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INTENSIFICATION OF HEAT EXCHANGE WITH SURFACE BOILING OF WATER IN PIPES WITH ANNULAR TURBULIZER

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The article demonstrates the possibility of greatly intensifying heat exchange with surface boiling of water moving in pipes with annular diaphragm.

Reducing the weight and dimensions of evaporative heat exchange apparatus used in the chemical and food industry and other fields of engineering is an important scientific and technical as well as an economic problem. One of the most promising ways of solving this problem is intensification of heat exchange by artificial turbulization of the flow.

In many evaporative apparatuses the heating medium is condensing steam, and inside the pipes surface boiling takes place. The practical realization of most of the known methods of intensifying heat exchange in these apparatuses is prevented because there is no technology for the mass production of the investigated heat exchange surfaces, because it is necessary to work out a special technology of assembling heat exchange apparatuses consisting of these surfaces, because of the relatively low efficiency, and because of the lack of simultaneous intensification of heat exchange outside and inside the pipes.

At the Moscow Aviation Institute a method of intensifying heat exchange in tubular heat exchange apparatuses was worked out, and the efficiency of the method was tested in pipes, annular channels, and longitudinally washed bundles of pipes with gas and liquid flow [1]. The essence of the method consists in producing evenly spaced annular grooves (by rolling) on the outer surface of pipes (Fig. 1). These grooves and the annular diaphragms with smooth configuration forming on the inner surface of the pipes turbulize the flow in the near-wall layer and intensify heat exchange outside and inside the pipe. Yet the outer diameter of the pipes is thereby not increased, and this makes it possible to leave the existing technology of assembling tubular heat exchangers unchanged. Such pipes are also fairly free of pollution and salt deposition. Production of the pipes with rolled grooves is carried out on standard equipment.

Investigations [2] showed that with film condensation on the outer surface of vertical pipes, the annular grooves increase the heat transfer coefficient by a factor of 1.7-2.8. The object of the present work is to study the possbility of intensifying heat exchange by the method in question when there is surface boiling of a liquid in pipes.

The experimental section (Fig. 1) was a vertical single-pipe evaporator 1. Experiments were carried out with the boiling of water heated to 95-97°C in tank 6. Water circulation was ensured by pump 5. The water-steam mixture from the evaporator was fed to the separator 9 where the steam was separated from the liquid. The liquid was returned to tank 6, and the steam was pumped by the vacuum pump via condenser 8 into the measuring vessel 4. The water flow rate at the inlet to the experimental section was measured by the rotameter 3.

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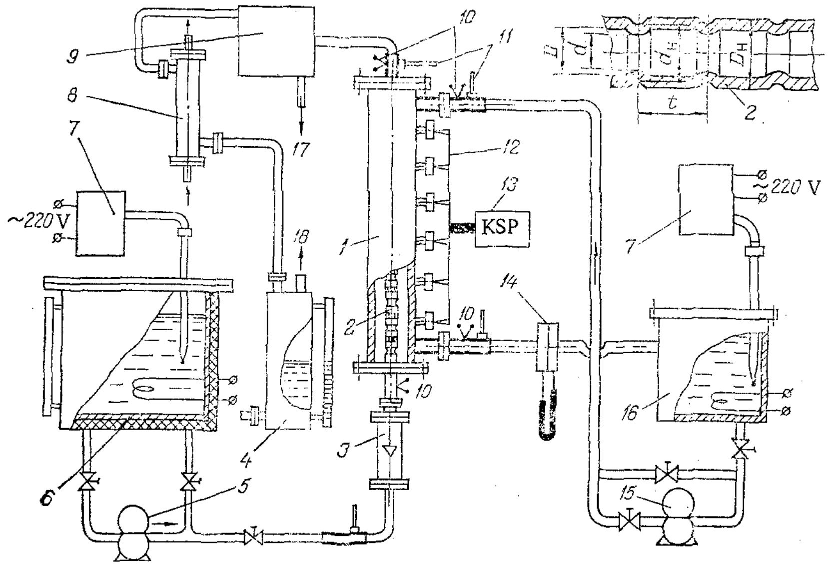

Fig. 1. Diagram of the experimental installation: 1) experimental evaporator; 2) test pipe; 3) rotameter; 4) measuring vessel; 6) tank for heating water; 7) regulating contact thermometer; 8) auxiliary condenser; 9) separator; 10) thermocouples; 11) thermometers; 12) thermocouples for measuring the wall temperature; 13) potentiometer KSP-4; 14) diaphragm flow meter; 15) oil pump; 16) tank for heating oil; 17) discharge of liquid into tank 6; 18) main to vacuum pump.

Industrial oil I-20 heated in tank 16 to 130-150°C was fed by pump 15 into the space between the pipes. The oil flow rate was ascertained with the aid of a measuring diaphragm mounted in a pipe with 50-mm diameter and produced in accordance with [3].

The heat exchange pipe of the experimental section, with 16/1 mm diameter, 1500 mm long, was made of steel 1Kh18N10 and was mounted inside a smooth pipe with inner diameter D_2 = 25 mm. We investigated apparatuses with a smooth pipe and with five versions of pipes with rolling parameters inside (three pipes with a pitch of rolling $t/D = 0.572$ and a ratio of the diaphragm and pipe diameters $d/D = 0.883$, 0.904, 0.931, and two pipes with $t/D = 0.286$ and $d/D = 0.884$, 0.908). The width of the annular diaphragms was ∿2 mm.

The wall temperature of the experimental pipes was measured at nine points over their length by Chromel—Copel thermocouples whose thermoelectrodes had a diameter of 0.15 mm. The temperature of the oil and water at the inlet and outlet was also measured.

The principal parameters in the experiments changed within the following limits: water temperature at the inlet $t_f' = 95\text{-}97°C$, at the outlet $t_f'' = 98\text{-}100°C$, water flow rate $G = (64\text{-}200)\cdot 10^{-3}$ kg/sec, Reynolds number $Re_f = (2\text{-}6)\cdot 10^4$, temperature of the inner surface of the pipes $t_w = 101.4\text{-}106.3°C$, water pressure ∿0.1 MPa, heat flux density $(1.8\text{-}8)\cdot 10^4$ W/m². On the hot side the regime parameters were: oil temperature at the inlet $t_{fo}' = 130\text{-}150°C$, at the outlet $t_{fo}'' = 123\text{-}144°C$, flow rate $G_o = (0.37\text{-}0.5)$ kg/sec, $Re_{fo} = (4.8\text{-}8.4)\cdot 10^3$, Prandtl number $Pr_{fo} = 47\text{-}60$. Divergence in the heat balance of the experimental section did not exceed ±7%. The relative error of determining the heat-transfer coefficient corresponding to a confidence level of 0.997 was equal to 7-8%.

We determined the heat-transfer coefficient averaged over the length, outside and inside the pipe. Yet we did not take into account the increase of the heat-exchange surface on account of the grooves outside and the protrusions inside, and the heat flux was calculated for the surface of a smooth pipe.

In the determination of the mean heat-transfer coefficient inside the pipe as

$$\alpha = \frac{q}{\bar{t}_w - t_s}, \tag{1}$$

the data for a smooth pipe are in satisfactory agreement with Labuntsov's interpolation dependence for calculating heat transfer in bulk boiling under conditions of forced convection in pipes [4]:

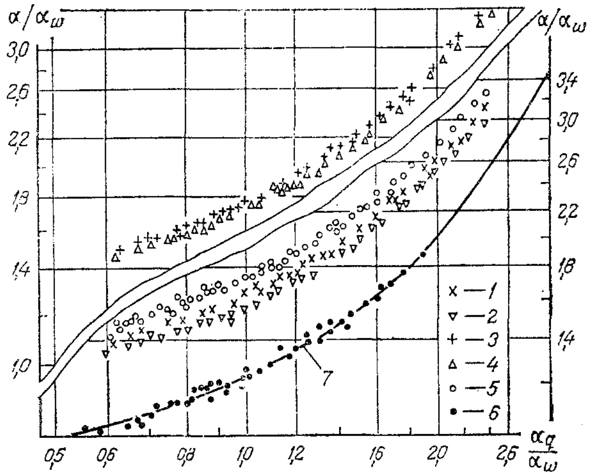

Fig. 2. Dependence of the ratio α/α_w on the ratio α_q/α_w in surface boiling of water in pipes with annular turbulizers: 1) d/D = 0.904; t/D = 0.571; 2) 0.931 and 0.571; 3) 0.884 and 0.286; 4) 0.908 and 0.286; 5) 0.883 and 0.571; 6) smooth pipe; 7) by formula (2).

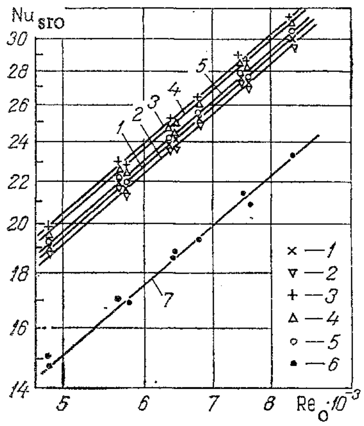

Fig. 3

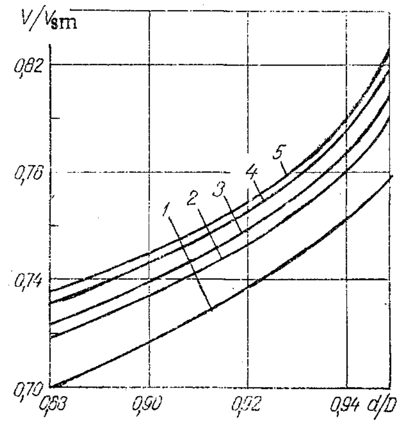

Fig. 4

Fig. 3. Intensification of heat exchange upon flow of oil in an annular channel on the inner surface $Nu_{sro} = Nu_{fo}/(Pr_{fo}^{0.4} \cdot (Pr_{fo}/Pr_{wo})^{0.25}(D_2/D_0)^{0.18})$: 1) $h/d_e = 0.0827$; $t/d_e = 0.889$; 2) 0.0613 and 0.889; 3) 0.0827 and 0.444; 4) 0.0613 and 0.444; 5) 0.1067 and 0.889; 6) smooth pipe; 7) by formula (6).

Fig. 4. Relative reduction of the volume of a tubular evaporator by the use of pipes with annular turbulizers in dependence on d/D and α/α_0 for t/d = 0.286: 1-5) α/α_0 = 0.2, 1, 2, 5, 10, respectively.

$$\frac{\alpha}{\alpha_w} = \frac{4\alpha_w + \alpha_q}{5\alpha_w - \alpha_q}, \tag{2}$$

where α_w is the heat-transfer coefficient determined by formulas of convective heat exchange of a single-phase liquid; α_q is the heat-transfer coefficient calculated by the dependences for bulk boiling (Fig. 2). To find α_w, we used the dependence [5]

$$Nu_f = 0.023\, Re_f^{0.8}\, Pr_f^{0.4} \left(\frac{Pr_f}{Pr_w}\right)^{0.06}. \tag{3}$$

As determining temperature we took $t_f = 0.5(t_f' + t_f'')$, and for α_q we took the dependence [4]

$$Nu_* = 0.125\, Re_*^{0.65}\, Pr^{1/3}, \tag{4}$$

where $Nu_* = \alpha_q l_*/\lambda$; $Re_* = q l_*/r\rho''\nu$, $l_* = c_p\rho'\sigma T_s/(r\rho'')^2$. The values of ν, c_p, λ, Pr were found for a liquid at the temperature t_s. It can be seen from Fig. 2 that the ratio α_w/α_q = 0.5-2.4, i.e., the experiments were carried out in a range in which the heat exchange was determined both by forced convection and by boiling.

Figure 2 also presents data on the heat transfer for pipes with annular turbulizers. The values of α_q and α_w were determined for a smooth pipe. It can be seen from the figure that annular diaphragms increase the mean heat-transfer coefficient by 30-40%, and they increase it the more, the deeper the rolled grooves are (the smaller d/D is), the smaller the pitch of the grooves t/D is, and the smaller the ratio α_q/α_w is, i.e., the larger the contribution of forced convection to the total heat transfer is.

The obtained experimental data on the intensification of heat exchange are generalized by the dependence

$$\frac{\alpha}{\alpha_{sm}} = 1 + 1.35\left(1 - 0.371\frac{t}{D}\right)\left(1 - \frac{d}{D}\right)^{0.418}\left(1 - 0.104\frac{\alpha_q}{\alpha_w}\right), \tag{5}$$

which is correct for t/D = 0.25-0.6; d/D = 0.88-0.94; α_q/α_w = 0.5-2.4, whereby α_{sm} is determined by (2), α_w by (3), α_q by (4).

Figure 3 presents the experimental data on the mean heat transfer when oil is cooled in an annular gap. It can be seen from the figure that the data for the smooth pipe agree satisfactorily with the dependence [6]

$$Nu_{fo} = 0.017\,Re_{fo}^{0.8}Pr_f^{0.4}\left(\frac{Pr_{fo}}{Pr_{wo}}\right)^{0.25}\left(\frac{D_2}{D_o}\right)^{0.18}. \tag{6}$$

As determining temperature we used $t_{fo} = 0.5(t'_{fo} + t''_{fo})$.

According to Fig. 3, the annular grooves on the inner pipe increase the mean heat transfer by 25-37%, and the increase is the greater, the deeper the grooves are and the smaller their spacing is. In the investigated range of Re_{fo} the intensification of heat exchange is generalized by the dependence

$$\frac{Nu}{Nu_{sm}} = 1 + 0.42\left[1 - \exp\left(-33.8\frac{h}{d_e}\right)\right]\left(1 - 0.282\frac{t}{d_e}\right), \tag{7}$$

which is correct for h/d_e = 0.06-0.11, t/d_e = 0.4-0.9 and D_2/D_o = 1.56. The intensification of heat exchange in the given channel for the same h/d_e and t/d_e is somewhat lower than according to the data of [1] obtained for channels with smaller D_2/D_o.

Thus, the investigations showed that heat exchange can be substantially intensified in forced flow of a liquid in pipes under conditions of surface boiling. The use of pipes with annular turbulizers makes it possible to reduce the volume of evaporative heat exchangers while maintaining their thermal power.

In the case of evaporators with single-phase hot heat carrier the volume of the apparatus can be reduced by 30% (Fig. 4). The calculation was carried out by a method explained in [1]. If condensing steam is used as heating medium, then the intensification of heat exchange on the outer surface of the pipes is more substantial than in flow of a single-phase liquid, and the volume of the heat exchanger may be reduced by 40-44% as against an apparatus with smooth pipes.

NOTATION

c_p, heat capacity; D, inner pipe diameter; D_o, outer pipe diameter; d, diameter of the annular diaphragms; d_o, diameter of the annular grooves; D_2, inner diameter of the outer pipe of the annular channel; d_e, equivalent diameter of the annular channel; h, depth of the grooves; q, heat flux density; r, heat of evaporation; t, spacing of the diaphragms and grooves; t'_f, t''_f, temperature of the flow at the inlet and outlet, respectively; T_s, saturation temperature, °K; α, heat-transfer coefficient; ρ', ρ'', density of the liquid and vapor, respectively, at T_s; ν, coefficient of kinematic viscosity; σ, surface tension; λ, thermal conductivity; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number. Subscripts: f, liquid; w, wall; s, saturation; o, outer pipe surface; sm, smooth pipe.

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DEGREE OF NONEQUILIBRIUM OF THE VAPOR AND LIQUID PHASES DURING THE BOILING OF BINARY CRYOGENIC MIXTURES

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Results of a theoretical and experimental investigation are presented for liquid-vapor compositions during the boiling of binary cryogenic mixtures. Factors affecting the degree of phase nonequilibrium are set down.

The majority of processes utilized in cryogenic engineering is accompanied by heat and mass transfer during the phase transitions of binary and multicomponent mixtures. Realization of different technological operations during the storage, transportation, and retention in a cryostat is associated with the boiling of liquid mixtures and with their partial or total evaporation.

Mass transport of components within the phase and between the phases occurs together with phase transformation during the boiling of mixtures. One of the quantities exerting substantial influence on the integrated characteristics of the mixture boiling process is the distinction between the compositions of the liquid and vapor phases. By the equilibrium condition a greater low-boiling component is contained in the vapor than in the liquid. The gradual diminution of the low-boiling component in the liquid is associated with its excess concentration in the vapor and, as a result, so is the rise in the mixture boiling point. This exerts influence on the dynamics of the formation, growth, separation, and buoyancy of the vapor bubbles [1].

The change in composition of the liquid residue is determined by the concentration of the mixture components in the outgoing vapor, which is also related to the hydrodynamic and thermal conditions under which the boiling process progresses. The question of the vapor composition being formed here is studied extremely minimally and data in the literature are contradictory. Existing computational dependences of the change in mixture component concentration during boiling are obtained for equilibrium conditions, the deviation from which in real processes can be quite substantial [2, 3]. The determination of the nonequilibrium of the liquid-vapor phases is especially urgent for cryogenic mixtures since the accumulation of the fast-boiling components in the liquid residue is associated with the possibility of their deposition in solid form in different elements of the system and thereby creation of a dangerously explosive situation.

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