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Heat transfer during the quench process that occurs in the reflood of a single vertical tube

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Abstract—Wall temperature histories for one elevation on a vertical tube being quenched by water fed into the bottom of the tube, at pressures of 1 and 4 atm, are used with the system operating parameters, to predict the relation between the heat flux to the water and the temperature difference during the quench process. During nucleate boiling, the relation between the flux and the temperature difference is of the nature specified by theories for forced convection boiling, but there are differences in detail. Maximum fluxes are somewhat higher than for pool boiling, but cannot be related to the operating conditions. The transition boiling behavior is shown to be predictable if the experimental values of the flux and the temperature difference at the maximum and minimum flux are used in existing prediction methods. Another method, based on the data, is also proposed.

INTRODUCTION

THE NATURE of the heat transfer during the boiling process is essential to any analysis that proposes to specify the progress of the quench front as that occurs in a reflood process. Commonly, this nature is specified by a correlation for the heat transfer coefficient for the nucleate boiling region, terminating at a separately specified heat flux, given, for instance, by the Zuber relationship. There follows a transition boiling region for which there is a number of relations for the transfer coefficients which, in general, all require the specification of a heat flux and a wall temperature at the extremes of the transition region. It is important, therefore, to appraise experimentally the nature of the boiling process during quench and to compare this to the usual predictions that are made for it.

Experimental values of the heat flux during the quench that occurs in the reflooding of a heated vertical tube, 14.5 mm i.d., with 0.8 mm wall thickness, have been deduced from the history of the temperature at a position on the outside wall of the tube, obtained as the quench passed that position. By assuming a constant velocity for the quench during the time in which the local quench occurs, and treating the radial temperature variation only approximately, the history of the flux on the inside surface of the tube could be deduced. These fluxes, the inside wall temperature deduced from the outside wall temperature, and the saturation temperature of the water within the tube, gave the relation between the flux and the temperature difference to which the predictions could be compared. These results, and some of the comparisons, have been given in refs. [1, 2]. This paper presents some of these results to show that fair predictions are realized for the nucleate boiling region and the critical heat flux. For the transition region, there is proposed a correlation that predicts the transfer coefficient fairly well when the experimental results are used to specify the limits of the region.

EXPERIMENTAL DETERMINATION OF THE FLUX

Histories of the outside wall temperature of the tube were obtained mostly for one location, 1.83 m (6 ft.) from the bottom of the 3.66 m (12 ft.) high tube, heated to obtain an initial temperature at which the losses from the uninsulated exterior were equal to the input from the passage of d.c. current through the tube. The 'reflood' was by water at constant temperature introduced into the bottom of the tube with velocities from 0.0254 m s^{-1} (1 in. s^{-1}) to 0.0762 m s^{-1} (3 in. s^{-1}). The progress of the quench, identified by the rapid drop in the wall temperature, was determined by obtaining, as a function of time, the occurrence of this drop in temperature at locations 0.305 m (1 ft.) apart; from this the quench velocity at the 1.83 m location was determined. These quench histories were like those found in ref. [4] for this system which is described in detail in that report.

The history of the wall temperature at the 1.83 m location was produced from recorded values of the thermocouple voltage at intervals of 0.046 s, and this record was irregular enough so that the differentiation of the temperature needed for the determination of the flux produced for it a very irregular history. The temperature history was, therefore, smoothed by a

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NOMENCLATURE

c	specific heat	ΔT_{sub}	$(T_{sat}-T_L)$, liquid subcooling
f	fraction of surface wet in transition boiling	u_Q	quench velocity
g	gravity acceleration	x	quality; x_1, x_2, just below and above quench region; x_{max}, at q_{max}
h	heat transfer coefficient; h_{max}, at maximum flux; h_{min}, at minimum flux	z	distance from bottom of vertical tube; z_Q, quench height; z_c, collapsed liquid level.
h_{fg}	latent heat of evaporation		
k	thermal conductivity		
P	pressure	Greek symbols	
q	heat flux; q_{max}, maximum; q_{min}, minimum	δ	wall thickness of tube
		θ	time
r	radius, from tube center line	$\bar{\theta}$	dimensionless temperature, $(T_{min}-T_W)/(T_{min}-T_{max})$
T	temperature; T_{sat}, saturation; T_q, quench as defined on Fig. 1; T_W, inside wall temperature	μ	dynamic viscosity
		ν	kinematic viscosity
ΔT	(T_W-T_{sat}); ΔT_{min}, ΔT_{max}, at minimum and maximum flux	ρ	density
		σ	surface tension.

program which fitted a cubic spline approximation for seven intervals of the record, adjusting the intervals until the error in the approximation was a minimum. This spline fit program produced continuous first and second derivatives at the interval limits (knots). There are eight knots for the seven intervals, the seven were selected as to give reasonable error for a logical amount of computation time, giving an overall r.m.s. error usually less than 0.05. The fit was made to values of temperature obtained from the millivolt conversion and the output was the constants of the cubic equations that fitted each of the defined temperature intervals. Because the thermocouple junction itself experienced some voltage difference produced by d.c. current flow through the tube, the 'true' output, mv_t, was related to the actual mv by the relation

$$mv_t = mv + FI \tag{1}$$

where I is the current and F a factor such that mv_t yielded the true tube wall temperature in steady-state conditions with all of the input being the loss from the tube exterior. The temperatures so specified were used with the energy equation

$$\rho c \frac{\partial T}{\partial \theta} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q'''. \tag{2}$$

In this, the distance z was related to the quench velocity as $dz = u_Q\, d\theta$, u_Q being assumed constant in the short period in which the temperature history was obtained. If the temperature is assumed to be invariable with radius, and the variation of radius over the small wall thickness is neglected, integration of equation (2) gives

$$\rho c \frac{dT}{d\theta} = \left(\frac{1}{u_Q}\right)^2 \frac{d}{d\theta}\left(k\frac{dT}{d\theta}\right) + \frac{1}{\delta}(q_{GEN} - q_{LOSS} - q_{TRAN}). \tag{3}$$

The flux, q_{TRAN}, at the inner wall of the tube, is given by equation (3) in terms of the loss from the outer wall, evaluated as a flux, q_{LOSS}, the electrical input, expressed as a flux, q_{GEN}, at the inner wall, and the derivatives of the wall temperature history. In evaluation, equation (3) was expressed in terms of the constants of the cubic for the intervals of the spline fit, and the temperature dependence of the properties was considered.

The error involved in the use of equation (3) for the flux and of the neglect of the radial temperature variation in it were examined by Denham [3] on the basis of the Burgraff approximation for the radial temperature variation. From the temperature T_{WO} as determined for the outside of the tube, the inside tube temperature and the flux are indicated to be

$$T_W = T_{WO} - \frac{\delta}{2k} q_{TRAN} + \frac{\delta^2}{24}\left(\frac{\rho c}{k}\right)\frac{d^2 T_{WO}}{d\theta^2} \tag{4}$$

$$q = q_{TRAN} - \rho c \frac{\delta^2}{6}\frac{d^2 T_{WO}}{d\theta^2}. \tag{5}$$

The second derivative as evaluated from the temperature history produced a negligible contribution from the last terms of equations (4) and (5). Therefore, q was taken as q_{TRAN} and the inside temperature was evaluated from the two terms of equation (4). The effect is significant, and to indicate the magnitude, the use of a constant value of the thermal conductivity k typical of the quench interval gives, from equation (4)

$$T_W = T_{WO} - q/45 \quad (T \text{ in } ^\circ\text{C}, q \text{ in kW m}^{-2}). \tag{6}$$

This still somewhat questionable basis of predicting the inside wall temperature from the measured outside

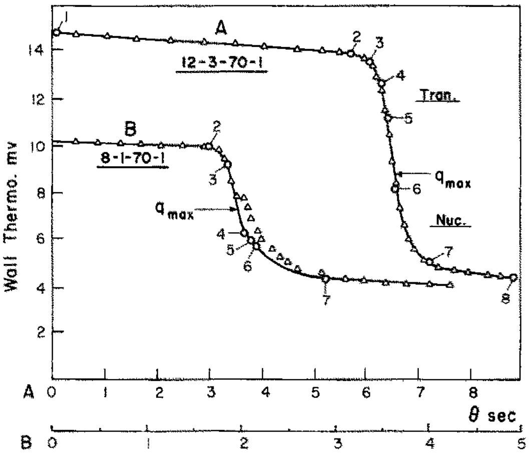

FIG. 1. Wall thermocouple response, runs 12–3–20–1 and 8–1–70–1. The triangles are the data and the curves are the fit, based on knots at the numbered circles.

wall temperature produces a large difference when the flux is large, for a typical maximum flux of 1800 kW m^{-2} at atmospheric pressure, the inside wall temperature is, from equation (6), 40°C less than the outside temperature. The uncertainty in the prediction is unknown and, thus, there is some question about the inside temperature in the region near the maximum heat flux.

Figure 1 illustrates two of the temperature histories showing some of the data with triangles and the spline fitted history by curves. Small circles, numbered, show the knot locations. Two runs are shown, designated in terms of a number sequence of: nominal initial temperature, hundreds of °F; fluid feed velocity, in. s^{-1}; inlet water temperature, °F; system pressure, atm. For run 12–3–70–1, the correspondence is good. The record for 8–1–70–1 is shown as an indication of irregularity that sometimes existed when the quality within the quench zone was larger than zero. The double differentiation of such a record would lead to anomalous results for the time interval in which the tube wall temperature is almost constant, as though the transfer had ceased completely. To obtain results, this interval, $\Delta\theta$, was removed from the record to make it continuous at the temperature of the interval, so that the curve shown for the history was then obtained from the spline fit program.

Table 1 summarizes the operating conditions and contains some results as obtained from the relation between the heat flux and the temperature difference that was established from the temperature histories obtained at the 1.83 m location. Additional runs for different elevations are similarly tabulated in refs. [1, 2]. The table gives in successive columns, 1, the nominal run conditions; 2, the location, quench height, at which the temperature history was obtained; 3, the collapsed liquid level for the quench height. Column 4 is the quench velocity as u_Q, the slope of the quench history, $z_Q = f(\theta)$, determined from the time at which the rapid drop in tube wall temperature occurs at successively higher elevations. These quench velocities are somewhat lower than found in earlier operation of the experimental system [4]. The reason for the reduction was not appraised. Column 5 is the feed water flow mass flow rate; 6, the average initial equilibrium tube wall temperature before the initiation of the water flow; 7, the subcooling $(T_{sat} - T_{in})$ of the water at inlet and 8, the value of q_{GEN} corresponding to the energy rate produced by the current flow in the tube. There follow results obtained from the temperature history; 9, q_{max}, the maximum flux; 10, the temperature difference $(T_{max} - T_{sat})$ when q_{max} occurs; 11, the value of $(T - T_{sat})$, denoted as ΔT_q at the 'knee' of the temperature history, where the wall temperature first diminishes rapidly, obtained by the intersection of tangent lines as illustrated on Fig. 1. Column 12 is the flux at ΔT_q.

At the end of transition boiling, when film or possibly dispersed flow boiling began, the rapid decrease in the flux should terminate, with $dq/d\theta$ becoming much less at higher ΔT. While some irregularities exist in the experimental results in this region, an estimate of a minimum heat flux for the transition boiling region can be made. These values, somewhat approximate, are in Column 13 and Column 14, gives the values of ΔT_{min} associated with these fluxes.

Finally, three calculated values of quality are given. Column 15 is x_1, the quality of the water state just below the quench front as calculated for steady conditions, from the feed water flow rate and temperature and the heat transfer to the fluid in $0 < z < z_Q$. Column 16 is x_2, a quality calculated from this initial water state, assuming steady conditions for a stationary quench region, so that velocities are taken relative to the quench velocity, and the tube wall velocity is the quench velocity. The basis of calculation indicated in ref. [2] is uncertain in some of its aspects, but x_2 does indicate the effect of the quench on the fluid state at exit from the quench region. Column 17 is x_{max}, the quality calculated for the point at which the maximum flux occurs. This is calculated on the same basis as is x_2, but the evaluation requires the integral of the flux history over the nucleate boiling region, in the manner indicated by the discussion following Fig. 2. Column 18, the final entry on Table 1, indicates those runs for which the history of the wall temperature contained an irregularity like that illustrated on Fig. 1 for run 8–1–70–1. The entry in this column is a footnote that gives the time interval, $\Delta\theta$, s, that was removed and the temperature of the deleted region.

Before proceeding to the examination of the results, a consideration of Fig. 2, the history of the flux at the inner wall for two of the runs, one with a high and the other with a low quench velocity, indicates the regions of nucleate and transition boiling and of their extent relative to the length of the quench region. For the latter a distance scale, $z = u_Q\theta$, is shown, with its zero location at the location of the maximum flux. Transition boiling occurs in the region between T_q, as marked, and q_{max}. The situation for run 10–2–

Table 1

1 Run Condition	2 z_Q (ft.)	3 z_c (ft.)	4 u_Q (ft. h^{-1})	5 G (kg m^{-2} s^{-1})	6 T_{wi} (°F/°C)	7 ΔT_{sub} (°C)	8 q_{GEN} (kW m^{-2})	9 q_{max} (kW m^{-2})	10 ΔT_{max} (°C)	11 ΔT_q (°C)	12 $q_{\Delta T_q}$ (kW m^{-2})	13 q_{min} (kW m^{-2})	14 ΔT_{min} (°C)	15 x_1 (%)	16 x_2 (%)	17 x_{max} (%)	18 $\Delta T/\Delta\theta$ (°C s^{-1})
6–3–70–1	6	7.49	568.4	74.02	624/329	77.2	8.79	1747	43.3	121	55	40	123	−12.00	−2.7	−6.48	
8–3–70–1	6	7.15	443.4	74.01	800/427	76.7	15.32	1754	50.7	162	55	45	170	−9.90	−2.8	−6.12	
10–3–70–1	6	7.05	234.0	74.01	1009/543	76.7	26.83	1956	50.0	220	55	45	230	−6.38	−3.2	−4.68	
12–3–70–1	6	6.82	71.2	74.01	1187/642	76.7	40.80	2177	89.0	240	55	45	230	−2.10	−0.03	−1.45	
6–2–70–1	6	6.64	461.2	51.24	623/328	75.6	8.87	1568	48.4	120	55	30	135	−10.20	8.0	−1.60	
8–2–70–1	6	6.43	308.1	51.25	805/429	76.1	15.53	1800	56.6	145	50	24	160	−7.78	−0.8	−3.71	
10–2–70–1	6	6.30	130.9	51.25	1002/539	76.1	26.32	1929	64.2	181	30	30	182	−3.01	−0.7	−1.49	
6–1–70–1	6	6.20	270.0	25.25	616/324	76.7	8.53	1428	40.1	112	42	22	132	−7.63	40.0	10.41	
8–1–70–1	6	6.05	122.4	25.25	810/432	76.7	15.64	1717	37.7	140	40	22	142	−1.26	3.7	1.56	(1)
6–3–150–1	6	7.04	504.0	74.01	619/326	32.2	8.68	1671	49.4	115	40	—	—	−3.68	2.6	0.87	
8–3–150–1	6	6.54	307.7	74.08	809/431	35.6	15.49	1690	52.5	133	52	40	157	−2.22	1.0	0.01	
10–3–150–1	6	5.70	126.0	74.09	1004/540	36.1	26.38	1994	69.2	211	40	28	212	1.00	2.5	1.92	(2)
12–3–150–1	6	3.53	68.6	74.12	1188/642	37.2	40.93	2120	84.5	228	110	—	—	5.24	6.2	6.00	(3)
6–2–150–1	6	6.03	400.0	48.88	631/333	34.4	8.89	1605	51.1	120	40	—	—	−2.78	0.8	4.55	
8–2–150–1	6	5.32	192.0	49.37	802/428	33.9	15.15	1645	57.1	145	20	20	142	0.12	3.2	1.84	
10–2–150–1	6	4.22	60.0	49.36	959/515	33.3	26.48	1966	42.9	212	180	46	240	5.42	6.6	6.12	(4)
6–3–150–4	6	7.21	818.0	73.66	635/335	80.4	9.04	2463	34.1	115	45	17	130	−13.56	40.0	11.9	
8–3–150–4	6	7.02	651.8	75.52	808/431	77.1	15.54	2692	44.5	141	42	42	140	−10.89	6.0	−0.91	
10–3–150–4	6	6.85	470.3	72.85	1014/546	77.1	26.85	2911	45.5	161	46	46	162	−7.01	1.0	−1.20	
12–3–150–4	6	6.36	250.0	74.61	1189/643	78.7	40.84	3159	49.4	175	52	48	166	−3.03	0.0	−0.47	
6–2–150–4	6	7.10	580.0	48.62	633/334	81.0	8.87	2525	43.2	125	46	46	127	−12.66	†	41.3	
8–2–150–4	6	6.90	502.8	48.62	830/443	81.0	16.47	2604	54.2	140	46	22	151	−8.84	25.0	13.4	
10–2–150–4	6	6.76	317.0	47.87	955/513	79.3	26.38	2728	37.9	150	46	46	144	−3.44	4.6	2.21	
12–2–150–4	6	6.46	160.5	49.09	1180/638	79.8	40.38	2887	69.7	185	52	52	183	3.00	6.0	5.12	(5)
6–1–150–4	6	6.17	311.1	25.92	629/332	77.1	8.90	2483	37.3	131	50	40	138	−8.89	†	34.1	
8–1–150–4	6	6.06	306.5	25.74	812/433	78.2	15.60	2579	20.6	133	65	40	152	−2.81	†	28.8	
10–1–150–4	6	5.54	170.9	25.76	1003/539	78.7	26.27	2639	33.6	141	40	40	141	7.00	15.7	10.1	(6)

(1) 88/0.0918; (2) 48/0.0918; (3) 88/0.0918, 51/0.0459; (4) 79/0.2377; (5) 131/0.0459; (6) 140/0.0918, 68/0.0918.

† The value of x_2 is greater than 1.

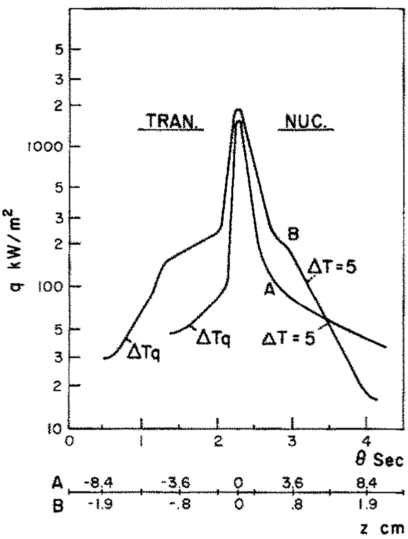

FIG. 2. Heat flux histories with high and low quench velocities

Curve	Run	x_1 (%)	u_Q (cm s^{-1})
A	6–3–70–1	−12	4.8
B	10–2–150–1	5.4	1.7

150 is ambiguous because Curve B, the temperature history for this run, is such that the flux does not attain a relatively constant value until $\Delta T_q = 235$, compared to $\Delta T_q = 212$, Column 11 of Table 1, that is indicated on Fig. 2. Nucleate boiling occurs when the flux diminishes again and as a limit for this region there is indicated the location when ΔT is 5°C. Beginning at the time θ_q at which ΔT_q occurs, the transfer for the interval $\theta_q < \theta < \theta_{max}$ is

$$2\pi r u_Q \int_{\theta_Q}^{\theta} q\,d\theta, \text{ kW}.$$

The logarithmic scale of Fig. 2 prevents the visualization of this magnitude but an approximate evaluation of the integral gives the values in Table 2 for the transition region $\theta_q < \theta < \theta_{max}$ and the total region θ_q to the time at which $\Delta T = 5$°C occurs. The larger values for condition 6–3–70–1 are due to its high quench velocity, as can be judged from the length scale on Fig. 2. For both runs, the fraction of the transfer in transition boiling is a large part of the total transfer.

NUCLEATE BOILING

The relationship of q to $(T - T_{sat})$ is shown for the nucleate boiling region for 1 atm pressure on Fig. 3 for runs with $x_1 < 0$ and on Fig. 4 for runs with

Table 2

	Q' (kW) Transition	Q' Total	Fraction transition
6–3–70–1	0.51	1.10	0.46
10–2–150–1	0.19	0.52	0.36

$x_1 > 0$. The dashed line indicates the Rohsenow pool boiling prediction for C_{sf}, the coefficient in that relation, equal to 0.021. Solid curves show the prediction according to the proposal of Bjorge *et al.* [5], which, for the case of initially subcooled or low quality, $x_1 < 5\%$, specifies the flux as

$$q = [(h_{FC}(\Delta T + \Delta T_{sub}))^2 + (q_B S)^2]^{1/2}$$

$$S = 1 - \left(\frac{\Delta T_{ib}}{\Delta T}\right)^3, \quad \Delta T > \Delta T_{ib}. \qquad (7)$$

For atmospheric pressure, $q_B = 0.034\Delta T^3$. This happens to correspond to a Rohsenow pool boiling specification with $C_{sf} = 0.021$. ΔT_{ib} is the incipient boiling temperature and h_{FC} the forced convection heat transfer coefficient. From ref. [5], the value of ΔT_{ib} is predicted to be 35°C. Curves A–C on Fig. 3 show this prediction for a water flow velocity of 0.0762 m s^{-1} (3 in. s^{-1}) for low and high subcooling and for 0.0254 m s^{-1} (1 in. s^{-1}) for high subcooling. For low values of $(T_W - T_{sat})$, forced convection is the only contribution, and the prediction, Curve A, is acceptable for 6–3–70 and 8–3–70. For 8–1–70, with $x_1 = -1\%$, a subcooling of about 5°C, the prediction fails, for while the data are near Curve C, that prediction, to be for a subcooling of 5°C, must be reduced by the ratio $(\Delta T + 5)/(\Delta T + 75)$. It then falls below the scale of Fig. 3. As ΔT increases, the predicted q varies but there is no boiling contribution from equations (7) until $\Delta T_{ib} = 35$. To obtain any correspondence with the data, lower values of ΔT_{ib} would be required. As an example, the data for 6–3–70, 8–3–70, 10–3–70 correspond to a prediction from equations (7) with $\Delta T_{ib} = 10$, and the exponent of $(\Delta T_{ib}/\Delta T)$ in the suppression factor S made unity instead of 3.

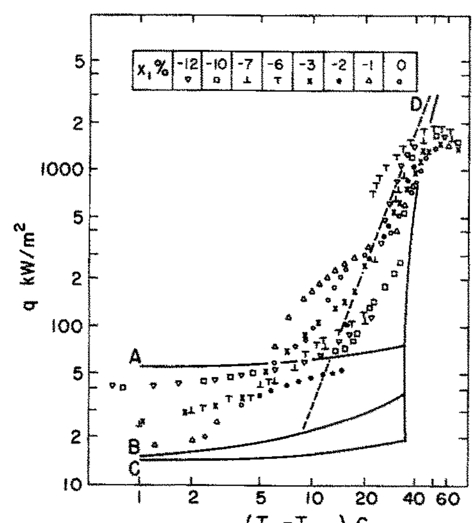

FIG. 3. Nucleate boiling at 1 atm pressure for qualities less than zero. Curves A–C are from ref. [5] for values of feed velocity u_{in}, and quality, x_1 (or ΔT_{sub}). Curve A, 7.62 cm s^{-1}, −14% (75°C); Curve B, 7.62 cm s^{-1}, −3.7% (20°C); Curve C, 2.54 cm s^{-1}, 14% (75°C). Curve D is the saturated pool boiling prediction for $C_{sf} = 0.021$.

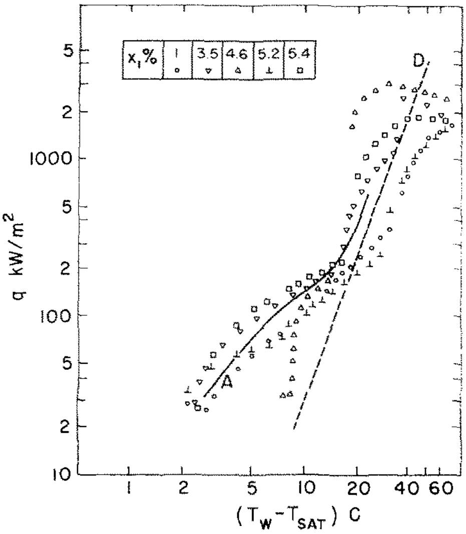

FIG. 4. Nucleate boiling at 1 atm pressure for qualities greater than zero. Curve A is from ref. [5] for $h_{FC} = 10$ kW m^{-2} °C^{-1}. Curve D is as on Fig. 3.

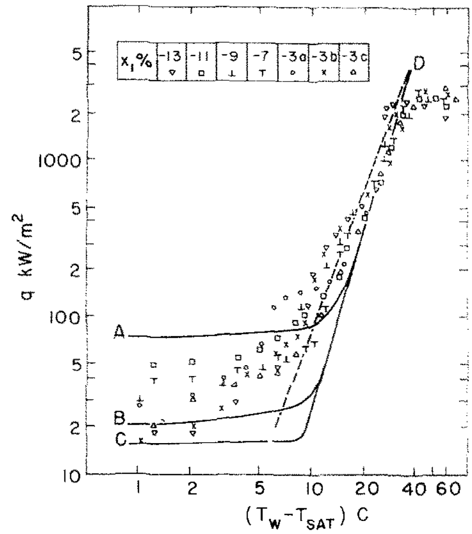

FIG. 5. Nucleate boiling at 4 atm pressure for qualities less than zero. Curves A–C are from ref. [5] for values of feeding velocity u_{in} and quality, x_1. Curve A, 7.62 cm s^{-1}, -15%; Curve B, 7.62 cm s^{-1}, -4%; Curve C, 2.54 cm s^{-1}, -15%. Curve D is the saturated pool boiling prediction for $C_{sf} = 0.021$.

Figure 4 shows the results for higher initial quality, for most runs indicated there $x_1 \simeq 5\%$, near the upper limit of Bjorge *et al.*'s prediction for low quality. Now $\Delta T_{sub} = 0$ and predictions A and C of Fig. 3 for low ΔT would be lower in the ratio $\Delta T/(\Delta T+75)$, but ΔT_{ib} would still be 35°C. Clearly, the prediction will not correspond to the results. For Bjorge *et al.*'s 'high quality', $x > 5\%$, specification, $\Delta T_{ib} = 0.2$°C for h_{FC} as predicted for single phase flow with a velocity of 0.0762 in. s^{-1} (3 m s^{-1}). For two-phase flow with $x = 5\%$, the prediction is $\Delta T_{ib} = 0.6$°C, higher than 0.2 because the two-phase flow prediction gives an h_{FC} three times that for the single phase flow. Even with the higher h_{FC}, and using the specification $q = (q_{FC}+Sq_B)$ as recommended for $x > 5\%$, the predictions are farther from the data than those of Fig. 3. It can be noted that if h_{FC} is taken as 10 kW m^{-2} °C^{-1}, about three times Bjorge *et al.*'s specification for two-phase flow, then ΔT_{ib} becomes 2°C. With these values, there is obtained the solid curve shown on Fig. 4 that is located near the majority of the data points.

For a pressure of 4 atm, Fig. 5 shows data for $x_1 < 0$ and on it predictions like Curves A–C of Fig. 3 are shown. These predictions differ from those of Fig. 3 because of the reduction in ΔT_{ib}, which depends on the value of v_{fg}, so that for 4 atm ΔT_{ib} is about 10°C. The correspondence of the prediction and the data is better than it is on Fig. 3, though this situation would be improved by a further reduction of ΔT_{ib}. Data for $2.6\% < x_1 < 7\%$ are not shown here, but are given in ref. [2]. There are only three runs, for them the trend with x is not consistent, but they show the same relative aspects as the results on Fig. 4.

MAXIMUM HEAT FLUX

The maximum heat flux can be noted on Figs. 3–5, and the values are contained in Table 1, where the quality, x_{max}, predicted for that location is included. Observation of Fig. 3 and of the tabulated values of x_{max}, for $x_{max} < 0$, the first seven runs in the table, reveals no trend with x_{max}. The remaining 1 atm runs of the table, for most of which $x_{max} > 0$, reveal no trend either. All that can be deduced is that $q_{max} = 1850$ kW m$^{-2} \pm 15\%$. The nature of q_{max} for 4 atm pressure is essentially the same, and it is possible to establish only that $q_{max} = 2780$ kW m$^{-2} \pm 15\%$. The Zuber pool boiling specification, slightly adjusted, is given by Lienhard [6] as

$$q_{max} = 0.15\rho_g^{1/2}h_{fg}[\sigma g(\rho_f-\rho_g)]^{1/4}. \qquad (8)$$

This, for saturated pool boiling from a horizontal surface, gives $q_{max} = 1260$ for 1 atm and 2180 for 4 atm. The experimental values cited above are 1.47 and 1.27 times these values. It can be noted that, for a vertical surface, Lienhard recommends an increase in the q_{max} obtained from equation (8) by the factor $1.4/[H(g(\rho_f-\rho_g)/\sigma)^{1/2}]^{1/4}$ when the bracketed term is less than 6, and for greater values by the factor of 0.9. For atmospheric pressure, the value of H, the height of the surface, that gives a factor of 1.47 is 0.2 cm, and for 4 atm, the value that gives 1.27 is 0.34 cm. This citation is made because the boiling surface in the tube is indeed vertical, though in it the geometry and the fluid state differ from that of the system for which the Lienhard factor is specified. Moreover, the heights, H, needed to give the required factors cannot be related to the present system, though the length scale on Fig. 2 implies that the value of $\Delta z = u_Q\Delta\theta$ for the period, $\Delta\theta$, in which fluxes like the maximum exist might be quite small.

It is also important to define the temperature difference, ΔT_{max}, at which the maximum heat flux occurs. An inspection of Figs. 3–5 indicates the difficulty in making such an evaluation but Table 1 contains the best estimate of ΔT_{max}. This value is mostly higher than what is predicted when q_{max} is used in the pool boiling relation $q = A\Delta T^3$. For 1 atm, $A = 0.034$, $q = 1850$ gives $\Delta T_{max} = 38°C$; for 4 atm, $A = 0.048$, $q = 278$ gives, also, 38°C.

MINIMUM HEAT FLUX

The transition boiling region is specified to extend from (q_{max}, ΔT_{max}) to (q_{min}, ΔT_{min}). Theoretically, there should be film boiling or possibly dispersed flow boiling for $\Delta T > \Delta T_{min}$ and the nature of transition boiling is such that there should be a rapid change in $dq/d(\Delta T)$ at ΔT_{min}. The irregularity of the results is such, however, that ΔT_{min}, and q_{min}, are not found very accurately from the location of a large change in slope, $dq/d\Delta T$. Table 1 contains these values; because of the uncertainty ΔT_{min} for some runs disagrees markedly with ΔT_q.

The minimum flux can be compared to the prediction for saturated pool boiling, given by Lienhard [6] as

$$q_{min} = 0.9\rho_g h_{fg}\left(\frac{\sigma g(\rho_f-\rho_g)}{(\rho_f+\rho_g)^2}\right)^{1/4} = 0.65\left(\frac{\rho_G}{\rho_L}\right)^{1/2} q_{max}. \quad (9)$$

The final part of equation (9) applies for $\rho_G \ll \rho_L$, and q_{max} specified by equation (8). For atmospheric pressure, the factor on q_{max} is 0.015 and for 4 atm it is 0.028. Using equation (8) for q_{max}, q_{min} is given as 19 and 68 kW m^{-1} for 1 and 4 atm, respectively. If the average experimental values of q_{max} are used, then equation (9) gives $q_{min} = 28$ and 72 kW m^{-2}. The values in Table 1 for q_{min} for 1 atm pressure indicate only a range of about 20–50 depending on whether ΔT_{min} or ΔT_q is used for the evaluation. For 4 atm, the situation is similar, with values of q_{min} mostly in the range of 40–52. There is no indication of the more substantial effect of pressure that is indicated by equation (9).

The values of ΔT_{min} vary considerably with the operating condition, with a range of 112–240°C at atmospheric pressure and of 115–180°C at 4 atm. A prediction of ΔT_{min} is often made by the use of q_{min} in the modified Bromley film boiling expression

$$h = 0.62\left[\frac{g(\rho_f-\rho_g)k_g^3(h_{fg}+0.34c\Delta T)}{\sigma v\Delta T}\right]^{1/4}. \quad (10)$$

In this modification, the film length that is contained in the Bromley result appears to have been replaced by a distance depending on σ as obtained from the specification of the minimum stable wavelength for the interface between the gas and liquid phase, with zero velocity, and the gradual acceleration normal to the interface. In the vertical tube, this direction is parallel to the surface. Berenson combined equations (9) and (10) and solved for ΔT, in the process the term $0.34c\Delta T$, negligible for water, was omitted. The values of ΔT_{min} so obtained are 86°C for 1 atm and 198°C for 4 atm, the difference being primarily due to the change in the density of the gas. For comparison, if the spontaneous nucleation temperature, of $27/32T_{crit}$, which is 546 K (273°C), is used with the transient conduction solution for one semi-infinite solid in contact with another, both of different properties with different initial temperature and the constant interface temperature equal to the spontaneous nucleation temperature, 273°C, then the relation between the wall temperature and the liquid temperature is

$$\frac{T_W-27/32T_{crit}}{27/32T_{crit}-T_L} = \left[\frac{(\rho ck)_L}{(\rho ck)_W}\right]^{1/2}. \quad (11)$$

To this elementary appraisal, due to Henry, more complicated ones have been added. Using equation (11) for water and the properties of the tube wall, gives the term on the right as 0.19, so that ΔT_W, a prediction for the wall 'rewet temperature' gives $\Delta T_W = 164°C$ for 1 atm and $\Delta T_W = 109°C$ for 4 atm.

In consequence, neither the values of ΔT from equation (10) or equation (11) indicate the type of variation of ΔT_{min} that is indicated in Table 1.

TRANSITION BOILING

From the values of $(q, \Delta T)_{max}$ and $(q, \Delta T)_{min}$, the relation $q = f(\Delta T)$ is to be predicted for the transition region. Winterton [7] has reviewed many proposals. There are, in fact, predictions that are proposed only in terms of $(q, \Delta T)_{max}$; therefore, these terminate the transition region only by the attainment of $q/\Delta T$ equal to a film boiling, or other specification such as equation (10). Of these, a typical one is, $q/q_{max} = (\Delta T_{max}/\Delta T)^n$, so that $d(\log q)/d\Delta T = -n/\Delta T$. Typical experimental distributions are shown by points on Fig. 6 as $\log q = f(\Delta T)$ and it is obvious that any proposal that produces the steepest slope for small ΔT cannot fit the experimental results. Other predictions based only on $(q, \Delta T)_{max}$ also fail in this respect. The only proposals that produce the appropriate shape for $q = f(\Delta T)$ require the specification of $(q, \Delta T)_{min}$ as well as these values for the maximum. One is by Bjornard and Griffith [8]

$$q = q_{max}f + (1-f)q_{min} \quad (12)$$

and the other is that of the TRAC Code [9]

$$q = h\Delta T = (h_{max}f + (1-f)h_{min})\Delta T. \quad (13)$$

In both equations (12) and (13), $f = ((T_{min}-T)/(T_{min}-T_{max}))^n$ and an exponent of 2 is recommended for both relations. For given terminal conditions, $(q, \Delta T)_{max}$ and $(q, \Delta T)_{min}$, the flux predicted from either equation (12) or equation (13) increases as the exponent, n, decreases and for a given exponent equation (13) gives fluxes higher than those from equation (12).

Figure 6 shows by points the experimental results

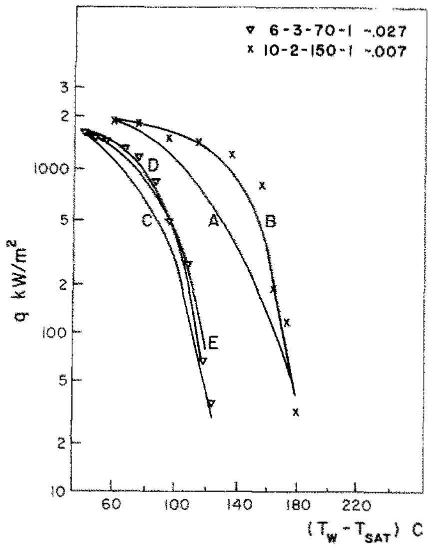

FIG. 6. Transition boiling results and predictions. Curve A is equation (12) with $n = 1.5$; Curve B is equation (13) with $n = 1.5$, both for 10–2–150–1. Curve C is equation (12) with $n = 1.5$; Curve D is equation (13) with $n = 2$; Curve E is equation (13) with $n = 1.5$, all for 6–3–70–1.

for two runs, 6–3–70–1 and 10–2–70–1. Curves show predictions made with the terminal conditions listed in Table 1. Curves A and C are from equation (12) with $n = 1.5$; for each of the runs, the prediction is too low. Curve B, for 10–2–70–1, from equation (13) with $n = 1.5$ shows an improved correspondence. A similar prediction for 6–3–70–1 produces values that are too high and to improve correspondence $n = 2$ is used to produce Curve D. Curve E is a prediction from equation (13) with $n = 1.5$ and the terminal conditions for run 6–2–70–1, except that ΔT_{min} is taken as ΔT_q. Thus, the terminal conditions differ from those for 6–3–70–1 only in the values of $(q, \Delta T)_{max}$. Using the lower q_{max}, combined with the lower exponent, makes the correspondence with the results for 6–3–70–1 almost as good as that of Curve D. In fact, there is equal correspondence with the data for 6–2–70–1, which, except for ΔT near ΔT_{max}, differ little from those for run 6–3–70–1.

The limited comparisons of Fig. 6 imply some preference for equation (13) and suggest that the exponent might be related to an operating condition. This has been tried for all of the runs at the point where $q/q_{max} = 1/2$, by obtaining ΔT from the curve of the experimental results, as on Fig. 6, and then solving for the value of 'n' from equation (13), with h_{min} neglected in the equation since $h_{min} \ll h_{max}$. Except for a few runs, the resulting values for 'n' range from 1.5 to 2.25 but there is no trend with an operating condition, such as with the value of x_2. Thus, it appears that equation (13), with $n = 1.75$, might produce relatively acceptable predictions for most of the runs.

Another prediction was developed by using a portion of the experimental results to develop a relation for 'f' to be used in equation (13). In this, the experimental values of q_{max} were used but ΔT_{max} was determined from the use of q_{max} in $q = A(\Delta T)^3$, A being as before, 0.034 and 0.048 for 1 and 4 atm pressure, respectively. For ΔT_{min} the values of ΔT_q and h_{min} obtained from equation (10) were used. Then, equation (13) was used to calculate f from the experimental heat transfer coefficients. It was found that these values of 'f' could be correlated as

$$\ln \frac{f}{\theta} = a - b\Delta T, \quad \theta = (T_{min} - T)/(T_{min} - T_{max}) \qquad (14)$$

for 1 atm $a = 0.0133$, $b = 0.0071$
for 4 atm $a = 0.398$, $b = 0.0116$

and considering this pressure dependence

$$a = 0.0133P^{2.45}, \quad b = 0.0071P^{0.36}.$$

This correlation agrees within $\pm 8\%$ with the deduced value of 'f' from which it was established for five runs at 1 atm and five runs at 4 atm. It was then used to predict $h = f(\Delta T)$, for all of the runs. All comparisons are given in ref. [1] and a number of the comparisons are given in ref. [2]. The correspondence, of course, had to be good for those runs upon which the correlation was established. For the others, the worst cases gave predictions about 50% in excess of the experimental values of the flux in the region of q/q_{max} of the order of 0.4. Figure 7 contains runs for which the agreement was good and also runs for which it was poor.

Finally, this prediction is applied to some of the results of Denham [3] for a pressure near 4 atm, these results being obtained in the way that the present results were, from temperature histories obtained at three different elevations during the quench produced by the reflood of a vertical tube. Figure 8 shows by points the deduced experimental heat transfer coefficients in the transition region and Table 3 contains values of q_{max}, ΔT_{max} and ΔT_q as estimated from

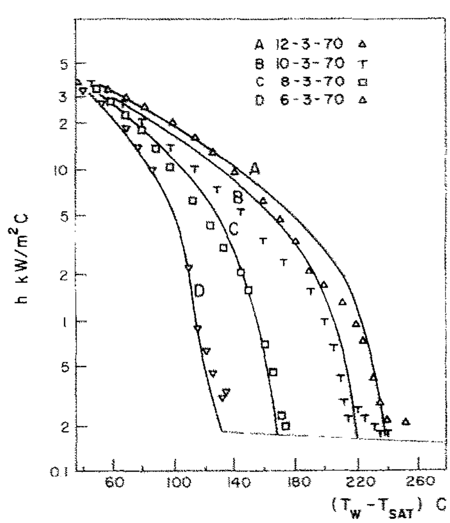

FIG. 7. Transition boiling at 1 atm pressure, results and predictions.

Table 3

z (cm)	q_{max} (kW m^{-2})	ΔT_{max} (°C)	ΔT_q (°C)	x_1 (%)	x_2 (%)	$(T_q - T_{max})$ (°C)	$(q_{max}/0.048)^{1/3}$ (°C)
15	1910	130	285	−0.02	0.08	155	34
80	1400	115	220	0.03	0.08	105	31
190	800	75	175	0.09	0.12	100	25

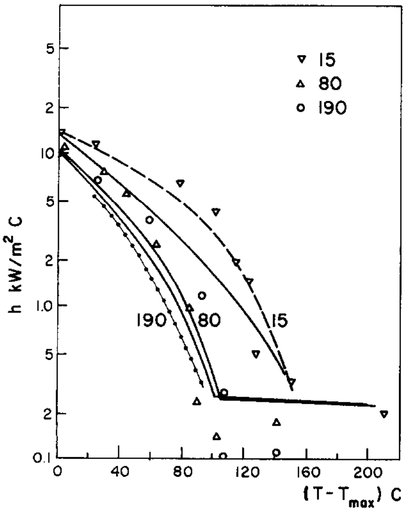

FIG. 8. Transition boiling, results from ref. [3] with the present predictions. The results are those for run 0.1X092 of ref. [3] for a pressure of about 4 atm, obtained at the three elevations indicated in the legend for which the qualities, x_1, were given as −2, 3 and 9.

those results, together with the values of x_1 and x_2 given in ref. [3]. Table 3 also includes the value of ΔT_{max} obtained from the relation, $(q_{max}/0.048)^{1/3}$, to indicate how much below the experimental values of ΔT_{max} these values are. Therefore, h_{max} was calculated from q_{max}, and from ΔT_{max} as estimated from the experimental results, equation (10) was used for h_{min}. The dotted curve on Fig. 8 is the prediction for the 190 cm location; this prediction is low. With the constants in equations (14) taken for 1 atm instead, the prediction is the solid curve immediately above the dotted curve. Similar solid curves are indicated for the 80 and 15 cm locations. Very little potential is demonstrated by the prediction method. In fact, equation (13) with the factor, f, calculated with an exponent of 1.5 produces the dashed curve for the 15 cm location, and for the 190 cm location a prediction that happens to coincide with the solid curve for the 80 cm location.

SUMMARY

Wall temperature histories, obtained for system pressures of 1 and 4 atm at one elevation on a vertical tube being quenched by water fed into the bottom of the tube, have been analyzed to produce the relation between the heat flux and the temperature on the inside wall of the tube during the quench process, to define the nature of the nucleate and transition boiling regions that occur during the quench.

The relation between the heat flux and the difference between the wall and the saturation temperature during nucleate boiling is of the nature associated with forced convection boiling and shows some of the trends indicated by the prediction method of Bjorge *et al.*, though a lower incipient boiling temperature than that of that method is needed to properly predict the experimental data.

The maximum heat fluxes are of the order of those for pool boiling and indicate no definitive effect of the water velocity or the quality estimated for that region.

The relation between the heat flux and the temperature difference in the transition boiling region is predictable by existing recommendations provided that both the heat flux and the temperature difference are taken as experimental values for the terminal points of maximum and minimum heat flux. Another method relating these indications also works for the present results, but does so only marginally for the results of Denham.

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TRANSFERT DE CHALEUR PENDANT LA TREMPE LORS DU REMOUILLAGE D'UN TUBE VERTICAL

Résumé—L'histoire de la température pariétale pour une élévation dans un tube vertical dont l'alimentation en eau se fait par le bas, à des pressions de 1 et 4 atm, est utilisée pour prédire la relation entre le flux de chaleur et la différence de température pendant le mécanisme de trempe. Durant l'ébullition nucléée, la relation entre le flux et la différence de température est comme spécifiée par les théories pour l'ébullition en convection forcée, mais il y a des différences de détail. Les flux maximaux sont supérieurs à ceux de l'ébullition en réservoir, mais ne peuvent pas être reliés aux conditions opératoires. Le comportement de transition en ébullition peut être prédit si les valeurs expérimentales du flux et de la différence de température au flux maximal et minimal sont utilisées dans les méthodes existantes de prédiction. On propose aussi une autre méthode basée sur les données expérimentales.

WÄRMEÜBERGANG WÄHREND DES KÜHLPROZESSES BEIM FLUTEN EINES EINZELNEN SENKRECHTEN ROHRES

Zusammenfassung—Der zeitliche Verlauf der Wandtemperatur eines senkrechten Rohres, das am unteren Ende durch Wasserzufuhr bei Drücken von 1 bis 4 atm plötzlich gekühlt wird, dient zur Ermittlung des Zusammenhangs zwischen der Wärmestromdichte an der Wand und der Temperaturdifferenz beim Abschreckvorgang. Während des Blasensiedens wird dieser Zusammenhang durch die Theorien für erzwungenes konvektives Sieden beschrieben; jedoch sind im Detail Unterschiede vorhanden. Die maximalen Wärmestromdichten sind etwas größer als die beim Behältersieden; aber sie können nicht mit den Betriebsbedingungen in Zusammenhang gebracht werden. Das Siedeverhalten im Übergangsbereich ist vorhersagbar, wenn die experimentellen Werte der Wärmestromdichte und der Temperaturdifferenz bei maximaler und minimaler Wärmestromdichte in den vorhandenen Berechnungsmethoden genutzt werden.

ТЕПЛОПЕРЕНОС В ПРОЦЕССЕ РЕЗКОГО ОХЛАЖДЕНИЯ, КОТОРЫЙ ПРОИСХОДИТ ПРИ ПОВТОРНОМ ЗАПОЛНЕНИИ ОДИНОЧНОЙ ВЕРТИКАЛЬНОЙ ТРУБЫ

Аннотация—Изменения во времени температуры стенки в одном поперечном сечении вертикальной трубы при быстром охлаждении водой, которая подается на дно трубы под давлением 1–4 атм., и параметры, управляющие процессом, используются для расчета зависимости между потоком тепла к воде и разностью температур в процессе охлаждения. При пузырьковом кипении зависимость между тепловым потоком и разностью температур имеет тот же характер, что и в случае кипения вынужденной конвекции, хотя существуют некоторые различия в деталях. Максимальные потоки несколько выше по сравнению со случаем кипения в большом объеме, но они не могут быть отнесены к рабочим условиям. Показано, что закономерности кипения в переходном режиме могут быть рассчитаны, если в существующих методах расчета используются экспериментальные значения потока и разности температур в случае максимального и минимального потоков. Кроме того, предлагается другой метод, основанный на полученных в работе результатах.