BOILING CRISIS ON SURFACES WITH POROUS COATING

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Experimental values on nucleate and film boiling of carbon dioxide on polished and porous cylindrical surfaces under conditions of saturation at reduced pressures, $p/p_{crit} = 0.93$ and 0.97 are discussed. A considerable increase of the maximal, minimal specific heat fluxes and maximal heat transfer coefficient was observed on a horizontal tube with thin porous coating.

During the past few years brief notes have appeared in the literature about the enhancement of heat transfer from surfaces with porous coatings [1, 2]. Study of the boiling processes at such surfaces and also in the porous materials is of practical interest both for improved heat transfer available and for opportunity of producing novel heat transfer equipments such as heat pipes with porous structures. There is little detailed quantitative data about the effect of surface porosity on heat transfer with nucleate boiling. Nor to the authors' knowledge has the heat transfer behavior of porous heaters with film boiling been adequately investigated.

The authors have made tests with boiling carbon dioxide in natural convection from horizontal copper pipes with thin coatings of porous nickel and with polished surfaces. Isobaric boiling data $q = f(t_W)$ were obtained for two reduced pressures of $p/p_{crit} = 0.93$ and 0.97.

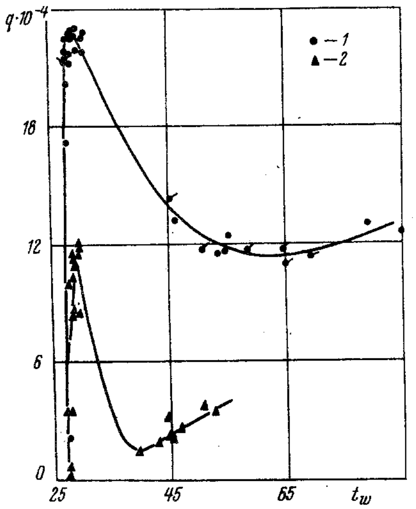

Fig. 1

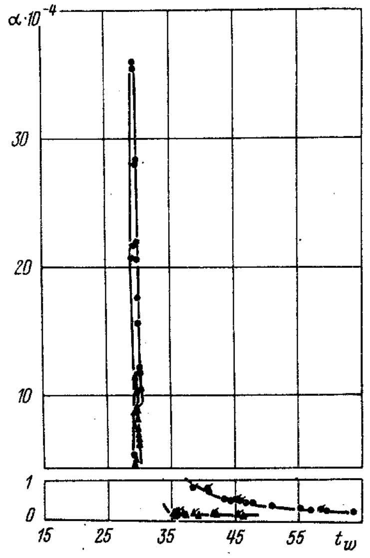

Fig. 2

Fig. 1. Specific heat flux q (W/m²) versus mean surface temperature t_W (°C) at carbon dioxide boiling: ($p/p_{crit} = 0.93$). 1) tube with porous coating; 2) smooth tube.

Fig. 2. Temperature variation of maximum heat transfer coefficient α_{max} at reduced pressure $p/p_{crit} = 0.97$. For designation see Figure 1.

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TABLE 1

p/p_K	$q_{max}\cdot 10^{-4}$, W/m^2	t_{max}, °C	$q_{min}\cdot 10^{-4}$, W/m^2	t_{min}, °C	$\alpha_{max}\cdot 10^{-4}$, W/m^2, deg	Surface
0,93	12,3	29,6	—	—	5	Smooth
0,93	11,5	28,5	1,4	39,4	10	
0,93	11,4	28,7	—	—	8	
0,97	6,1	29,7	0,8	35,4	11	
0,97	6,2	30,1	1,1	35,3	9	
0,93	22,7	29,2	11,1	64,9	31	With porous coating
0,93	22,9	30,8	—	—	19	
0,93	23,1	29,5	—	—	38	
0,97	14,1	30,3	9,7	58,5	22	
0,97	14,4	29,5	9,0	57,0	36	
0,97	14,4	29,8	9,2	59,4	36	

The test chamber used without significant changes has been previously described [3]. Its working volume (650 cm^3) was filled with pure carbon dioxide for which p_{crit} = 73.8 bar, t_{crit} = 31.1°C. Boiling occurred on a horizontal ~31 mm length of copper pipe of 3.8/3.0 mm diameters and on another pipe of similar dimensions but with an 0.03 mm thick nickel coating. The surface of the first pipe was polished and used to establish a reproducible test procedure. The coating of the second pipe was deposited electrolytically from a solution of finely dispersed nickel. Both pipes were internally heated with distilled water. The mean temperature of the heating surface was determined from four copper—constantan thermocouples ϕ 0.12 mm (three constantan wires were placed on the top and one on the bottom of the pipe, the copper pipe itself acted as the other component of the hot junction).

The specific heat fluxes were determined with maximum (systematic) errors of 2-6%, the rms errors in the maximum t_{max} and minimum t_{min} temperatures for the various fluxes taking into account calibration and fluctuation in individual tests) were ±0.1°C.

Boiling curves for the polished and porous surfaces for a reduced pressure p/p_{crit} = 0.93 are given in Fig. 1. The curves $q = f(t_w)$ for the reduced pressure of 0.97 are qualitatively similar. The experimental points with tagged notation were taken at the lowered temperatures. In the graph the isobaric data were obtained in a series of tests with each heater. The scatter of the plotted points each of which is averaged from three values is not significant, thereby establishing the reproducibility of the results. The values of the maximum (critical) heat flux q_{max} for steady nucleate boiling on the porous surface are ~2.0 times greater than those for the smooth surface (Fig. 1, Table 1) and with a reduced pressure of 0.97 the former were 2.3 times the latter. The increase in the maximum heat flux for boiling on the porous surface can be explained by the breakaway bubble diameter with this surface being smaller and by the number of nucleation centers being greater than for the smooth surfaces [4]. The rate of bubble breakaway from nucleation centers on the porous surface is also greater as evidenced by the uniformity of the diameter of the bubbles [4, 5]. As a result of all these factors, the heat transfer is greater from the porous surface than from the smooth one.

The maximum heat flux is produced at a similar surface temperature for both the smooth and porous tubes which confirms the validity of the above thermodynamic analysis of the boiling crisis [6].

The maximum heat transfer coefficient α_{max} with established nucleate boiling on the porous surface is enhanced three times (Fig. 2). The authors and others [2] also observed coefficient increases of 2-4 times for freon-12 boiling on a porous cylindrical pipe (heat flux from 2750 to 100, 000 W/m^2).

The transition boiling region for the porous heater is extended along the temperature axis. The minimum heat flux q_{min} occurs at a higher surface temperature t_{min} than with the smooth surface. Values of q_{min} for the porous surface exceed the corresponding values, for the smooth surface by a factor of (p/p_{crit} = 0.93) and a factor of 10 (p/p_{crit} = 0.97). The heat flux q_{min} from the porous surface with steady film boiling is the same (p/p_{crit} = 0.93) or a little higher (p/p_{crit} = 0.97) than the corresponding maximum flux q_{max} for nucleate boiling on the smooth pipe.

The boiling crisis on the porous surface is less pronounced. The ratio of the maximum and minimum fluxes $\bar{q}_{max}/\bar{q}_{max}$ for the smooth surface is 8.4 (p/p_{crit} = 0.93) and 6.5 (p/p_{crit} = 0.97). The values of this ratio are 2.1 and 1.5 respectively for the porous surface.

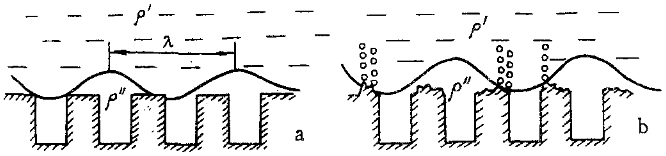

Fig. 3. Scheme of film boiling on heater with porous coating: a) no roughness; b) with roughness.

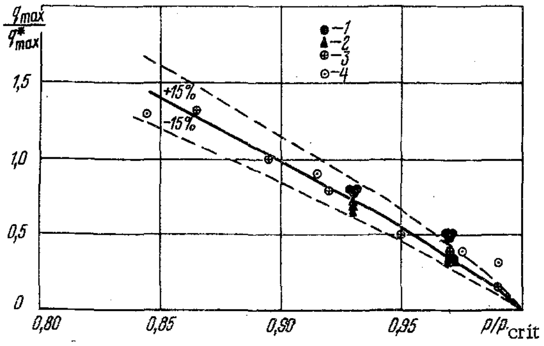

Fig. 4. Generalization on experimental results by maximum heat fluxes: 1, 2) carbon dioxide boiling on porous and smooth horizontal copper tubes ∅ 3.8/3.0 mm, ~31 mm long, heating from inside by heat transfer agent; 3, 4) boiling carbon dioxide and sulphur hexafluoride on external surface of horizontal brass tube ∅ 4.0/3.0 mm, ~22 mm long, heating by heat transfer agent [9]. Solid curve, by equation (1).

The increase in the minimum flux from the porous surface above that from the smooth can be explained by the following boiling phenomenon.

The minimum heat flux can be explained by nonuniformity of the interface between the phases according to Taylor [7], when the vapor phase (ρ'') is on the lower side. If the interface varies cyclically with some wavelength λ, at the sharp edges of cavities or pores, there is possible contact between the liquid phase and the heated surface with penetration into the cavity and heating to boiling point (Fig. 3a). The porosity and roughness of the surface result in a greater heat flux. Nucleate boiling is then possible on the cavity edges (Fig. 3b). Such a model can in the authors opinion explain both the increased minimum flux from the porous surface and the extended transitional boiling region.

Allowing for surface effects in calculating the maximum and minimum fluxes is not easy.

It is advisable to use equations ensuring corresponding conditions and excluding surface effects [8-10]. The ratio of the extreme fluxes is then related to the pressure. The results may be easily generalized for comparison with other data by the heat flux q^* at $p^* = 0.9\ p_{crit}$. Calculations of generalized data from numerous authors for the boiling crisis take the form (9.11)

$$q_{max}/q^*_{max} = 8.24\,(p/p_{crit})^{0.35}\,(1 - p/p_{crit})^{0.9}, \tag{1}$$

$$q_{min}/q^*_{min} = 4.18\,(p/p_{crit})^{0,24}\,(1 - p/p_{crit})^{0.61}. \tag{2}$$

In Fig. 4 are given the generalizations of the present authors results for the carbon dioxide boiling crisis on smooth and porous surfaces and for sulfur hexafluoride on a smooth surface. The continuous line represents equation (1). It can be seen that values of the minimum heat flux can be generalized by equation (2).

NOTATION

q_{max}, q_{min}	are the maximum and minimum specific heat fluxes (first and second critical densities of heat flux);
$\bar{q}_{max}$, $\bar{q}_{min}$	are mean values of fluxes for given pressure;

t_w	is the mean temperature of heat releasing surface;
t_{crit},	is the critical temperature;
t_{max}, t_{min}	are the temperatures of surface corresponding to maximum and minimum heat fluxes at isobar;
p_{crit}, p/p_{crit}	are the critical and reduced pressures;
α_{max}	is the maximum heat transfer coefficient at isobar $q = f(t_w)$;
ρ', ρ''	are the density of liquid and vaporous phases;
λ	is the perturbation wavelength of interface;
$p^* = 0.9\, p_{crit}$	is the scale pressure;
q^*_{max}, q^*_{min}	are the values corresponding to scale pressure.

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