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PROPANE POOL BOILING IN POROUS STRUCTURES

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Abstract

Heat transfer on a porous coated surface of a single horizontal tube at pool propane boiling and on a partially flooded sample was experimentally studied. The porous coating was a sintered copper powder with porosity (50 - 55) %. Experiments were carried out at the saturation temperature $T_s = 293$ K in the heat fluxes range $q = (10^2 - 10^5)$ W/m^2. The experimental results show that a liquid level lowering to the certain height promotes to a boiling heat transfer intensification at the low heat fluxes region due to a difference between mechanisms of heat transfer at pool boiling and vaporization inside a porous layer on the nonflooded part of a tube.

KEYWORDS

Boiling, heat transfer, porous structure, propane.

INTRODUCTION

Evaporative heat exchangers are widely adopted in various branches of industry. In lot of cases the operating conditions of evaporative heat exchange apparatus are characterized by low temperature heads and small heat fluxes. Heat transfer intensification at low superheatings allows one to reduce overall dimensions of heat exchange equipment. Over the past decade, compact heat exchangers with dimensions in the order of centimeters used mainly due to their high thermal efficiencies, small size, low weight, design flexibility. An increase of a vapor phase formation activity at low temperature heads is realized most effectively by using of surfaces with a sintered copper porous coating. These coatings are firm and have a sufficiently good connection with a heat exchange surface, provides for high heat characteristics.

Propane and other hydrocarbons boiling takes place in refrigeration technology, liquid hydrocarbons gasification, evaporators of heat pipes, thermosyphons, heat pumps, cooling systems of electronic components, etc. Possible applications of miniature two-phase heat exchangers could be space heating or cooling in vehicles or buildings, microprocessor cooling, fuel cells for transport and portable cooling devices. At the Porous Media Laboratory of the A.V. Luikov Heat and Mass Transfer Institute (Minsk, Belarus) in the course of about 10 years a heat transfer at propane boiling on surfaces with porous coating is experimentally studied. The aim is to minimize a heat exchange equipment by means of boiling heat transfer enhancing.

EXPERIMENTS

Test Rig

The experiments described were carried out on the specially designed and built set-up. The main parts of rig are test vessel with a work section, insulated temperature-controlled chamber, cooling machines (refrigerators), thermostats, condenser liquid loop, heater electronic control system, temperature control system, vacuum pump, liquid feed system. The grouping of main units inside the temperature-controlled chamber is shown in Fig. 1.

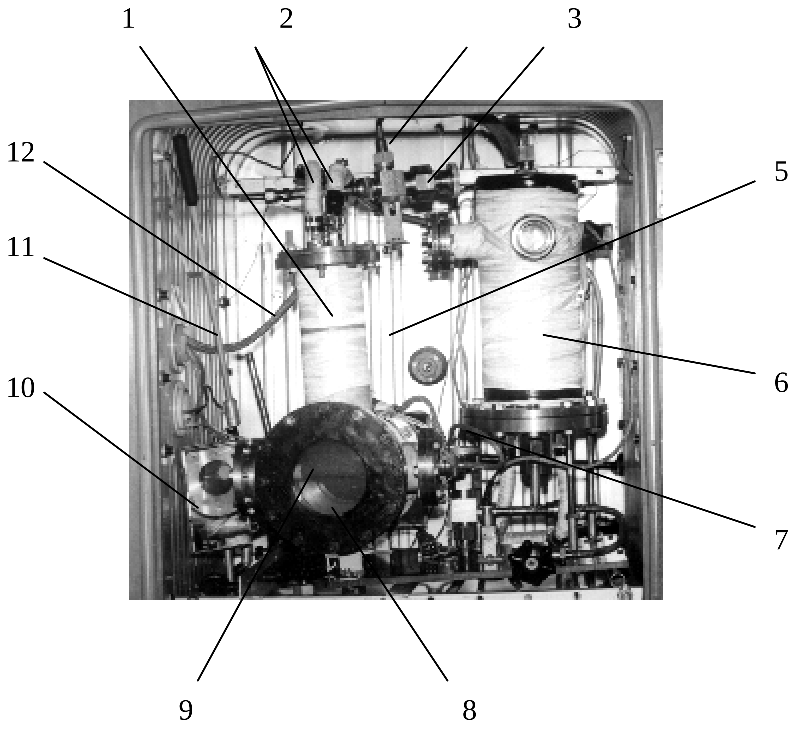

Fig. 1. The grouping of main units inside the temperature-controlled chamber: 1 – test vessel, 2 – hoses of a condenser coolant supply system, 3 – piping to a vacuum pump, 4 – vacuum tap, 5 – channel of a cooling loop, 6 – liquid reservoir, 7 –cable of a main electric heater, 8 – porthole, 9 – test sample, 10 – mirror for a flank view, 11 – strengthening beam of a hydrocarbon gas indicator, 12 – wisp of thermocouple wires

The test vessel was made as a cylindrical stainless steel boiler with outer diameter 160 mm and length 200 mm. Heat flux to a heat exchange surface was supplied by means of a cartridge electric heater placed inside of a tested sample. The measurements were carried out at the steady-state regimes. To the adiabatic conditions guarantee the test vessel is inserted into a temperature controlled chamber with a constant temperature equal to the temperature of saturation. The chamber has a good thermal insulation and cooling or heating circuit connected with cooling machines and thermostats to support a constant temperature equal to the saturation conditions. Test unit was heated by the cartridge electrical heater. Through the stainless steel pipes welded on the bottom and top the experimental vessel is connected with the gauge and liquid feeding system. The boiler has a sleeve for copper-constantan thermocouples lead-in to measure the temperature. A vapor pressure was measured by a gauge. A control of measuring process and a treatment of primary data were executed with help of a personal computer according to a special program.

The experimental set-up and method of experiments carrying out are described in detail in [1, 2].

Experimental Samples

An experimental samples were horizontal copper tubes (length 100 mm, outer diameter 20 mm, wall thickness 2 mm). Four longitudinal narrow grooves were cut to place thermocouple wires with lacquered and silk insulation. After laying wires were covered by copper brackets. Heads of thermocouples were caulked on a tube surface. External surfaces of tubes were coated by copper powder porous layer. Capillary-porous structure was sintered in the argon environment in the Byelorussian Powder Metallurgy Institute. For a good sintering of copper particles with a sample the activation of a tube surface by sand-blast processing was fulfilled. Samples with different geometrical parameters of capillary structures were produced. There results obtained on the tube with a porous layer thickness of 0.3 mm, powder particle diameter (0.063 - 0.1) mm and open porosity (50 -55) % are presented in the given paper.

Procedure of experiments

Experiments were carried out at the saturation conditions. The saturation temperature T_s inside a vessel was ensured by regulation of a cooling liquid flow rate through the condenser and with help of additional electric heater. To prevent heat exchange between test vessel and ambient medium the temperature inside a temperature-controlled chamber was supported equal to T_s. It was reached due to a liquid circuits formed by a system of channels inside of a chamber double-wall. Boiling was carried out on outer surface of tube. A heat input was supplied by electric heater. Temperature was measured at the steady state regime.

The tests on plain tubes without porous coating was carried out to verify the reliability of the method chosen for measurement and analysis of the results. Obtained results are in a good agreement (Fig. 2) with the data of other authors [3, 4], that testified to the necessary precision of the measuring equipment correctness of procedure

Experimental Results

Experiments on the porous tube were realized at saturation temperature $T_s = 293$ K, pressure $p_s = 8.4 \cdot 10^5$ Pa ($p^* = 0.197$), at heat fluxes up to 100 kW/m^2. Level of liquid h above the upper generatrix was varied from 70 to –20 mm (liquefied propane touched upon the lower generatrix of the test tube). The pool boiling characteristics are presented on Fig. 1. The height of liquid layer h = 70, 40 and 20 mm is large as compared with the departure diameter of bubbles, the conditions of vaporization heat transfer were identical and values of the coefficient α were approximately equal.

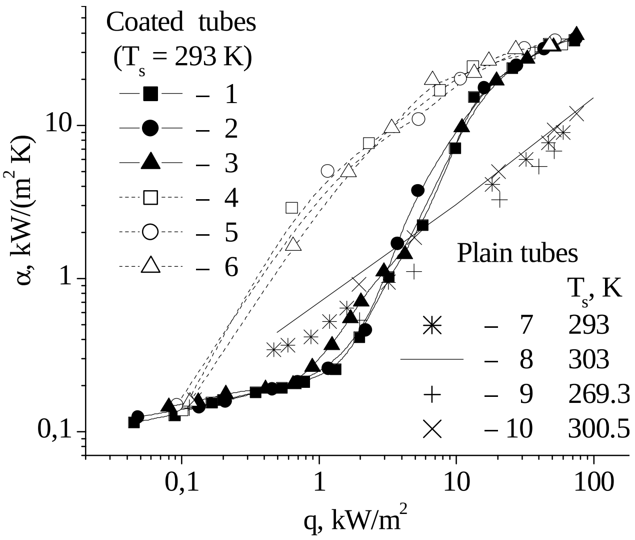

Fig. 2. Pool boiling heat transfer intensity: 1-3 – at heat flux increase; 4-6 – at heat flux decrease; 1, 4 – h = 70 mm; 2, 5 – 40 mm; 3, 6 – 20 mm; 7 – copper, d_t = 20 mm; 8 – stainless steel, d_t = 15 mm [3]; 9, 10 – mild steel St35.8, d_t = 88. 4 mm [4]

At small propane heights above the upper generatrix (to 2 mm) a liquid level began to influence on a heat transfer intensification. The first vapor bubbles arose at lesser fluxes than at high liquid levels, thus at the initial boiling stage (transition stage) heat transfer coefficients were higher, the temperature heads were less by (2 - 3) K (Fig. 3, b). At developed boiling regime all over the surface were covered by vapor bubbles, the dependencies $\alpha(q)$ at heat fluxes $q > 20$ kW/m^2 merge for h = (2 - 70) mm, as it can be seen in Fig. 3.

There are the experimental data obtained at boiling on a flooded (h = 70 - 0 mm) or partially flooded (h = –5, –10, –15, –20 mm) tube are presented in Fig. 4. It is obvious that a heat transfer intensity in these cases differs from this characteristic at pool boiling. The obtained data shows that a liquid level lowering below of the upper generatrix to certain height promoted to the heat transfer enhancing at low heat fluxes. It is because of different heat transfer mechanisms at compared conditions.

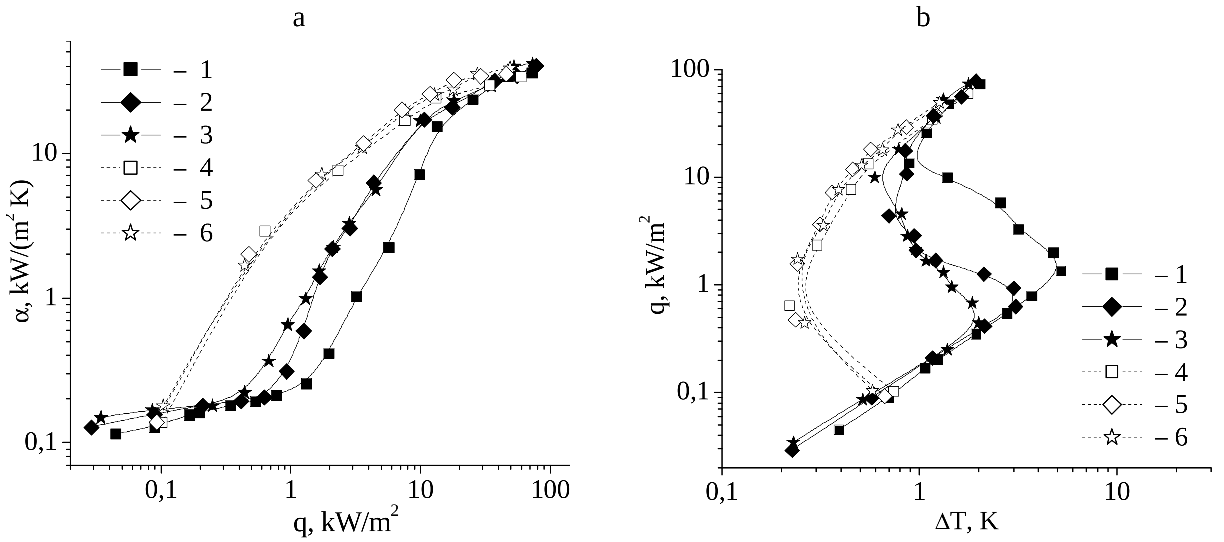

Fig. 3. Propane boiling characteristics at lowered liquid levels: 1-3 – at heat flux increase; 4 - 6 – at heat flux decrease; 1, 4 – h = 70 mm; 2, 5 – 4 mm; 3, 6 – 2 mm

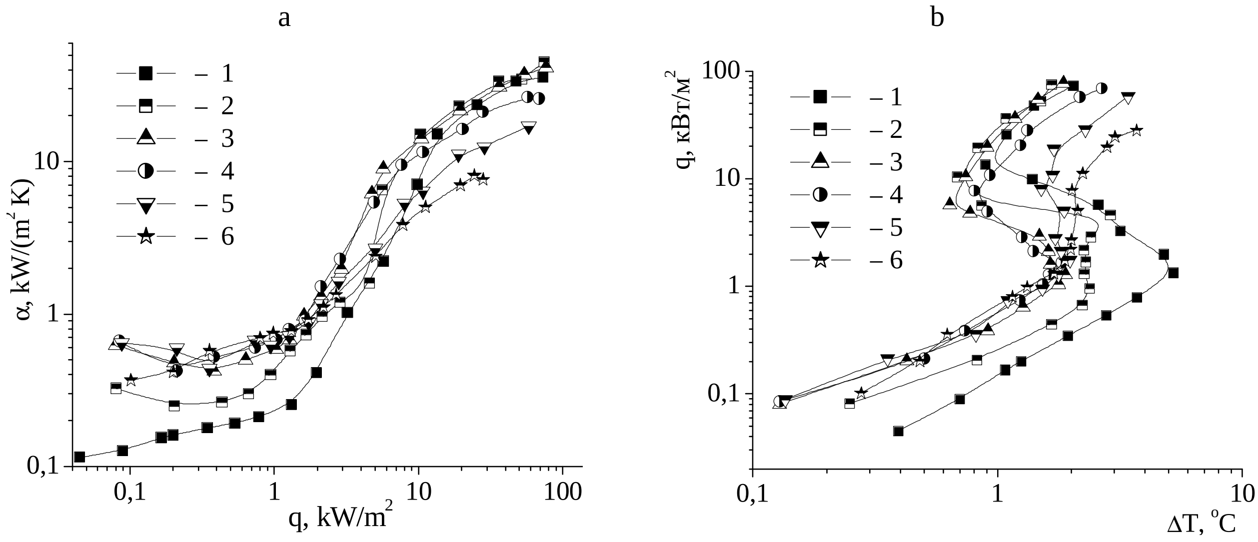

Fig. 4. Heat transfer characteristics at boiling on flooded and partially flooded samples: 1- 6 – h = 70, 0, –5, –10, –15, –20 mm

A creation of universal all-embracing model of pool boiling heat transfer on surfaces with porous coatings is hardly possible. At present few models are known [5 - 9]. In most cases porous structures are considered as a system of large and small pores. Large through pores function as vapor exhaust channels, small pores are filled by liquid phase and take the part of liquid leading channels. In accordance with majority of models [8, 9], a thin liquid film takes place constantly on sides of macropores equally with a presence of vapor phase within such channels. A liquid film makes worse the conditions for a vapor exhaust.

In the case of partially flooded samples the another mechanism functions on the part of heat exchange surface above a liquid-level. It can be supposed that liquid phase is supplied to zones of vaporization by capillary forces in micropores of wick, a vapor is evacuated through macropores, and a liquid microfilm on porous sides is absent. Thus thermal and hydrodynamic resistances of liquid film are absent too. A vapor phase is generated in orifices of micropores with outlets to macropores. A number of active centers of vaporization automatically rises proportionally to increasing of heat flux. In the heat loads range from 0.1 to 1.5 kW/m^2 the increase of heat transfer intensity up to 1.5 times was noticed at the “zero” liquid level (a liquid covers an upper generatrix of a sample), 2.5 - 3 times as high at h = –5 mm. In the developed boiling regime there were the close values of heat transfer coefficients at the liquid levels h = 0 and –5 mm. A liquid level lowering as high as –10 mm (a middle of tube diameter) has the negative influence on heat transfer intensity at the heat fluxes $q > (1.5\text{-}2)$ kW/m^2. It is connected with an increase of the average superheating of the heat exchange surface (Fig. 4, b) due to a worsening of a liquid phase supplying to centers of vaporization.

There are two limitations for increasing of heat transfer intensity: hydrodynamic ability of porous coating for transport of liquid phase and finite number of potential centres of vaporization. On reaching the certain quantity of heat flux a heat exchange surface above liquid-level doesn't receive sufficient amount of liquid phase, a “dry spot” appears and then spreads to all over this part of surface. The liquid level is lower, the maximum heat transfer coefficient is less. But at some liquid-levels and heat fluxes a heat transfer intensity is higher than at pool boiling (Fig. 4).

CONCLUSION

The results of investigation show that at the heat fluxes less than 100 kW/m^2 the boiling heat transfer coefficients on a partially flooded horizontal tube can be some time as higher as at pool boiling due to different heat transfer mechanisms.

The practical significance of obtained data is that is possible to reduce overall dimensions of heat exchange equipment.

Nomenclature

d – diameter, mm; h – height of liquid level, mm; p – pressure, Pa; $p^*=p/p_{cr}$ – relative pressure; q – heat flux, W/m^2; T – temperature, K; α – heat transfer coefficient, W/(m^2, K)

Superscripts

cr – critical, s – saturation, t –– tube

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1. Vasiliev, L.L., Khrolenok, V.V., Zhuravlyov, A.S., Intensification of heat transfer at propane boiling on single horizontal tubes, *Proc. of 3rd Minsk Int. Seminar ‘Heat Pipes, Heat Pumps, Refrigerators”*, Minsk, Belarus, 1997, pp. 96-101.
2. Vasiliev, L.L., Zhuravlyov, A.S., Novikov M.N., Vasiliev L.L. Jr., Heat transfer with propane evaporation from a porous wick of heat pipe, *Journal of Porous Media*, 2001, No. 4 (2), pp. 103-111.
3. Klimenko, A.P., Kozitsky, V.I., Experimental investigation of heat transfer at propane boiling, *Oil and Gas Industry* (*Neftyanaya i gazovaya promuishlennoste*), 1967, No. 1, pp. 40-43. – *In Russian*.
4. Gorenflo, D., Blein, P., Rott, W. et al., Pool boiling heat transfer from GEWA-T-x finned tube to propane and propylene, *Proc. of Int. Seminar “Eurotherm No. 8: Advanced in Pool Boiling Heat Transfer”*, Paderborn, F.R.G., 1989, pp. 116-126.
5. Polonsky, V.S., Zuikov, A.V., Leontiev, A.I., Stuirikovich, M.A., Model of a concentrating process at boiling in capillary-porous structures, *Papers of the Academy of Sciences of USSR (Dokladi AN SSSR)*, 1978, Vol. 241, No. 3, pp. 579-583. – *In Russian*.
6. Kovalev, S.A., Soloviev, S.L., *Evaporation and Condensation in Heat Pipes*, Nauka, Moscow, 1989, 112 p. – *In Russian*.
7. Webb R.L., Nucleate boiling on porous coated surfaces, *Heat Transfer Engineering*, Vol. 4. Nos. 3-4, 1983, pp. 71-82.
8. Shaubach, R.M., Dussinger P.M., Bogart J.E., Boiling in heat pipe evaporator wick structures. *Proc. of 7th Int. Heat Pipe Conf.*, Minsk, Belarus, 1990, pp. 1-15.
9. Smirnov, H.F., Afanasiev, B.A., Poniewski, M., Boiling in capillary-porous structures, *Proc. of Int. Conf. on Heat Transfer with Change of Phase*, Kielce, Poland, 1996, Part II, pp. 197-220.