A REGIME OF TRANSITION FROM NUCLEATE TO FILM BOILING FOR WATER AND WATER–ALCOHOL MIXTURES WHEN THE HEAT-EXCHANGE SURFACE IS HEATED BY THE VAPOR

N. Yu. Tobilevich, I. I. Sagan',
and N. A. Pryadko

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We have undertaken an experimental study of the regime for the transition from nucleate to film boiling on a horizontal tube. We have derived the relationship between the heat-transfer coefficient and the specific heat flux, as well as the relationship between the alcohol content in the mixture and the critical values of the heat flux, the heat-transfer coefficient, and the average temperature difference.

In studying the heat-transfer crisis we primarily make use of electrical heating of the heating surface because of the relative simplicity of the experimental installation in this case, and because of the simplicity in carrying out the experiments, in addition to the fact that the experimental errors are small. However, from a practical standpoint, in the case of electrical heating it is difficult to establish reliably the instant of the heat-transfer crisis and to perform tests on experimental heating surfaces of substantial geometric dimensions, so that the diameter of most test elements is no greater than several millimeters. The critical heat fluxes achieved in electrical heating are determined either at the instant at which the heat-relief surface burns out, or at the instant at which the film boiling regime sets in.

The transitional regime from nucleate to film boiling precedes stable film boiling [1, 3]. The onset of the transitional regime corresponds to the instant at which the crisis in nucleate boiling sets in.

We can investigate the transition regime from developed nucleate boiling to film boiling by heating the experimental heating surface with a saturated water vapor. In the case of vapor heating we can establish the boiling crisis precisely, because the wall temperature for the heating surface has been fixed.

References [5, 6] outline the results of these experiments on the determination of the critical density of the heat flow for the boiling of water and other liquids when the heating surface is heated by vapor. However, the value for q_{cr} obtained in the cited references for water amounts approximately to $0.7 \cdot 10^6$ W/m^2, whereas for electrically heated horizontal cylinders, according to the data of [2-4] and other researchers, the value of q_{cr} for water amounts to about $1.2 \cdot 10^6$ W/m^2. Such divergence in the magnitudes of the critical heat flow between vapor and electrical heating is explained in [3, 4] by the nonuniformity in the heat flow about the circumference of the tube in the case of vapor heating as a consequence of the heating of the lower portion of the tube by the condensate, whereas in the case of a relatively low value for the average magnitude of the heat flow its local values at the upper half of the tube may reach and even exceed the true critical values.

Results from an experimental study of q_{cr} in the boiling of water–alcohol and other binary mixtures where the heat-exchange surface is heated electrically are presented in [7-10]. In the relationships between the magnitude of the critical heat flow and the composition of the mixture, as given in the cited references, the maximum corresponds to the maximum difference between the content of the low-boiling component in the vapor and liquid phases. In [7, 9] the minimum has been found as a function of $q_{cr} = f(C)$ for small concentrations of alcohol in the solution. In [7, 8] the values of α and Δt have been determined for the onset of the crises.

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TABLE 1. Experimental Data on the Transition Regime in the Boiling of Water and Water–Alcohol Mixtures

Temperature of the heating vapor, deg	Average wall temperature, deg	Average liquid temperature, deg	Δt_{av}, deg	$q \cdot 10^{-4}$, W/m^2	$\alpha_2 \cdot 10^{-3}$ W/m^2·deg
0 vol. % alcohol (water);					
172	114,7	99,4	15,3	61	40
177,5	115,6	99,6	16,0	70	44
187	117,8	99,6	18,2	85,5	47
194,2	118,9	99,6	19,3	98	51
194,2	119,4	99,4	20,0	102	51
201	120,5	99,5	21,5	116	54,5
201	119,5	99,5	20,0	122	61,5
204	120,5	99,5	21,0	140	66
212	125,3	99,5	25,8	155	60
212	127,7	99,5	28,2	147	52
212	129,4	99,4	30,0	155	52
225	136,4	99,4	37,0	148	40
230,5	138,8	99,4	39,4	150	38
232,5	140,4	99,4	41,0	147	36
236	139,5	99,5	40,0	134	34
3 vol. % water–alcohol mixture;					
136,5	107,7	97,3	10,4	26,5	25,5
136,5	108,3	97,5	10,8	29	27
143	110	97,5	12,5	37,5	30
143	110,5	97,5	13	39,5	30,5
153	112,1	97,7	14,5	49	34
158	115,7	97,6	17,6	54	30,7
158	115,7	97,6	18,1	57	31,5
175	121,2	97,7	23,5	61	26
175	122,4	97,6	24,8	64,5	26
193,5	128,6	97,6	31	71	23
193,5	125,8	97,6	28,2	72	25,5
205	140,5	97,5	43	73	17
205	140,5	97,5	43	76	17,5
215,5	153,5	97,5	56	73	13
215,5	153,4	97,4	56	76	13,6
5 vol. % water–alcohol mixture					
121,2	104,9	96,2	8,7	20,7	24
127,6	106,3	96,3	10	25	25
127,6	106,3	96,3	10	26	26
137	109,5	96,5	13	37	28,5
137	109,5	96,5	13	39	29,4
151	113	96,6	16,4	49	30
151	113	96,6	16,4	51	31
164,5	114,2	96	18,2	58	32
164,5	115,7	96	19,7	61	30,5
164,5	115,7	96	19,7	62,5	31,5
164,5	115,7	96	19,7	64	32,6
179,5	127,6	96,2	31,4	69	22
179,5	127,6	96,2	31,4	71	22,6
199	139	96	43	68,5	16
199	139	96	43	69	16,1
213	145,2	96,2	49	61	12,5
10 vol. % water–alcohol mixture;					
142	108,1	92,6	15,5	38	24,5
142	108,1	92,6	15,5	39	25,2
164,5	111,5	92,6	18,5	64,5	35
164,5	110,8	92,6	18,2	71	39,5
164,5	110,8	92,6	18,2	74	41
179,3	121,5	92,8	28,7	74	26
179,3	121,5	92,8	28,7	75	26,2
199,3	142,2	92,7	49,5	70	14,2
199,3	141,9	92,7	49,2	72	14,5
211	162,6	92,6	70	46	9,6
211	162,6	92,6	70	49	7
228,5	184,3	92,2	92,1	27,1	2,95
228,5	184,3	92,2	92,1	27,9	3,03
20 vol. % water–alcohol mixture					
143	113,4	88,4	25	26,5	10,5
143	113,4	88,4	25	27,5	11
170	120,7	88,6	32,1	45	14
170	120,7	88,6	32,1	50	15,4
188,2	126,9	88,2	38,7	62	16
188,2	126,9	88,2	38,7	64	16,4
188,2	126,9	88,2	38,7	65,5	17
194	128,8	88,6	40,2	69,5	17,3
205	133,4	88,4	45	60,7	13,5
205	133,4	88,5	46	63	13,5

TABLE 1 (Continued)

Temperature of the heating vapor, deg	Average wall temperature, deg	Average liquid temperature, deg	Δt_{av}, deg	$q \cdot 10^{-4}$, W/m^2	$\alpha_2 \cdot 10^{-3}$ $W/m^2 \cdot deg$
205	137,8	87,8	50	62	12,5
217,9	137,8	87,8	50	64	12,8
228,5	152,7	88,2	64,5	64,5	10
228,5	152,7	88,2	64,5	59	4,15
35 vol. % water–alcohol mixture					
142	112,1	84,6	27,5	30,5	11,1
142	112,1	84,6	27,5	30	11
154	114,6	84,2	30,4	34	11,2
159,5	120,9	84,4	36,5	51,5	14,1
169,5	120,9	84,4	36,5	58	15,9
188	127,5	84,5	43	59	13,7
188	127,5	84,5	43	60	14
192	131	85	46	64,5	14
203,3	133,8	84,8	49	66	13,7
218	139,6	84,6	55	69	12,5
218	139,6	84,6	55	71	12,8
218	139,6	84,6	55	70,5	12,8
224	150,8	84,8	66	69	10,5
224	150,8	84,8	66	67,5	10,2
228	161,4	84,7	77	63	8,2
228	161,4	84,7	77	64,5	8,4
45 vol. % water–alcohol mixture					
142	114,8	82,8	32	24	7,5
170	120,6	83	37,6	35	9,3
170	124,1	83,1	41	37	9
188	134,5	83	51,5	55	10,7
188	134,5	83	51,5	55,5	11,2
205	138,7	83,2	55,5	55,5	10
208,6	141,7	83,3	58,4	59	10,1
218	152,9	82,9	70	52	7,4
218	152,9	82,9	70	48,5	6,92
228,6	163,1	83,1	80	47	5,9
60 vol. % water–alcohol mixture					
124	100,8	81,8	19	18	9,5
127	101,9	81,8	20,1	24	11,9
127	101,9	81,8	20,1	24,5	12,1
137,6	105,1	81,7	23,4	32,5	13,9
137,6	105,1	81,2	23,4	34	14,5
142,1	107	82	25	35	14
151	111,3	81,8	29,5	36	12,2
151	111,3	81,8	29,5	37,5	12,7
164,5	119,4	81,4	38	41,5	10,9
164,5	119,4	81,4	38	43	11,3
164,5	119,4	81,4	38	44,5	11,7
176	123,4	81,7	41,7	42,5	10,2
196	139,2	81,6	57,6	42	7,3
196	139,2	81,6	57,6	45,6	7,9
213	149,5	81,5	68	36	5,3
213	149,5	81,5	68	36	5,3
213	149,5	81,5	68	37	5,73
75 vol. % water–alcohol mixture					
113	92,9	79,7	13,2	18,3	13,9
122	94,4	79,7	14,7	25	17
124	95,4	79,7	15,7	27	17,2
128	95,7	79,7	16	32	20
128	95,7	79,7	16	33,5	21
128	96,5	79,8	16,7	35	21
138	100,3	80	20,3	37,5	18,6
138	100,4	80,1	20,3	39	19,4
151,5	107,1	80,1	27,1	46	17
165	114,7	79,7	35	49	14,2
175	116,7	79,7	37	52	14,2
185	126,7	79,7	47	51	11
192	130,2	79,7	55	56,5	11,2
96 vol. % water–alcohol mixture					
118	99,9	78,2	13,7	15,1	11
120	94,1	77,9	16,2	29	17,9
127,5	96,7	78,2	18,5	36	19,5
132	97,7	78,2	19,5	35	18
132	98,8	78,2	20,6	35	17
132	98,2	78,2	20	35	17,5
142,5	105	77,9	27,1	32,5	12
142,5	103,3	77,9	25,4	32	12,6
151	119,7	78	41,7	19,2	4,6
151	120	78	42	20,5	5,35
151	120	78	42	19,5	4,63
164	134,2	78,2	56	12,6	2,25
175	138,3	78,3	60	8,45	1,41
184	148,7	77,7	71	5,97	0,84
191,7	158,9	77,9	81	6,05	0,75

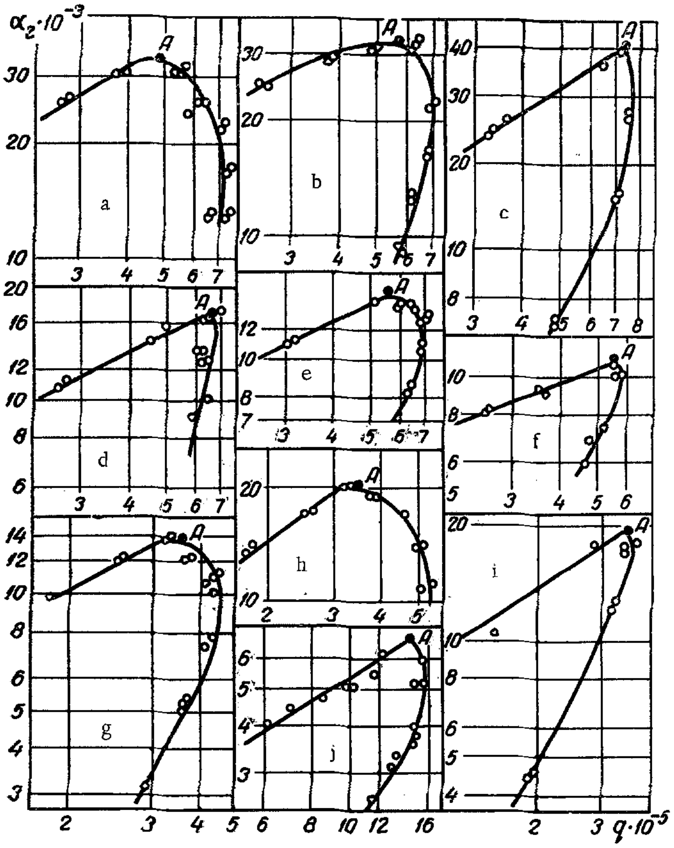

Fig. 1. The function $a_2 = f(q)$ for water and water–alcohol mixtures: a) 3 vol. % C_2H_5OH; b) 5 vol. %; c) 10 vol. %; d) 20 vol. %; e) 35 vol. %; f) 45 vol. %; g) 60 vol. %; h) 75 vol. %; i) 96 vol. %; j) water.

It is the purpose of this paper to investigate the regime of transition from nucleate to film boiling, to determine the critical heat flows, the coefficients of heat transfer, and the difference in temperatures between the wall and the medium in the boiling of water and water–alcohol mixtures in a large volume at atmospheric pressure on a horizontal tube when the heat-exchange surface is heated by vapor.

In studying the transition regime for water we employed the method of heating the experimental tube by moving saturated water vapor through it at high speed. This made it unnecessary to intensify the transfer of heat between the condensing vapor and the tube walls, since we were unable to achieve the required heat flows in previous experiments involving heating by means of a nonmoving vapor; if at all possible, we sought in this way to avoid the nonuniform distribution of the heat flow about the circumference of the tube.

In the case of water–alcohol mixtures the experimental tube was heated with a nonmoving saturated vapor.

The outside diameter of the experimental tube was 10 mm, and its inside diameter was 5.7 mm; the tube itself was made of pure copper. The working length of the tube was 235 mm. The wall temperature was determined by means of eight thermocouples located on the outside of the tube in two sections separated from each other by 100 mm, with four thermocouples in each section.

We determined the amount of condensate formed on the experimental tube for the case of heating with a nonmoving vapor. The specific heat flux was calculated from the relationship

$$q = \frac{1}{f}\left(\frac{Dr}{\tau} - Q_{\text{loss}}\right), \ \text{W/m}^2.$$

When heating with a moving vapor, we measured the condensate formed on the experimental tube, as well as the amount of vapor found behind the experimental tube. The specific heat flux in this case is equal to

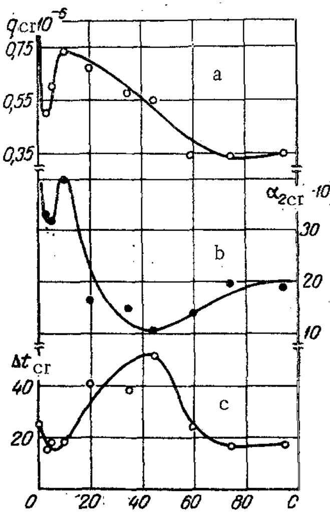

Fig. 2. The relationship between the alcohol concentration in the mixture and the values of q_{cr}, α_{2cr}, and Δt_{cr}.

$$q = \left(\frac{D_1 r + D_2(i_1 - i_2)}{\tau} - Q_{loss}\right)\frac{1}{f}, \ \mathrm{W/m^2}.$$

The average wall temperature was assumed to be equal to the arithmetic mean of eight points on the tube. The temperature of the liquid was assumed to be equal to the saturation temperature.

The average temperature difference $\Delta t_{av} = t_w - t_{liq}$, deg.

The heat-transfer coefficient $\alpha_2 = q/\Delta t$, $\mathrm{W/m^2 \cdot deg}$.

RESULTS OF THE INVESTIGATION

Table 1 shows the experimental data on the regime for the transition from nucleate to film boiling.

Figure 1 shows the results from an investigation of the transition regime in boiling, in coordinates of $\alpha_2 = f(q)$. The points A on these curves denote the onset of the transition from nucleate to film boiling. The specific heat fluxes and the coefficients of heat transfer at point A correspond to the critical values.

For water the value of q_{cr} from the data of our experiments is $1.4 \cdot 10^6$ $\mathrm{W/m^2}$, which is in good agreement with the data of other researchers, who obtained similar values for q_{cr} in the case of water when the heat-exchange surface is heated electrically. Thus q_{cr} is independent of the means employed to heat the surface.

Figure 2a shows the critical heat flux as a function of mixture composition, on the basis of the data from Fig. 1. This function exhibits two extremal values: a minimum corresponding to low concentrations of alcohol in the solution (approximately 3 vol. %), and a maximum which corresponds to an alcohol concentration of 10-20 vol. %.

It should be noted that the absolute value of q_{cr} for the mixtures in our experiments is somewhat lower than in [7-9]. However, in the case of ethyl alcohol the value of q_{cr} is in agreement with the data of other authors [8, 9] within the limits of experimental error.

Figures 2b and c show the heat-transfer coefficient α_2 and the average temperature difference Δt_{av}, corresponding to q_{cr}, as functions of the alcohol concentration in the solution.

For the transition regime in the boiling of water we find local formations of an unstable film on the tube surface, and the dimensions of this film increase as the pressure of the heating vapor rises.

In the boiling of water–alcohol mixtures we also observed visually the formation (in the region of the transitional regime) of a film about the tube, this film being more stable in the upper portion and unstable in the lower portion of the tube, forming separate spots 1.5-2 mm in thickness. Here we clearly saw the formation of finely dispersed vapor bubbles at the film surface, and these are characteristic of developed nucleate boiling. In addition to the visual observation, this could be seen from the readings of the thermocouples, with the temperature at the points of thermocouple insertion rising on occasion to the temperature of the heating vapor.

NOTATION

Q_{loss}	denotes the heat losses of the installation, in W, determined from calibration tests as a function of the pressure of the heating vapor;
D	is the quantity of condensate formed on the experimental tube when heated with a nonmoving vapor, kg;
D_1	is the quantity of condensate formed on the experimental tube when heated by a moving vapor, kg;
D_2	is the quantity of vapor passing beyond the experimental tube when it is heated by a moving vapor, kg;
r	is the heat of vapor formation, J/kg;
q and q_{cr}	are, respectively, the specific and the critical heat flux, $\mathrm{W/m^2}$;
t_w and t_{liq}	are, respectively, the temperature of the wall and of the liquid, deg;

Δt_{av} and Δt_{cr}	are, respectively, the average and the critical temperature difference, deg;
α_2 and α_{2cr}	are, respectively, the heat-transfer coefficient and the critical heat-transfer coefficient for the wall and the boiling liquid, in $W/m^2 \cdot deg$;
i_1 and i_2	are, respectively, the enthalpies of the vapor ahead of and beyond the experimental tube, J/kg;
f	is the heat-exchange surface of the experimental tube, m^2;
τ	is the duration of the test, sec;
C	is the alcohol content in the mixture, % by volume.

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