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RESEARCH AND CALCULATION OF HIGH-FORCED CAPILLARY-POROUS HEAT EXCHANGER

Abstract. A capillary-porous cooling system for caissons of melting units has been studied, developed and calculated. The experimental type of the mesh porous structure $(2\times0.55)\cdot 10^{-3}$ m is defined. The heat transfer capacity of the cooling system is increased six times. The hydraulic resistance at boiling of water will be 40.4 times less than in mesh heat pipes, and even more so for the wicks of heat pipes with fibrous, powder and ceramic materials. The caisson allows to carry out cooling of furnaces is explosion-proof due to the maintenance of a trace amount of liquid in the porous structure. The system of caisson of the lining of the unit and the cooling scheme of the caisson by a capillary-porous system is presented. The hydraulic resistance in the capillary-porous structure, the criterial heat transfer equation, taking into account the excess fluid, which determines the speed and underheating of the flux, and the heat-storage capacity of the wall, are obtained by us as a result of experimental studies.

Key words: capillary-porous system; hydraulic resistance; cooling system; caisson; heat flux.

1. INTRODUCTION

The capillary-porous heat exchanger is designed to ensure the explosion-proof operation of melting units in metallurgy. It contains a very small amount of liquid, which eliminates the danger of explosion at the burnout of the cooled element. It is also excludes the ingress of water into the melt, which leads to the explosion of the furnace, as in the case for water and evaporative cooling systems, made in the form of caissons.

The next stage of development of the heat exchanger was the study of a capillary-porous structure. To increase the removal of thermal loads, the control of heat transfer processes is used. For this purpose, the separation of the energy of the boiling stream in the porous structure into energy of the thermal wave and the energy of the vapor flow is investigated [1].

For this purpose also, the process of explosive production of a steam germ is simulated.

The next step in controlling heat exchange is the joint action of mass and capillary forces for coolant transport, creating underheating and forced flow velocity in the structure [2]. Also, the system is capable to increase the critical heat loads by an order of magnitude and can be allocated into a separate class of heat exchangers, characterized by high forcing and intensity of heat transfer. In addition, mass forces make it possible to control the shape and intensity of generation of internal characteristics of a boiling stream in a capillary-porous structure and intensify heat transfer processes [3,4].

2. METHODOLOGY

Physical and mathematical models of processes of boiling in a porous structure are developed for all modes of boiling (initial, transitional, developed and crisis (limiting)) [5-8].

Generalization of experimental data on the basis of the theory of similarity and modeling makes it possible to obtain a criterial equation for calculating the heat exchange of boiling and foam flows in porous structures [9] and to create an engineering calculation technique.

We give an example of calculation of such system in relation to the heat exchanger executed in the form of a caisson. The system of caisson of lining (garnissazh lining) of the melting unit is shown in figure 1. The scheme of the caisson with the garnissazh lining consists of: 1 – meling film; 2 – garnissazh;

3 - fireproof packing; 4 – thermal isolation; 5 – outside metal covering; 6 - temperature variation in the thickness of the lining; 7 – viscosity variation in a garnissazh layer; 8 – caisson wall; 9 – caisson. The following designations are accepted: q_{pi} , q_u , q_{env}- - the specific heat flux from a melt; the specific heat flux is carried away by a cooling system; the specific heat flux coming to an environment; t_m , t_{mf} , t_{met} , t_w - temperatures of melting, of melting films, of metal and the protecting wall.

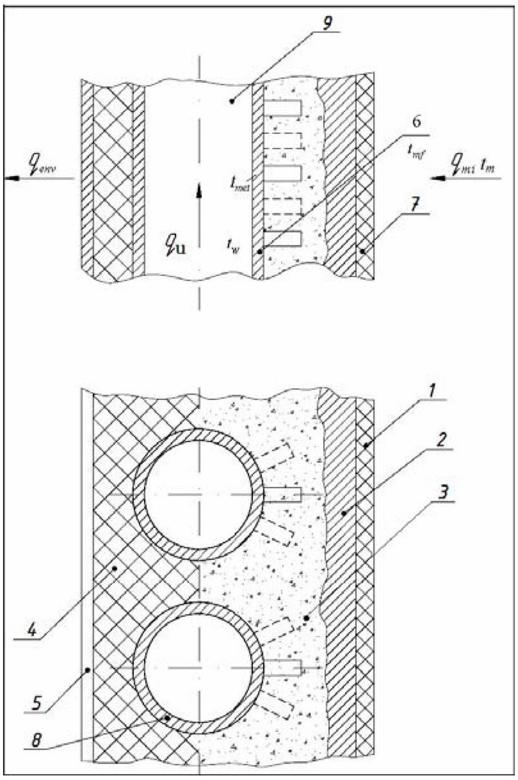

Figure 1 - The scheme of the caisson with the garnissazh lining

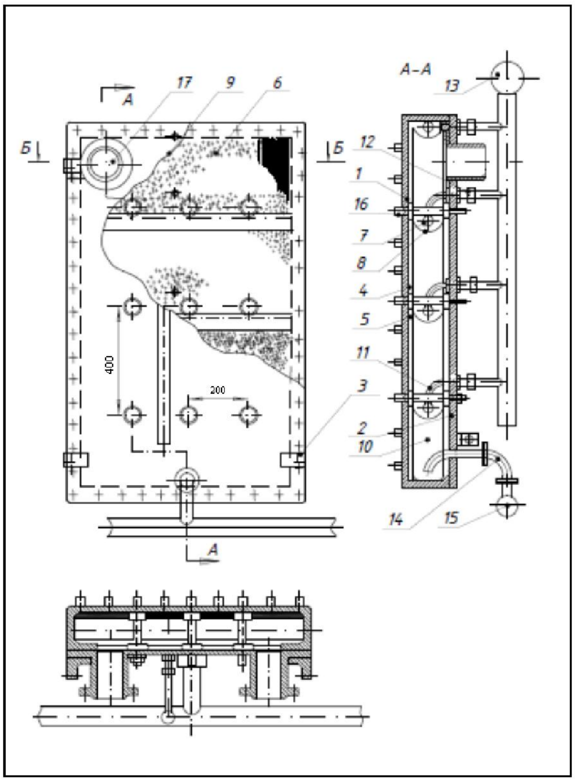

Figure 2 - The cooling scheme of the caisson of a capillary-porous system with struts

Figure 2 shows the cooling scheme of the caisson of a capillary-porous system with stiffening ribs made in the form of struts. It consists of: 1 – housing; 2 – cover; 3 – bolt; 4 – wall; 5 - capillary-porous structure; 6 – plate; 7 – artery; 8 – basket; 9 – opening; 10 – channel; 11, 17 – branch pipe; 12 – pipe; 13, 15 – collector; 14 – siphon; 16 – struts.

It can be seen from figure 2 that a capillary-porous structure has a small thickness (a fraction of millimeters), every second contains a small amount of cooler, which is not dangerous for the formation of an explosive mixture in case of its enter in a melt of furnace.

The design of caissons (figure 2) represents a box-shaped form. It consists of the housing 1 and a removable cover 2, hermetically bolted on perimeter 3. The internal surface of a wall 4 is covered with the capillary-porous structure 5 pressed by perforated plates 6. Arteries 7 are connected to top ends of structure through the end face of which to the cooled surface liquid is supplied by mass and capillary forces. The lower ends of structure are usually free and immersed in baskets 8 where liquid accumulates due to leaks, droplet entrainment or the excess. On a surface of plates the openings 9 are stamped which provide a steam-out from structure in channel 10 and also serve as catchers of the drops which are thrown out from the structure and the flowing-down excess liquid on an external surface of a plate. The artery is connected to a branch pipe 11, with the distributing pipes 12 and a collector 13. The excess of cooling liquid accumulates in the bottom of a caisson and is removed by a siphon 14 in the lower collector 15 and further in the store for return to system. For the purpose of facilitation of a design and preservation of sufficient rigidity, the caissons are provided with struts 16. If the struts made in the form of ribs, they may be located either on the outside or inside the shell and the caisson cover. On a cover, in its upper part, branch pipes 17 with flanges for connection with a steam line are welded. The structure can be extended in the vertical or horizontal direction, the upper or lower ends of which (or both) are connected to an artery. The perforated plates make in a form and the sizes according to structure. The stamped and perforated recesses in them can have the form of the truncated cone, or longitudinal slots with openings facing upwards.

We will calculate the capillary-porous cooling system, made in the form of a box-shaped form (caisson).

The hydraulic resistance is determined by Darcy's law

$$\Delta P = \mu_{liq} \cdot m_{liq} \cdot l \,/(p_{liq} \cdot F_{\phi} \cdot K_{cond}),\ N/m^2,$$

where K_{cond} is the conditional permeability coefficient, which we determined experimentally [2];
$K_{cond} = 5.5 \cdot 10^{-7} \cdot (b_h/d)^{-1.29} = 5.5 \cdot 10^{-7} \cdot (0.55/0.2)^{-1.29} = 1.49 \cdot 10^{-7} \text{m}^2$;
b_h – hydraulic structure diameter; $b_h = 2 \cdot 5.5 \cdot 10^{-3}/2 = 0.55 \cdot 10^{-3}$ m;
d – average diameter of wire mesh; $d = 0.2 \cdot 10^{-3}$ m;
μ_{liq} – dynamic viscosity of a liquid;
at p = 146 bar, $t_w = 360$ °C, $\mu_{liq} = 77.5 \cdot 10^{-6}\ Pa \cdot s$;
m_{liq} – flow rate of a liquid;
$m_{liq} = \beta \cdot q \cdot F_u/\text{r} = 1.1 \cdot 6 \cdot 10^5 \cdot 0.942/1027 \cdot 10^3 = 0.605$ kg/s;
β – coefficient of fluid excess; the optimal value is determined experimentally by us, $\beta = 1{,}1$ [5];
q_u – heat load, $q_u = 6 \cdot 10^5$ W/m^2 (take the maximum value);
r – heat of vaporization, r $= 1027 \cdot 10^3$ J/kg;
F_u – heat exchange surface; take $F_u = 1 \cdot 0.942 = 0.942$ m^2;
p_{liq}– density of the liquid; $p_{liq} = 610$ kg/m^2;
F_{ϕ} – "live" section of the capillary-porous mesh structure;
$F_{\phi} = l \cdot \delta_{\phi} = 1 \cdot 1.04 \cdot 10^{-3} = 1.04 \cdot 10^{-3}$ m^2;
ε – porosity of structure; $\varepsilon = 0.7$;
δ_{ϕ} – thickness of structure; $\delta_{\phi} = 2 \cdot 0.52 \cdot 10^{-3} = 1.04 \cdot 10^{-3}$ m.

Then

$$\Delta P = \frac{77.5 \cdot 10^{-6} \cdot 0.605 \cdot 1}{610 \cdot 1.04 \cdot 10^{-3} \cdot 1.49 \cdot 10^{-7}} = 494 \text{ Pa}.$$

The hydraulic resistance of the mesh structure operating only in the field of capillary forces, as in the case of heat pipes, will be equal to

$$\Delta P = \frac{77.5 \cdot 10^{-6} \cdot (0.605/6) \cdot 1}{610 \cdot 1.04 \cdot 10^{-3} \cdot 7.14 \cdot 10^{-10}} = 2 \cdot 10^4 \text{ Pa},$$

where 0.605/6 is recalculation by the magnitude of the critical heat load, which in heat pipes is six times less; the value of K_{cond} in the field of capillary forces is [2]:

$$K_{cond} = 4.305 \cdot 10^{-10} \cdot (b_h/d)^{0,5} = 4.305 \cdot 10^{-10} \cdot (0.55/0.2)^{0,5} = 7.14 \cdot 10^{-10} \text{ m}^2,$$

i.e. the hydraulic resistance of the offered structure will be in $494/2 \cdot 10^4 = 404$ time less. When comparing the mesh structures with ceramic-metal, felt and powder materials, for which the maximum permeability can be $11 \cdot 10^{-10}$ m^2, i.e. in total, in $\frac{1.1 \cdot 10^{-9}}{7{,}14 \cdot 10^{-10}} = 1{,}54$ times more than for the mesh structures operating in the field of capillary forces, and the hydraulic resistance is less in 1.54 times.

In the proposed capillary-porous structure operating under the combined action of mass and capillary forces, the hydraulic resistance at boiling of water will be 40.4 times less than in heat pipes with fine-cell meshes, and even more so with fibrous and ceramic materials that allows to cool the heating surfaces of the larger sizes in relation to caissons of melting furnaces.

To calculate the heat transfer coefficient, we use the criterial equation [9], which we received as a result of generalization of the experimental data at boiling of water in a capillary-porous structure operating in the field of capillary and mass forces:

$$St_u' \cdot Pr_{liq}^{0.6} \cdot (F_u/F_\phi)^{0.74} = 59 \cdot N_g^{0.3} \cdot \overline{m}^{\,a} \cdot \left(\frac{\lambda_{ef}}{\lambda_{liq}}\right) \cdot k_w^{-1} \cdot \overline{N}_p^{0.23} \cdot Re_v^{-0.53}, \quad (2)$$

where St_u' - Stanton number, $St_u' = a_u/(G_{liq} \cdot C_{Pliq})$,
$a_u = q_u/(t_w - t_v)$, $W/m^2 \cdot K$;
N_g – Bond criterion: $N_g = (1 + \cos\beta) \cdot \rho_{liq} \cdot g \cdot b_h^2/\sigma$;
σ - surface tension coefficient, $\sigma = 0.00416\ N/m$;
$\beta = 90°$ - inclination angle of the evaporator;
$\overline{m} = 1.1$ – parameter considering excess of liquid;
G_{liq}- specific flow rate, $G_{liq} = p_{liq} \cdot w_{liq} = q_u \cdot F_u/(\varepsilon \cdot F_\phi \cdot r)$, kg/m^2s ;
ρ_{liq}- liquid density, $\rho_{liq} = 610\ kg/m^3$;
$N_g = (1 + \cos 90°) \cdot 610 \cdot 9.81 \cdot (0.55 \cdot 10^{-3})^2/0.00416 = 0.435$;
q_u – heat load, $q_u = 6 \cdot 10^5$ W/m^2;
C_{Pliq} – isobaric heat capacity of a liquid, $C_{Pliq} = 9185\ J/kg \cdot K$;
F_u – evaporator surface, $F_u = 0{,}942\ m^2$;
ε – porosity of structure ($\varepsilon = 0.7$);
F_ϕ – cross-sectional area of the wick, $м^2$; $F_\phi = 1.04 \cdot 10^{-3}\ m^2$;
r - evaporation heat, r = $1027 \cdot 10^3$ J/kg;
$G_{liq} = 6 \cdot 10^5 \cdot 0.942/(0{,}7 \cdot 1.04 \cdot 10^{-3} \cdot 1027 \cdot 10^3) = 776\ kg/m^2c$;
$Pr_{liq} = \nu_{liq}/a_{liq}$- Prantl number;
ν_{liq} – kinematic viscosity coefficient, $0.13 \cdot 10^{-8}\ m^2/s$;
a_{liq} – coefficient of thermal diffusivity of a liquid,
$a_{liq} = \lambda_{liq}/(\rho_{liq} \cdot C_{Pliq}) = 0.457/610 \cdot 9185 = 8.1 \cdot 10^{-8}\ m^2/s$;
$Pr_{liq} = 0.13 \cdot 10^{-8}/8.1 \cdot 10^{-8} = 1.606$;
$a = 0$ – coefficient at parameter $\overline{m}$ in the equation (2), since $q_u > 5 \cdot 10^4\ W/m^2$;
$\lambda_{ef}, \lambda_{liq}$– coefficients of thermal conductivity (effective and for liquid);

$$\lambda_{ef}/\lambda_{liq} = 1 + (0.5 \cdot a' \cdot b_h + c)^{-1}, \quad (3)$$

where the coefficient for the brass $a' = 1.8 \cdot 10^3$ m^{-1}; $c = 0.73$;

$$\lambda_{ef}/\lambda_{liq} = 1 + (0.5 \cdot 1.8 \cdot 10^3 \cdot 0.00055 + 0.73)^{-1} = 1.816;$$

k_w – coefficient considering the heat storage capacity of the wall,

$$k_w = 1 + \left[\frac{(\rho \cdot C \cdot \lambda)_{liq}}{(\rho \cdot C \cdot \lambda)_w}\right]^{0,5}, \quad (4)$$

where for brass wall $\rho = 8.5 \cdot 10^3\ kg/m^3$; $C = 392\ J/kg \cdot K$; $\lambda = 109\ W/m \cdot K$,

$$k_w = 1 + \left[\frac{(610 \cdot 9185 \cdot 0{,}457)_{liq}}{(8500 \cdot 392 \cdot 109)_w}\right]^{0,5} = 1.084;$$

N_p – pressure criterion, $N_p = \sigma/(P_v \cdot b_h)$;
$N_p = 0.00461/(14.6 \cdot 10^6 \cdot 0.00055) = 5 \cdot 10^{-7}$;
Re_v – Reynolds criterion; $Re_v = b_h \cdot w_v/\nu_v$,

where w_v - average vapour velocity, $w_v = q_u/(r \cdot \rho_v)\ m/s$;
ρ_v – vapour density, $\rho_v = 101.01\ kg/m^3$;
ν_v – kinematic viscosity of vapour, $\nu_v = 0.2 \cdot 10^{-6}\ m^2/s$;
$w_v = 600000/(1027000 \cdot 101.01) = 0.0058\ m/s$;
$Re_v = 0.00055 \cdot 0.0058/0.2 \cdot 10^{-6} = 13.9$.

Then the Stanton number from the criterion equation (2) is equal to

$$St_u^{'} = 8.2 \cdot 10^{-4}.$$

The heat transfer coefficient α_u is equal to

$$\alpha_u = St_u^{'} \cdot G_{liq} \cdot C_{Pliq} = 8.2 \cdot 10^{-4} \cdot 776 \cdot 9185 = 5898\ W/m^2 \cdot K.$$

Further, the caisson wall temperature is defined

$$t_{w.u} = q_u/\alpha_u + t_v = 600000/5898 + 350 = 470\ °C.$$

The received value of the wall temperature satisfies the conditions of reliable operation of the equipment. Therefore, a structure with such geometric characteristics should be adopted.

3. CONCLUSION

Thus, in comparison with other existing cooling systems (ceramic-metal, felt or powder) the mesh capillary-porous structure working in the field of mass forces has a number of advantages. The permeability coefficient becomes smaller and the hydraulic resistance of the entire structure decreases. There is no need for additional settings for a delivery or drive of such a system, because the motion of the liquid is due to mass and capillary forces in the capillary-porous structure selected experimentally.

Hydraulic resistance at boiling water will be 40.4 times less than in heat pipes with fine cell meshes, and even more so with fibrous, powder or ceramic materials. This allows to cool caisson surfaces of large dimensions.

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ЖОҒАРҒЫ ҮДЕМЕЛІ КАПИЛЛЯРЛЫҚ-КЕУЕКТІК ЖЫЛУАЛМАСТЫРҒЫШТЫ ЗЕРТТЕУ ЖӘНЕ ЕСЕПТЕУ

Аннотация. Балқыту агрегаттарының кессондарын салқындатудың капиллярлық-кеуектік жүйесі зерттеліп, әзірленіп және есептелді. $(2\times0.55)\cdot10^{-3}$ м торлы кеуекті құрылымның тәжірибелік түрі анықталды. Салқындату жүйесінің жылу беру қасиеті алты есе артты. Әсіресе, талшықты, ұнтақты және керамикалық материалды жылулық құбырлардың білтелері үшін, судың қайнау кезінде гидравликалық кедергісі торлы жылулы құбырларға қарағанда 40,4 есе аз болады. Кессон кеуектік құрылымдағы сұйықтың аз мөлшері есебінен пештердің салқындатуын жарылыссыз жүргізуге мүмкіндік береді. Агрегат қаптауының кессондау жүйесі және капиллярлық-кеуектік жүйесімен кессонды салқындату сұлбасы көрсетілген. Біздің тәжірибелік зерттеулерде капиллярлық-кеуектік құрылымдағы гидравликалық кедергі, ағынның жылдамдығы мен толық қызбауын анықтайтын, сұйықтың артығын ескеретін жылуалмасудың критериалық теңдеуі және қабырғаның жылуаккумуляторлық қасиеті алынды.

Тірек сөздер: капиллярлық-кеуекті жүйе; гидравликалық кедергі; салқындату жүйе; кессон; жылулық ағын.

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ИССЛЕДОВАНИЕ И РАСЧЕТ ВЫСОКОФОРСИРОВАННОГО КАПИЛЛЯРНО-ПОРИСТОГО ТЕПЛООБМЕННИКА

Аннотация. Исследована, разработана и рассчитана капиллярно-пористая система охлаждения кессонов плавильных агрегатов. Определен экспериментальный вид сетчатой пористой структуры $(2\times0.55)\cdot10^{-3}$ м. Увеличена в шесть раз теплопередающая способность системы охлаждения. Гидравлическое сопротивление при кипении воды будет в 40,4 раза меньше, чем в сетчатых тепловых трубах, и тем более для фитилей тепловых труб с волокнистыми, порошковыми и керамическими материалами. Кессон позволяет проводить охлаждение печей взрывобезопасно за счет содержания малого количества жидкости в пористой структуре. Представлена система кессонирования футеровки агрегата и схема охлаждения кессона капиллярно-пористой системой. Гидравлическое сопротивление в капиллярно-пористой структуре, критериальное уравнение теплообмена с учетом избытка жидкости, определяющим скорость и недогрев потока, и теплоаккумулирующей способностью стенки получены нами в результате экспериментальных исследований.

Ключевые слова: капиллярно-пористая система; гидравлическое сопротивление; система охлаждения; кессон; тепловой поток.