checking the probability of occurrence of a deteriorated mode in the evaporator tubes in a given mode;
- The change of the temperature regime of the pipes in the area around the two-phase critical pressure is subject to general regularity;
-The temperature regime of the pipes changes mainly depending on the heat load (q), the mass velocity of the liquid (□u), the temperature of the liquid at the entrance of the pipe (t_{gir}) and the pressure (P). In this case, the impact of all parameters should be taken into account during reporting.

REFERENCES

[1] Tairov E.A., doctor of technical sciences dissertation, Methods for a comprehensive study of the dynamics of power plants and their elements, 2000.

[2] Physical principles of operation of nuclear steam generating plants, Temperature regime of the coil element, https://leg.co.ua

[3] Lokshin V.A., Peterson D.F., Shvarts A.L., Hydraulic calculation of boiler units, Boiler installations M.: Energia, 256, 1978, https://www.studmed.ru

[4] Fundamentals of hydraulic calculation of steam generators and temperature conditions of heating surfaces, Equipment, materials science, mechanics, Encyclopedia of Mechanical Engineering XXL, https://mash-xxl.info

[5] Rzaev M.A., Kalbaliev R.F., Bayramov N.M., Ashurova U.I., Questions about the efficiency of a 300 MVt unit at partial loads, Conference proceeding First International Conference on Technical and Physical Problems in Power Engineering, Baku: Azerbaijan, pp. 267-268, 2002. http://www.iotpe.com/ictpe-past.html

[6] Bayramov N.M., Indicators of efficiency of power units in thermal power plants in partial load modes, Problems of Enepgetics, №2, pp. 78-81, 2011.

[7] Kalbaliev F.I., Heat transfer at supercritical pressures of substances, Dis.dr. tech. Science Baku, 412, 1985.

[8] Shitsman M.E., Investigation of heat output during cooling of water in the near-critical region, Thermal Energy, №1, pp. 83-86, 1962.

[9] Myropolsky Z.L., Heat transfer during film boiling of a steam-water mixture in vapor-generating tubes, Thermal Energy, №5, pp. 49-52, 1963.