Application areas and calculation method for capillary-porous heat exchangers of the new heat-removing class

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Abstract. The paper is centered on research focused on the fundamental studies of capillary-porous systems working in the mass forces field. Examined are the effects of pressure, excess fluid, the methods for heating and for supplying coolant, as well as the type of material used, in addition to the intensifier type amongst others, on the integral and thermo-hydraulic characteristics of the heat transfer process. The information obtained from the research can be used in the design, engineering calculations and operation of different energy installations of power plants. Experimentally obtained approximation for the law of the growth of a bubble in a cell of a porous structure, taking into account the influence of underheating, velocity and thermal properties of liquid and a heating surface, was used for determination of the radius of a "dry" spot. The heat transfer control permits to form a new class in the system for heat removing. Devices for heat exchange were built to raise their efficiency, reliability and to be loyal to environment. Capillary-porous heat exchanger shaped as a box provides safety from an explosion. The engineering method for calculation is done for limiting and operational characteristics of capillary-porous heat exchanger. The heat transfer control permits the development of a new class in the system for heat removal. Devices for heat exchange were built with the purpose of increasing both efficiency and dependability in an environmentally conscious manner. A capillary-porous heat exchanger shaped as a box provides protection against an explosion. Obtaining Its limiting and operational characteristics is done by means of an engineering method for calculation.

1. Introduction

The development and study of capillary-porous cooling systems acting under both mass and capillary forces, which create underheating and flow rate in the cross section and on the surface of the structure, made it possible to expand the removal of heat fluxes, increasing the heat transfer rate [1-3] and intensify heat transfer processes [4-8]. Intensification of heat exchange processes [4] is achieved by controlling the heat wave energies, the characteristics of boiling [5] and the heat transfer parameters [6]. Experimental data were summarized by means of the theory of similarity, modelling and analogy of heat exchange phenomena [7], which allowed receiving the calculated dependences on definition of heat flows and temperature pressures depending on regime and design parameters of structure and a heat exchange surface [8-14].

The most important factor in the intensification of energy production is the strengthening of the economy with regard to environmental requirements. It is necessary to satisfy the growing needs for fuel, energy and raw materials mainly due to economy of material and raw resources, improvement of using of secondary resources. It can be promoted by porous systems.
Energy savings in the industry are particular importance now, since primary energy resources will be depleted in the foreseeable future if they are used in the same way as at the present stage. The solution for the problem of pollution of the biosphere can't be postponed anymore and this problem should be solved not locally, but on a global scale. A considerable number of equipment in thermal power installations needs the utilization of heat recovery systems. Even a small list of equipment and processes reveals significant reserves of energy saving, but requires the development of new technical solutions.

2. Application areas of capillary-porous heat exchangers

Porous systems made in the form of heat pipes are being introduced in power plants. They allow to take away and transport the high temperature heat fluxes, with high intensity and reliability, solving a number of the environmental problems which are put forward as a result of anthropogenous impact on surrounding environment: to promote economy of natural resources, water, oxygen, to reduce the amount of harmful emissions.

Porous cooling has proven effective for gas turbine blades. Air was introduced into the internal cavities of the blade and forced through the porous wall. Compared to convective or convective-film cooling, the air flow was reduced, but it was necessary to thoroughly clean the air of dust and prevent pores from clogging with particles contained in combustion.

The heat transferring device found practical application in electrical machines. Rotor cooling systems by means of a centrifugal thermosiphon and the stator cooling by heat pipes and vaporizing contours were considered. Heat pipes create areas with the uniform temperature field in radio-electronic devices, thermally stabilize the heating surfaces, and structurally solve the heat removal problem by moving their surface out of limits of blocks and knots.

The heat exchanger with ridge heat pipes is used in utilization of heat ventilating emissions. The wall of a pipe can be considered as additional thermal resistance; however, efficiency of a heat transfer in the pipe is so considerable that about 70% of waste heat was utilized in the device. The main advantage of heat exchangers is their reliability in comparison with the rotating regenerator and the device with the intermediate heat carrier. Failure of several pipes only slightly reduces efficiency of work; there are no rotating parts and the related noise and vibration.

The field of application of porous mesh materials was cooling systems, dust-gas cleaning and foam generation devices, filtering elements for cleaning station wastewater with a rather wide range of filter material cleaning fineness – from 5 to 100×100\(^2\) m, mixers, fire prevention devices, aerators, noise mufflers, chemical towers, evaporators, distillation columns.

The mesh materials from knitted grids possessing high porosity were applied in sound-absorbing designs of power stations. Acoustic efficiency of the noise-absorbing panels installed with a clearance of 10×10\(^2\) m in the range of frequencies (200 … 10000) Hz, was (5 \ldots 10) dB. The development of the proposed porous systems operating in the field of mass forces in the future should be aimed at creating compact, reliable and explosion-proof devices for cooling heat-loaded boilers and gas turbines, utilization heat exchangers that can drastically reduce low-temperature corrosion of heating surfaces and utilize the heat of exhaust gases of boiler rooms, metallurgical furnaces compressor station. Porous systems have to increase reliability, efficiency and manoeuvrability of work of the heat-loaded elements of boilers, turbines, recovery boilers, burners, drills, to reduce concentration of nitrogen oxides in furnace chambers and to improve the ecological environmental conditions. Solving the problems of preventing water and soil pollution from oil and oil products, utilizing low-grade heat in cooling towers, cooling ponds, for heating buildings, structures, greenhouses and air conditioning are required. New technical devices of porous filters for gas cleaning are required. Porous systems can be useful in solving the food program and a number of tasks to ensure electrical and fire safety when heating studs and flanges of turbines and production and domestic premises [2-4, 6-9].

Approximate values of heat exchange coefficients \(a\), W/m\(^2\)K and heat transfer coefficients \(k\), W/m\(^2\)K in heat-exchange devices of power plants can be presented in a general view in table 1.
### Table 1. Approximate values of heat exchange and heat transfer coefficients.

| No | Heat exchange process                        | Heat exchange coefficient $\alpha$, Wm$^{-2}$K$^{-1}$ |
|----|---------------------------------------------|-------------------------------------------------|
| 1  | When heating and cooling air                | $\alpha = 1 \ldots 50$                          |
| 2  | When heating and cooling superheated steam  | $\alpha = 20 \ldots 100$                        |
| 3  | When heating and cooling oils               | $\alpha = 50 \ldots 1500$                       |
| 4  | When heating and cooling water              | $\alpha = 200 \ldots 10000$                     |
| 5  | When boiling                                | $\alpha = 500 \ldots 45000$                     |
| 6  | At film condensation of water vapour        | $\alpha = 4000 \ldots 15000$                    |
| 7  | At drop condensation of water vapour        | $\alpha = 40000 \ldots 120000$                  |

| Heat transfer process | Heat transfer coefficients $k$, Wm$^{-2}$K$^{-1}$ |
|-----------------------|-------------------------------------------------|
| 8                     | At a heat transfer from gas to gas               | 25                                              |
| 9                     | At a heat transfer from gas to water             | 50                                              |
| 10                    | At a heat transfer from water to water           | 1000                                            |
| 11                    | At a heat transfer from the condensing vapours to water | 3500 |

To increase of reliability and efficiency of stationary heat exchangers taking into account ecology we developed the following devices [2, 4, 8, 9]:

1. Condensers of turbines on porous structures;
2. Intensifiers of deaeration in condensate collectors;
3. Recyclers of waste heat through the use of the "triad": heat pipes, vortex tubes, heat pumps, the establishment of power plants without cooling towers and without chimneys;
4. Cooling tower with porous elements;
5. The porous inserts to prevent cavitation in the condensate and feed pumps;
6. Heat exchange intensifiers in heaters with porous elements;
7. The porous structures in deaerators increasing efficiency of decontamination;
8. Porous structures for increase of efficiency of separation of steam and heat exchange of superheaters;
9. Oil coolers on heat pipes, excluding the contact of oil with the water and vice versa;
10. Porous oil coolers;
11. Bubblers in porous deaerators;
12. Porous evaporators;
13. Heat pipes in greenhouse facility (management of blossoming phenophases, porous watering, storage of fruits);
14. Wavy porous two-phase heat exchangers;
15. Porous network heaters;
16. Porous heaters;
17. Porous heat exchangers on Coanda effect;
18. Porous heat exchangers in the form of a penetrator;
19. The porous heat exchangers using effect of separation, concentration, transport, drain and energy control of a wave and gases;
20. Heat exchangers on the basis of the operated flexible porous structures.

### 3. Capillary-porous heat exchangers

We will consider as an illustration the use of capillary and porous systems in the cooling of melting units for the purpose of their explosion safety.

The design of caissons (Figure 1) represents a box-shaped form. They consist of a housing 1 and cover 2 which allow for detachment and are tightly closed around the perimeter using bolts 3. The
interior side of the caisson’s 4 is covered by the capillary-porous structure 5. Perforated plates 6 are intended to press this structure to the wall’s internal surface. The top ends of the structure are connected with feed liquid channels 7. Cooling liquid is supplied to the cooled surface through the upper end of the structure by mass and capillary forces. The lower ends of the structure are generally loose and submerged in tray 8 where the liquid accumulates due to leakage, dripping or excess. On the surfaces of the plate, which are smoothed with holes 9, there is provided exit steam of structure in groove 10, as well as traps which are formed by the structure of the glass and the outer surface of the outer surface. The liquid channel is connected to a branch pipe 11, with the conducting tubes 12 and the collector 13. The excess refrigerant accumulates at the caisson’s base, where it is removed using siphon 14 to the lower collector 15, which circulates it back to the supply system.

To facilitate construction and to maintain sufficient rigidity, the spacers 16 fitted in the caissons are composed of either reinforcing ribs or perforated plates.

The ribs may be located either internally or externally of the caisson’s housing and its cover. On the cover, at its upper part, the junction tubes 17 are welded with flanges for the connection to the steam pipe. The structure may be enlarged vertically or horizontally, with the upper or lower ends (or both) of the structure connected to feed liquid channels. The perforated plates are made in shape and size commensurate with the structure. Stamped perforated grooves in the plates can take the shape of a truncated cone, or longitudinal grooves with upwards facing holes.

![Figure 1](image)

**Figure. 1** The caisson of capillary-porous system with internal ribbing: 1 – housing; 2 – cover; 3 – bolt; 4 – wall; 5 - capillary-porous structure; 6 – plate; 7 – feed liquid channel; 8 – tank; 9 – hole; 10 – channel; 11, 17 – branch pipe; 12 – tube; 13, 15 – collector; 14 – siphon; 16 – internal ribbing.

4. Calculation method
Engineering calculation of operating and limit characteristics of the capillary-porous cooling system can be executed with use of nomogram’s method.

For creation of characteristics the geometrical parameters of the cooling system and the porous structure are previously determined.

Calculation is made on the basis of equation for the thermal power:
The coefficient of heat exchange of the evaporator \( \alpha_E \) is determined by the criteria equation [7] received by us, or by the calculated dependences [3, 6, 8].

Assuming the wall temperature of the condenser \( T_W^C = \) constant for a number of steam temperature values \( T_S \), the required physical parameters of the liquid in the condenser are defined and \( \alpha_c = f(T_S) \) is plotted. From the equation:

\[
Q = \alpha_c F_c (T_S - T_i^c), \quad W
\]  

where \( T_i^c = 0.5(T_S + T_L^c) \), for the number of values \( T_S \) the corresponding values of \( Q \) are defined.

Assuming the several values for \( T_W^E \), the parameters of liquid in an evaporator at the chosen temperature of steam are determined and schedules for \( \alpha_E = f(T_W^E) \) are built on mentioned formulas and on the formula:

\[
\alpha_E = \frac{Q}{(T_W^E - T_S)F_E}, \quad \text{W/m}^2\text{K}
\]

The cross point of curves gives the required temperature \( T_W^E \). Thus, the grid of equidistant lines in the plane \( Q = f(T_W^E) \) for various \( T_W^C \) can be put, and it is necessary to take into account the heat-transferring opportunities limited by crisis phenomena [2, 3, 9].

To construct a nomogram it is also necessary to know the heat exchange laws of the cooling system with a surrounding medium (\( \alpha_{SM}^C = \) constant). For this purpose, for example, the coefficients of heat exchange with external environment are assumed, or the conditions of environment temperature (\( T_{env} = \) constant) are accepted.

The \( Q \) value is determined by the formula characterizing the heat exchange of an external wall of the condenser with environment

\[
Q = \alpha_{SM}^C F_c (T_W^C - T_{env}), \quad W
\]

Then to each value of \( Q \) (or \( T_W^C \)) corresponds a certain value of \( T_W^E \) (or \( Q \)). Therefore, by changing of external conditions of heat exchange with environment it is possible to regulate \( T_W^E \) for a given heat emission.

In case the wall temperature of the cooling element is given, it is necessary to ask a number of Reynolds (Re) values to calculate the number of Stanton (St) values and, having determined the value of \( \alpha_E \) clarify the temperature \( T_W^E \).

If the wall temperature exceeds a given value, it is necessary to reduce Re value and, hence withdrawn heat load.

5. The mechanism of the heat transfer process

In the process of boiling, the radius of the “dry” spot at the base of the steam bubble is given by:

\[
R_{ds} = \frac{\delta_0}{\tan \alpha} = \frac{\sqrt{3}}{2\tan \alpha} \frac{\rho \lambda^\prime}{\sqrt{\rho \lambda^\prime}} F \sqrt{\frac{\alpha_0}{f'(P)}},
\]
where: \( \alpha \) - the angle between the heating surface and a tapered microlayer located under the bubble with a radius \( R_{d0} \); \( \tau_0 \) - time which determines of complete evaporation of microlayer with thickness \( \delta_0 \), when under the bubble the "dry" spot is settled; \( \lambda, \lambda \) - thermal conductivity of the wall and liquid; \( c, \rho \) - heat capacity and density of the wall.

For capillary-porous system which working in the field of mass forces, the law of steam bubble growth [10] is defined as:

\[
R_j = 2\sqrt{54.1aJa} \tau_0 \left[ 1 + \left( \frac{m_{liq}}{m_v} \right)^{0.1} \right]^{-1}
\]

Then the equation for \( R_{d0} \) (5) is converted to the form:

\[
R_{d0} = \frac{\sqrt{3}}{2tga} \frac{\lambda'}{\rho c \lambda'} \frac{P}{\sqrt{\epsilon'(P)}} \frac{R_j [1 + (m_{liq}/m_v)]^{0.1}}{2\sqrt{54.1 aJa}}
\]

where: \( Ja = \frac{c' \Delta T}{r \rho''} \) - Jakobi number; \( m_{liq} \) - liquid flow rate; \( m_v \) - vapor flow rate; \( m_{liq}/m_v \) - the influence of the liquid flow rate expressed in terms of liquid excess; \( \rho', \rho'' \) - density of liquid and steam; \( r \) - evaporation heat; \( K = \frac{R_{d0}}{R_j} \) represents a coefficient of "dry" spot.

Generally speaking, in the studied capillary-porous cooling system the influence of subcooling, liquid velocity, liquid thermal properties and the characteristics of heating surface can be approximated by the averaged expression of the form:

\[
\bar{R} = \frac{R_j}{R_0} = 2.42 \left( k_{liq} k_w \right)^{-1}
\]

where \( k_{liq} = 1 + \tilde{m}^{0.1} \); \( k_w = 1 + \left[ \frac{\rho c \lambda}{\rho c \lambda} \right]^{0.5} \) - coefficients taking into account the excess of fluid and heat storage capacity of the wall; \( \tilde{m} = 1-14 \); \( \tilde{m} = \frac{m_{liq}}{m_v} \) - option, taking into account the excess of fluid.

Excess of fluid \( \tilde{m} \) in the cross-section of the porous structure makes a flow with low subcooling and low speed \( W_0 \), which reduces the averaged value of the detachable bubble radius \( \bar{R}_0 \) to the value of \( \bar{R}_j \). The values of \( W_0 = (1.1 \times 10 - 0.1) \text{ m/s} \); \( W_0 = \frac{m_{liq} l q}{m_v c \delta_o \rho' r \rho''} \) was found from experimental parameters, where \( l \) - height of the heat exchange surface; \( \epsilon \) - porosity of structure; \( \delta_0 \) - thickness of porous structure. This is due to a decrease in the average weight temperature, which leads to overheating falling of liquid film surrounding the bubble, and may cause partial condensation [11].

The low of steam bubble growth \( R_d \) takes into account deformation and outline of bubbles due to excess of fluid \( m_{liq} \) with in relation to the flow of generated steam \( m_v \).

6. Conclusion

Thus, on the basis of the fundamental research of the models and the nature of the thermal hydraulic properties of the heat transfer, the necessary information was obtained for the development, design, engineering and operation of capillary-porous systems in different thermal power plants of power plants. Examined are the effects of pressure, excess fluid, the methods for heating and for supplying coolant, as well as the type of material used, in addition to the intensifier type amongst others, on the
integral and thermo-hydraulic characteristics of the heat transfer process obtained. The information obtained from the research can be used in the design, engineering calculations and operation of various energy installations within power plants. Heat transfer regulation enables the formation of a new class in the system for heat removal. Heat exchangers were built with the purpose of increasing both efficiency and dependability in an environmentally conscious manner. A capillary-porous heat exchanger shaped as a box provides protection against explosions. Obtaining its limiting and operational characteristics is done by means of an engineering method for calculation.

Further development of high-performance apparatuses with porous structures makes it possible to turn energy production into environmentally friendly process, improve occupational safety conditions, significantly save natural resources, intensify processes in alternative sources, protect air, water and soil from pollution, including "thermal", solve methodological problems and long-term problems of generation, transport and energy storage.

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