STATE-OF-THE-ART OF THE HEAT TRANSFER INVESTIGATIONS OF TWO-PHASE FLOWS OF NATURAL HYDROCARBONS USED AS WORKING FLUIDS OF GEOTHERMAL BINARY POWER PLANTS

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KEYWORDS

Hydrocarbons, heat transfer, two-phase flow

ABSTRACT

The analysis of the existed experimental data and predictive correlations on heat transfer in two-phase flows of paraffin hydrocarbons is presented. These hydrocarbons are considered as promising coolants and working fluids of the binary geothermal power plants (GeoPP). The complicated nature of heat transfer in steam-generating channels, in which two zones with very different heat transfer rate exist, is considered. In the first (precrisis) zone, the heat transfer coefficient is high, whereas, in the second (postcrisis) one, it is low. The comparison of thermohydraulic characteristics of the channels is conducted, taking isobutane and Freon 142b as typical working fluids of GeoPP. The effect of different factors (such as a presence of oxygen or inert gases, using binary mixtures of hydrocarbons, and the like) on heat transfer rate is discussed.

1. INTRODUCTION

The design of heat-transfer equipment of a binary GeoPP, first of all of a steam generator, should be accomplished with an account of rather complex processes of two-phase heat transfer [1]. In this case, special emphasis should placed on a steam-generating (evaporation) part of the installation, where a considerable (by many times) change in a heat-transfer coefficient value can take place along the heat-exchanger tube. The latter occurs due to a change in a heat-transfer mechanism as the steam quality increases along the tube. The assessments show that 70—80% of the total heat power is transferred in the steam-generating part of the heat-transfer equipment.. The contribution of this part into the total area of the heat-transfer surfaces is as high as 80—90%. Correspondingly, the main portion of the equipment weight and cost are due to this part of equipment, as well. Thus, the main reserves in reducing the cost of equipment are connected with the steam-generating part of the installation. In contrast to steam-generating devices of common thermal power stations, the tubes of the steam generator of the bottoming part of the binary GeoPS, operate with small (of no more than 15—20°C) and, as a rule, constant (given) temperature differences between the heating agent and the working fluid. Therefore, there is no problem of overheating (rupture) of the heat-transfer surfaces with an incipience of the heat-transfer crisis and there is only a danger of reducing steam output.

To choose the design parameters of the tube bundles of heat-transfer devices (steam generators, superheaters), which provide the given regime of an efficient operation, the reliable and verified methods of calculating thermohydraulic characteristics, including heat-transfer coefficients and pressure drop under forced-flowboiling of saturated hydrocarbons in single tubes and tube bundles with different orientation in a space, are needed. This problem can be solved or by using

reliable correlations, which generalize experimental data on boiling heat transfer of hydrocarbons in a wide range of the regime parameters, or by conducting necessary experimental studies and developing corresponding engineering methods of calculations. In the present paper we analyze the state-of-the-art of the studies of heat transfer in two-phase flows of natural hydrocarbons.

2. COMPARATIVE CHARACTERISTICS OF PARAFFIN HYDROCARBONS AND FREONS

Among possible working fluids of a GeoPP, which utilizes heat of geothermal fluids with a temperature of from 120 to 165°C, Freons and natural hydrocarbons (propane, butane, isobutane, pentane, and isopentane) and their mixtures are considered [2].

In Table 1, thermophysical properties of the isobutane and Freon 142b at a pressure of approximately 1.6 MPa and a temperature of 90°C are compared. They are taken as typical representatives of Freons and hydrocarbons, respectively, that are widely used in heat transfer devices in refrigeration technologies. The VNIIKholodMash Holding considers these substances as the main alternatives of the working fluids for binary GeoPP. We see that the latent heat of evaporation and the specific heat of the liquid isobutane are approximately two times higher than those for the Freon 142b. This means that using hydrocarbons reduces the coolant flow rate by approximately two times and considerably decreases power for its pumping. In accordance with the estimates, such characteristics as the Pr number an the evaporation velocity $q/r\rho''$, which are important for heat transfer, are the same for both the substances. From this, it follows that, for both working fluids, the heat transfer coefficients should be close to each other.

The drawback of hydrocarbons is their relatively easy ignitability, explosion hazard, and toxicity. Propane, butane, and isobutane are the most explosion hazardous ones; their permissible concentration in the air is 1.5–8.5%. In the air, the inflammation temperature of pentane is 309°C. As to interaction of the working fluids with environment (destruction of the ozone layer of the atmosphere of the Earth), hydrocarbons are the most save ones.

Table 1. Properties of working fluids

Property	Isobutane	Freon 142b
Saturation pressure P_s (MPa)	1.54	1.65
Saturation temperature T_s (°C)	87	90
Liquid density ρ' (kg/m^3)	455	881.5
Vapour density ρ'' (kg/m^3)	42.2	78.5
Specific heat of liquid c_p' (kJ/kg K)	2.95	1.49
Latent heat of evaporation (kJ/kg)	239.6	152.1
Dynamic viscosity of liquid μ' (Pa s)	$74\ 10^{-6}$	$118\ 10^{-6}$
Kinematic viscosity of liquid ν', (m^2/s)	$0.162\ 10^{-6}$	$0.157\ 10^{-6}$
Thermal conductivity of liquid λ', (W/m K)	0.073	0.070
Thermal diffusivity of liquid a', (m^2/s)	0.54	0.57
Surface tension σ, (H/m)	$3.6\ 10^{-3}$	$4\ 10^{-3}$
Prandtl number Pr	2.99	2.72
Evaporation velocity $q/r\rho''$, m/s at q = 20 kW/m^2	0.002	0.0017

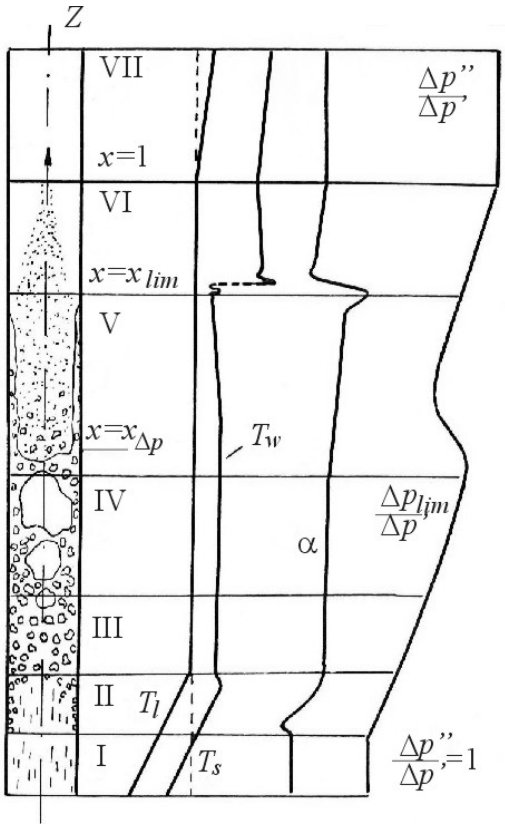

Fig. 1. Distribution of the main two-phase flow parameters along the length of vertical channel

When choosing a working fluid, the very important index is its cost. The low cost of hydrocarbons (isobutane and isopentane), as compared to that of Freons, and favorable physical properties enable us to consider them as rather promising working fluids for practical applications.

3. BOILING IN TUBES UNDER FORCED FLOW CONDITIONS

When a liquid boils in steam-generating channels, we have rather complicated distribution of the main thermohydraulic parameters along the channel length. As an example, Fig. 1 shows the known diagram of the distribution of the wall and liquid temperatures, the heat transfer coefficient, and the relative pressure drop along the length of the vertical channel in a two-phase flow. From the figure we see that the steam-generating part of the channel can be subdivided into two zones. The first one is the precrisis zone with a high level of heat transfer and the second one is the postcrisis zone with a low intensity of heat transfer. In its turn, the precrisis zone can be also subdivided into three regions: the region of dominating effect of nucleate boiling, the transition region, where both boiling and forced convection influence heat transfer, and the region, where forced convection has a main effect.

3.1. Experimental data

Studying of boiling heat transfer of paraffin hydrocarbons and their mixtures under conditions of forced convection is of great practical significance. Nevertheless, there is a very limited amount of experimental data in this field. In many respects this is due to large expenditures required to provide a safety of experiments with toxic and easily inflammable substances. Table 2 shows the

conditions of experiments in [3—11], in which boiling heat transfer of paraffin hydrocarbons in tubes was studied. From Table 2 we see that the experiments mainly embraces the range of low absolute pressures from 0.1 to 1.0 MPa with small and moderate mass flow rates. All the experiments were conducted with the upward liquid flow in vertical channels.

One of the first works was [3], in which boiling heat transfer of cyclohexane, pentane, and heptane was studied in vertical tubes heated by the oil circulated in an annular gap. Local heat transfer was measured in the regions of nucleate and convective boiling. In the experiments, it was recognized that, for the pentane and heptane, the effect of nucleate boiling on heat transfer was negligible and, in the convective boiling range, the experimental data are generalized by the following correlation

$$\alpha_b/\alpha_{conv} = 3.5\ (1/X_{tt})^{0.5}, \qquad (1)$$

where $X_{tt} = [(1-x)/x]^{0.9}\ (\rho''/\rho')^{0.5}\ (\mu'/\mu'')^{0.1}$ is the Martinelli parameter and α_{conv} is calculated for the liquid flow by means of the formula for the single-phase convective heat transfer.

Table 2. Conditions of experiments on heat transfer of boiling paraffin hydrocarbons in tubes

The authors	Liquid	Orientation, sizes, material of test sections	Pressure (MPa)	Mass flow rate (kg/m^2s)	Heat flux (kW/m^2)
Guerrieri & Talty [3]	Pentane Heptane Cyclohexa-ne	Vertical tubes, brass, d=19,25.4mm, l=1.83, 1.98m	0.1 0.1 0.1	165-409 184-448 392-484	17.7-38.2 18.5-30 7.9-31
Blinov et al. [4,5]	Propane Butane	Vertical tube, stainless steel, d=8mm, l=0.99mm	0.3-1.15 0.15-0.33	300 118-708	4.9-11.5 10.1-80
Wadekar at al. [6-9]	Pentane Isooctane Mixture of pentane and isooctane	Vertical tube, stainless steel, d=25.4mm, l=8.5m	0.23-1 0.15-0.6 0.23	100-500 70-500 300	20-140 7-140 20-80
Yusufova at al. [10]	Isooctane	Vertical tube, stainless steel, d=7.2mm, l=0.7m	0.25-2.05	684	55-490
Koblyakov [11]	Butane Propane	Vertical tube, stainless steel, d=9.7mm l=2.23m,	2-4 2-4	37-455 37-455	50-100 50-100

In [4, 5], the experiments on boiling of butane and propane in a vertical tube heated by alternating electric current were conducted. Preliminarily purified butane and propane were used; the residual concentration of admixtures was no more than 3%. The experimental technique applied allowed to determine local heat transfer coefficients α with a maximal error of

no more than 20%. When assessing the effect of the forced convection on boiling heat transfer in tubes, the velocity of circulation w_c was used.

In the experiments, it was recognized that, with an increase in the heat flow rate q, the effect of the actual flow velocity on the heat transfer coefficient gradually decreases and, with certain values of q, the coefficient α is completely determined by q. With an increase in w_c and a decrease in q, the dependence of α on q becomes less pronounced and, with certain velocities, the heat transfer coefficient α is completely determined by forced convection and can be calculated by means of the following formula

$$\alpha = \lambda/d\ 0{,}023 Re^{0.8} Pr^{0.4}, \qquad (2)$$

where Re number contains an actual velocity of the liquid phase w_{act}.

The obtained experimental data were generalized in the following criterion form, proposed in [12]

$$Nu_b/Nu_l = 5540\ \Pi^{0.7} \qquad (3)$$

Here, $\Pi = [q/r\rho'' w_o(\rho''/\rho')^{1.45}\ (r/c_p T_s)^{0.33}]^{0.7}$. Eq. (3) can be used with $\Pi > 0{,}45.10^{-5}$. With $\Pi < 0{,}45\ 10^{-0.5}$, $Nu_b = Nu_l$ and α is calculated by means of (2). As is stated in [4, 5], these equations can be used to determine heat transfer coefficients, when boiling liquefied hydrocarbons in vertical tubes.

In [11], the experiments were conducted at high pressures up to the critical one with the subcooled liquid and the negative value of the relative enthalpy of the flow at the tube inlet. This is the specifics of these experiments. In several cases, when the liquid (butane, propane) started to boil, unstable regimes with low-frequency oscillations of pressure, flow rate, and wall temperature took place in the channel. In the study, nonmonotonous behavior of the heat transfer coefficient along the tube was recognized. In the range of negative and small positive steam qualities the coefficient α dramatically increases, reaching extremely high values of 20—40 kW / (m^2K). Then the coefficient α sharply decreases. In the author's opinion, this decrease corresponds to transition from the surface boiling to the transient film boiling regime, without meeting the developed boiling regime. The film boiling regime occurs in the outlet part of the tube. The sharp decrease in the heat transfer intensity did not result in a burnout of the tube wall. In the zones of the surface and film boiling, with an increase in heat flux, heat transfer rate also increased; the effect of the mass velocity on heat transfer was not recognized. Because of a very complex nature of a change in the heat transfer rate, the author did not make an attempt to use the existed calculating correlations to treat the experimental data obtained. In our opinion, the sharp increase of the wall temperature is, apparently, due to the liquid-film dryout and transition to the disperse flow regime. Moreover, in the vicinity of the critical point, with certain combination of the regime parameters, a deteriorated heat transfer can appear.

Recently, a large scope of experimental data on boiling heat transfer of the paraffin hydrocarbons in tubes was obtained in the Heat Transfer and Hydrodynamics Laboratory at Harwell (Great Britain) [6—9]. The tests were conducted at the installation with a vertical tube, which was instrumented with probes and modern diagnostic devices to measure the liquid and the wall temperatures, the flow rate, the heat flux, and the void fraction. The error of determination of the heat transfer coefficient was no more than 10%.

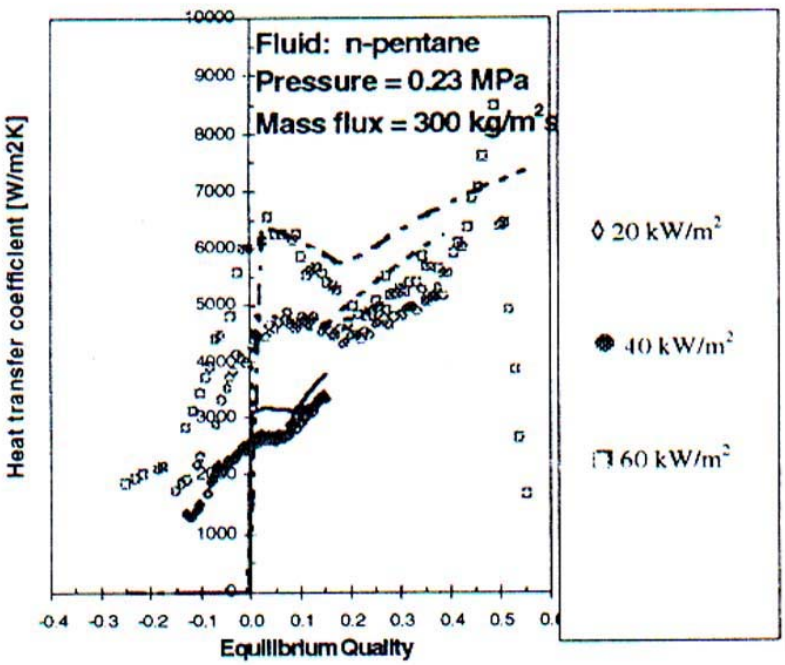

Fig. 2. Flow boiling heat transfer coefficients for pentane

The complicated nonmonotonous behavior of the heat transfer intensity along the tube length was also recognized in [6], when studying pentane boiling heat transfer with upward flow. The experimental data were treated as the dependence of α on the vapor quality x (Fig. 2). As in [11], the dependence had a maximum of α, after which the heat transfer intensity sharply decreased. The latter indicated the incipience of the heat transfer crisis due to liquid film dryout. Depending on a change in the vapor quality along the channel length, we can sort out the following three areas having different heat transfer intensity:

1) in the range of small x, nucleate boiling prevails and the heat flux q has a considerable effect on α;

2) in the intermediate range of x, the heat flux does not effect heat transfer, which, in the author's opinion, is caused by an incipience of the convective boiling;

3) with the high values of x, first, the heat transfer intensity dramatically increases and then sharply decreases due to the liquid film dryout.

We should note that the upper boundary of the vapor quality x, when deterioration of heat transfer occurs, is no more than 0.5, that is, the part of the channel downstream of this point will be occupied by the regime of the postcrisis heat transfer with a low intensity of the process. Therefore, a steam-generating channel can be conditionally divided into the range of the precrisis heat transfer, which incorporates the nucleate and convective boiling regimes with a high heat transfer coefficient of 2 to 5 kW / (m^2 K), and the postcrisis range with a low intensity of heat transfer of 1 kW / (m^2 K).

Fig. 3 shows the generalization of the experimental data as the dependence of the relative heat transfer coefficient $F = \alpha / \alpha_{conv}$ on the Martinelli parameter X_{tt}, with α_{conv} being calculated for the liquid phase by means of the correlation for a single-phase convective heat transfer. In the figure, we also find the curve, which corresponds to the Chen's equation [13]. The comparison of the experimental data with the calculations shows that, in the entire precrisis area, the experimental points locate considerably below the calculated curve. This is especially the fact with the small and moderate vapor qualities.

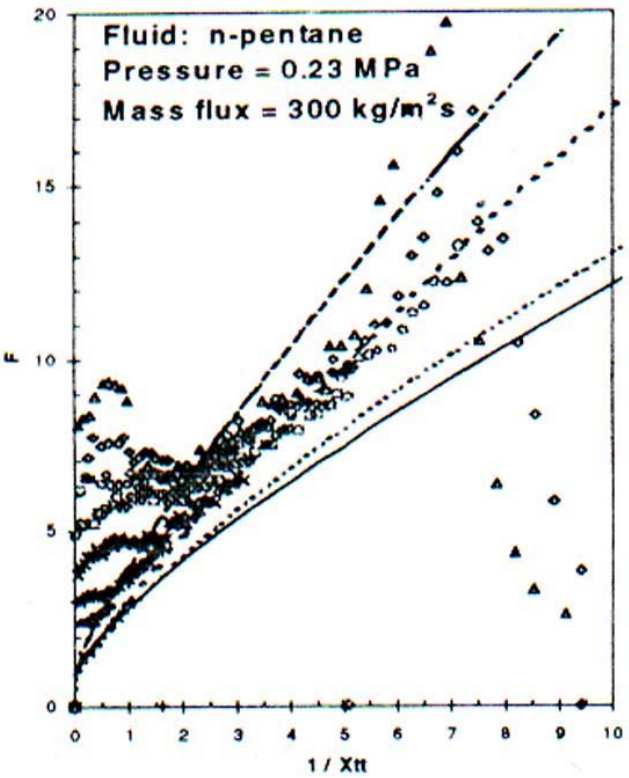

Fig. 3. Generalization of the experimental data [6]

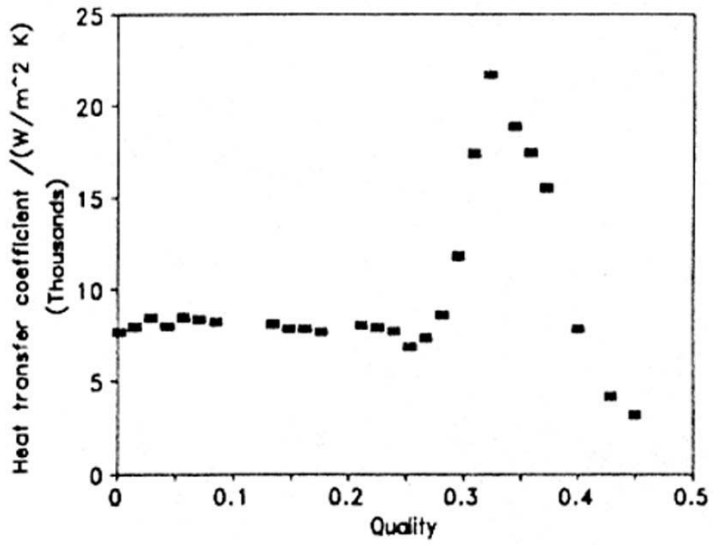

Fig. 4. Heat transfer coefficients at the dryout region under pentane flow boiling [7]

When boiling pentane [7], with $x = 0.3$, that is, in the area close to the boiling crisis, a decrease in the wall-temperature and a sharp increase in heat transfer took place (Fig. 4). This is, apparently, connected with formation of a churn film before its dryout.

In the tests on heat transfer with boiling of the pentane-isooctane mixture with a low vapor quality, the effect of degradation of the nucleate boiling regime was recognized. This effect was accompanied by extension of the range of the convective boiling. From Fig. 5, we see that a change in the heat flux essentially does not effect heat transfer coefficient. It reaches the

maximum value with $x = 0.3$; then, the coefficient monotonically decreases with an increase in the vapor quality. However, this effect is not connected with the film dryout. The authors explain such a change in the heat transfer coefficient with a decrease in the concentration of the low-volatile component in the wall layer. The authors also presented the analysis of the entrainment and deposition of droplets in the case of boiling of binary mixtures.

Fig. 6 shows the comparison of the experimental data on heat transfer under boiling of pentane, isooctane, and their mixtures having different concentration of the components in the range of small vapor qualities, with the mass flow rate, the pressure, and the heat flux being the same. We see, that for all the liquids investigated, the heat transfer coefficient does not depend on the vapor quality. As anticipated, with mixture boiling, the heat transfer coefficient was lower than that with boiling of pure pentane and isooctane.

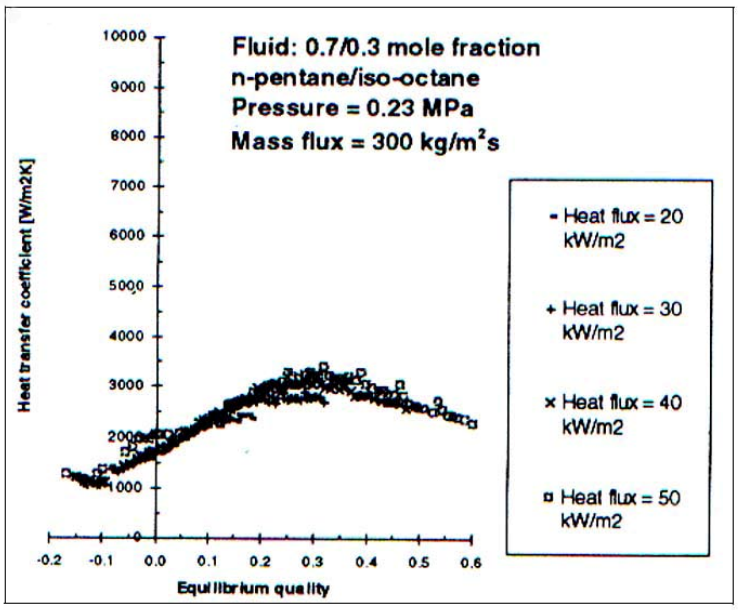

Fig. 5. Flow boiling heat transfer coefficients for pentane-isooctane mixture [6]

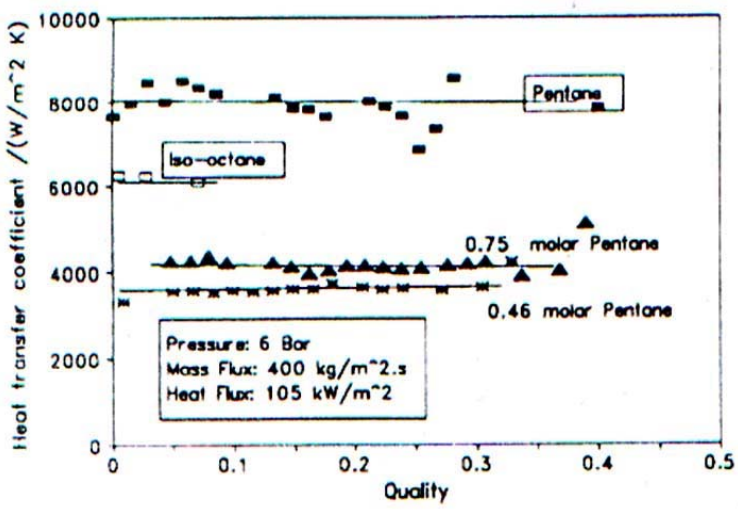

Fig. 6. Comparison of the heat transfer data with boiling pentane, isooctane and their mixtures in the range of small qualities [7]

When boiling takes place in the hydrocarbon two-phase flow, a degree of purification of the substance is of great importance. As is shown in [14], dissolved admixtures (inert gases, an oxygen, CO_2, hydrocarbons) can considerably effect saturated-hydrocarbon boiling heat transfer. However, this effect manifests itself in an ambiguous manner. According to [13], the presence of nitrogen, helium, argon, and carbon dioxide in the two-phase flow of heptane leads to an increase in heat transfer rate (CO_2 provides especially strong effect). At the same time, the presence of oxygen and hydrocarbons, noticeably decreases heat transfer rate. According to [15], the presence of O_2 of 0.2 to 5 volumetric percent provides formation of deposits, increases the thermal resistance of the wall, and decreases heat transfer irate because of hydrocarbon oxidation. The presence of the other hydrocarbons that promotes formation of binary mixture also leads to deterioration of heat transfer due to depletion of the wall layer with the low-boiling component.

3.2. Calculating correlations

Mechanism of the liquid boiling in tubes is a very complicated one. This makes it impossible to obtain physically substantiated similarity criteria to generalize experimental data. Therefore, theoretical calculations of heat transfer are not very suitable for engineering applications. Usually, to generalize experimental data on liquid boiling in channels, empirical correlations are used. In the literature on heat transfer studies in two-phase flows, different approaches to develop calculating correlations are met. These correlations manifest an attempt to account for the combined effect of several parameters typical of one or another regime of flow. In the range of the joint effect of boiling and forced flow, Kutateladze [16] proposed the following formula to calculate heat transfer coefficient α_{tp}

$$\alpha_{t\,p} = [1+(\alpha_b / \alpha_{conv})^2]^{0.5}, \qquad (4)$$

where α_b is determined by means of Kutateladze's formula for pool boiling [16], and α_{conv} is calculated for the single-phase flow in a tube with the circulation velocity.
For the flow with small vapor quality, when nucleate boiling prevails, Sterman [12] proposed the following correlation:

$$Nu_b / Nu_{conv} = 6150\,[q/r\rho'' w_o(\rho''/\rho')^{1.45}\,(r/c_p T_s)^{0.33}]^{0.7}, \qquad (5)$$

where Nu_b is the Nusselt number for the boiling heat transfer; Nu_{conv} is the Nusselt number without boiling, which is determined from (2). The correlation (5) is valid with $\Pi > 0{,}45.10^{-5}$.
To calculate heat transfer with liquid boiling under forced flow in vertical and horizontal tubes and channels, V.V.Klimenko [17] proposed the correlation, which generalizes a wide scope of liquids, including water, Freons, and cryogenic and organic liquids, as well. On the basis of experimental data, obtained in a wide range of the regime parameters, he proposed to divide the entire area of the two-phase heat transfer, which embraces different flow regimes, into two regions: the range of nucleate boiling, which is characterized by the bubble structure of the flow and a slight dependence of heat transfer on the mass flow rate, and the range of convective boiling, where heat transfer intensity is determined by the wall liquid film evaporation with the vapor bubbles formation being absent and with a strong influence of the mass flow rate. The following criterion was chosen to determine the boundary of the transition from the nucleate-boiling heat transfer to the convective-evaporation regime

$$N_{c.b} = (rG/q)[1+x(\rho'/\rho''-1)](\rho''/\rho')^{1/3} \qquad (6)$$

For all usual liquids considered, it was recommended: with $N<1,6.10^{-4}$, calculations should be made by means of the following correlation

$$Nu = 7.4.10^{-3}\, Pe^{0.6}\ K_p^{0.5}\, Pr'^{-1/3}\, K_\lambda^{0.15}, \tag{7}$$

and for the organic liquids, including paraffin hydrocarbons, by

$$Nu = 6.8.10^{-3}\, Pe^{0.6}\ K_p^{0.54}\, Pr'^{-1/3} K_\lambda^{0.12}. \tag{8}$$

These correlations are valid for the nucleate boiling region. With $N>1.6.10^{-4}$, which corresponds to the region of convective boiling, for all the liquids used for generalization, the calculations are conducted using the following formula:

$$Nu = 0{,}087\, Re^{0.6}\, Pr'^{-1/6}\, K_\lambda^{0.09}. \tag{9}$$

In the foreign literature, to generalize experimental data in the range of the convective boiling or under forced two-phase convection, the correlations, which are based on the Martinelli's parameter, are widely applied. These correlations have the following structure

$$\alpha_{tp}/\alpha_{conv} = F\, C\, (1/X_{tt})^n, \tag{10}$$

Among many formulae of such a type we can sort out the correlation of Chen [13], which embraces the range of the nucleate boiling. For the postcrisis zone, where there is no experimental data, the heat transfer coefficient can be assessed by means of the formula of Miropol'skii

$$Nu'' = 0{,}023\{Re''\, Pr''\, [x+\rho''/\rho'\, (x-1)]\}^{0.8}\, Y, \tag{11}$$

where $Y = 1 - 0{,}1(\rho'/\rho'' - 1)^{0.4}$

CONCLUSIONS

From the above brief analysis of the results of the experimental studies of boiling of paraffin hydrocarbons under forced convection and consideration of the methods of their generalization the following conclusions can be made.

1. Experimental data and the correlations given in the literature show that calculation of heat transfer with boiling of hydrocarbons in tubes in the precrisis range, apparently, can be made using the formulae presented in our paper. Nevertheless, none of them can be treated as an universal one. In the postcrisis range these correlations can not be used and the assessments should be done on the basis of the formulae developed for boiling water or additional experiments on boiling of saturated hydrocarbons should be conducted.
2. Presently, there are very limited experimental data on boiling heat transfer of natural hydrocarbons and their mixtures. This data spans rather narrow range of the regime parameters. Many problems of heat transfer and hydrodynamics of the hydrocarbon two-phase flow were not thoroughly studied. In essence, there is no comprehensive data on boiling crisis, deteriorated heat transfer, the pressure drop, flow pattern, and the mechanism of boiling. There is no

systematic studies of heat transfer with boiling hydrocarbon mixtures in tubes. The generalizing correlations existed require further refinement on the basis of modern concepts on the mechanism of liquid boiling in tubes and channels. All the above require further experimental and theoretical studies of the thermohydraulic characteristics of two-phase flows of hydrocarbonds.

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