Transition Boiling Heat Transfer and the Film Transition Regime

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The "Berenson" flat-plate transition-boiling experiment has been re-created with a reduced thermal resistance in the heater, and an improved access to those portions of the transition boiling regime that have a steep negative slope. Tests have been made in Freon-113, acetone, benzene, and n-pentane boiling on horizontal flat copper heaters that have been mirror-polished, "roughened," or teflon-coated. The resulting data reproduce and clarify certain features observed by Berenson: the modest surface finish dependence of boiling burnout, and the influence of surface chemistry on both the minimum heat flux and the mode of transition boiling, for example. A rational scheme of correlation yields a prediction of the heat flux in what Witte and Lienhard previously identified as the "film-transition boiling" region. It is also shown how to calculate the heat flux at the boundary between the pure-film, and the film-transition, boiling regimes, as a function of the advancing contact angle.

Introduction

Transition boiling has, for 50 years, held its place as the least understood of the several boiling mechanisms. Consequently it has been virtually impossible to design thermal processes to operate in this regime. Indeed, the threat of thermohydraulic nuclear accidents – the possibility of uncovering a nuclear core and then having to rewet it – has done more to demand an understanding of transition boiling than the more positive problems of process design.

The Berenson Experiment. For years, our best knowledge of the regime was that given us by Berenson (1960) in his pioneering study. Berenson used a copper block, heated from below by the condensation of high-pressure steam, and cooled on top by the boiling of a low-boiling-point fluid. He then measured the heat flux q as a function of the almost independently specifiable temperature difference between the top of the copper block and the saturated liquid: $(T_w - T_{sat}) \equiv \Delta T$. He was thus able to obtain nearly complete "boiling curves" (specifications of the $q(\Delta T)$ relationship) for the boiled liquid. The following are among Berenson's more important experimental findings:

• The nucleate boiling heat flux is extremely dependent on surface finish.

• The peak (or "burnout") heat flux q_{max} in pool boiling is only slightly dependent upon the surface condition of the heater. He obtained about a 15 percent total variation of q_{max} over the full range of surface finishes, with the roughest surfaces giving the highest values.

• The film boiling heat flux is independent of the surface condition of the heater.

• The minimum film boiling heat fluxes were fairly consistent with one another if the surface chemistry was such as to give a relatively large contact angle β. If the surfaces were polished with a lapping compound as well, the minimum heat flux q_{min} reached its lowest value which Berenson correlated using a modified Zuber (1959) theory as follows:

$$q_{min} = 0.09 \rho_g h_{fg} \sqrt[4]{\frac{g(\rho_f - \rho_g)}{(\rho_f + \rho_g)^2}} \qquad (1)$$

• If the liquid wetted the heater surface significantly, q_{min}

was exceedingly high, and the transition heat fluxes were also very high.

Accessibility of Points in the Transition Boiling Regime. Witte and Lienhard (1982) re-examined Berenson's data in light of an observation made by Stefan and Kovalev, Grassman and Ziegler, and others (see, e.g., Hesse (1973)). They noted that not all transition boiling states are accessible in this kind of apparatus. The heat fluxes and ΔT that can be attained for given saturation temperatures of the condensing steam ($T_{cond.stm.}$) and of the boiled liquid (T_{sat}) are

$$q = \frac{(T_{cond.stm.} - T_{sat}) - \Delta T}{R_h + R_c} \qquad (2)$$

where R_h is the thermal resistance of the copper plate, (plate thickness)/k_h, and R_c is the resistance of the condensation process, $1/h_{cond}$.

The nearly straight lines specified by equation (2) are displayed in Fig. 1 on q versus ΔT coordinates (for a given system pressure). We call these "accessibility lines" because all q and ΔT data for a given value of $(T_{cond.stm.} - T_{sat})$ must lie along them. Notice that one cannot reach a point lying on the intersection of an accessibility line, and the boiling curve in the transition region, if that point lies between two other points of intersection with the boiling curve. The reason is that, in an approach from either the film or nucleate boiling side, there will be no reason for the system to leave the outer intersections. The role of R_c was ignored by Witte and Lienhard; thus they plotted accessibility lines through Berenson's data that were straight, and which optimistically showed a steeper slope than they should have.
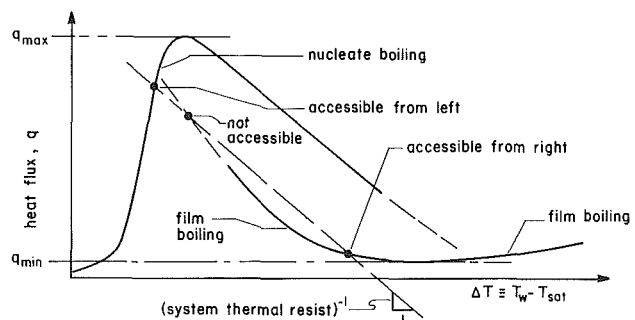

Fig. 1 Accessibility lines on Witte and Lienhard's double boiling curve (coordinates are linear)

The important point made by Witte and Lienhard (1982) was that, *for a given combination of liquid and heater condition*, there were two possible transition boiling curves: one that corresponded with a wetted surface and one that corresponded with an unwetted surface. They also noted that in a single process (such as the quenching of a heater) wetting can abruptly set in, causing a dramatic jump in the transitional boiling heat flux.

We shall subsequently argue that these jumps can occur because, once liquid contact becomes sustained, the relevant contact angle becomes the retreating one β_r, instead of the advancing one β_a.

The Minimum Heat Flux. As the wall superheat is decreased, the heat flux and the accompanying vapor volume production also decrease. As the vapor volume rate diminishes, one of two things can happen: One of these is the conventional q_{min} transition originally proposed by Zuber, and subsequently developed by others (see, e.g., Lienhard and Dhir, 1980). In accordance with Zuber's mechanism, q_{min} (as described by equation (1)) occurs when vapor is not generated rapidly enough to sustain the natural frequency of the Taylor wave at the liquid–vapor interface.

The other way in which q_{min} can be set appears to be by the onset of liquid–solid contacts that can occur well above this ultimate minimum value of q. As the vapor volume rate decreases, the vapor film becomes thinner and such contact becomes increasingly likely. Whether or not contact occurs at a given heat (and vapor volume) flux, will undoubtedly depend primarily upon the advancing (or "dry") contact angle since the surface will, in all probability, dry out between contacts.

In any event, while one conventionally identifies the beginning of a transitional boiling where the slope of the boiling curve becomes negative, we must now identify a transition *prior* to that point. This is the transition at which the boiling curve starts to deviate above what has been shown to be the predictable pure-film boiling curve. This kind of transition can occur when the boiling curve *still has a positive slope*. It is at this point that we might say that the liquid has been "informed" on the surface condition, presumably by having made contact.

Whether or not this transition leads into "film-transition," or into a rewetting "nucleate-transition" regime, boiling depends upon the magnitude of the contact angle. We presume that this should be the advancing angle β_a, since the heater surface must be dry before the liquid–vapor interface touches it each time.

Film Boiling. Berenson's original study included a prediction of film boiling heat transfer that involved heat conduction through the laminar vapor film flowing in the space between the heater and the liquid–vapor interface. The prediction was reasonably good at the lower film boiling heat fluxes; however, as ΔT was increased, it yielded values that decreased to about 80 percent of the measurements. While this error was not great, it was extremely systematic in ΔT.

The misbehavior of Berenson's straightforward prediction was studied by Klimenko (1981). Klimenko traced the development of film boiling predictions for horizontal heaters from Chang (1959) through Berenson and beyond, noting that virtually all of them took the form

$$\mathrm{Nu} = A[g\lambda_d^3(\rho_f - \rho_g)h'_{fg}/\alpha_g\nu]^b \qquad (3)$$

where the Nusselt number $\mathrm{Nu} \equiv q\lambda_d/k_g\Delta T$, and h'_{fg} is the conventional effective latent heat corrected to account for sensible heat transfer.

Klimenko proposed a new view of the heat transfer process. He suggested that it was the result of a gravity-driven, forced convection flow through the vapor film. This flow, he noted, would be turbulent if

$$M \equiv \frac{g^{1/3}\lambda_d}{\sqrt{3}\nu^{2/3}}\left[\frac{\rho_f - \rho_g}{\rho_f}\right]^{1/3} > 464 \qquad (4)$$

Using Reynolds analogy, he then predicted the Nusselt number

$$\frac{\mathrm{Nu}}{M\mathrm{Pr}^{1/3}} = \begin{cases} 0.0086, & \text{for } \mathrm{Ja} > 0.5 \\ 0.00611/\mathrm{Ja}, & \text{for } \mathrm{Ja} < 0.5 \end{cases} \qquad (5)$$

where Ja is the Jakob number, $c_p\Delta T/h_{fg}$.

All of the data we deal with subsequently satisfy both the criterion for turbulent flow, $M > 464$, as well as the Ja > 0.5

Nomenclature

A, B, b	=	unspecified constants
Bi*	=	modified Biot number, see equation (14)
c_p, c_h	=	heat capacities of the saturated liquid and the heater, respectively
g	=	acceleration of gravity
h_c	=	condensing heat transfer coefficient
h_{fg}, h'_{fg}	=	latent heat of vaporization; modified latent heat $= h_{fg}(1 + \text{const} [\mathrm{Ja}])$
Ja, Ja*	=	Jakob number $= c_p\Delta T/h_{fg}$; modified Ja, see equation (14)
K	=	dimensionless function of transport properties defined in equation (6)
k_f, k_g, k_h	=	thermal conductivities of the saturated liquid, the vapor in the film, and the heater, respectively
M	=	dimensionless group defined in equation (4)
Nu	=	Nusselt number for film boiling $= q\lambda_d/k_g\Delta T$
Pr	=	Prandtl number of the vapor
q, q_{max}, q_{min}	=	heat flux; peak pool boiling heat flux; minimum pool film boiling heat flux
R_c, R_h	=	thermal resistances of the heater block

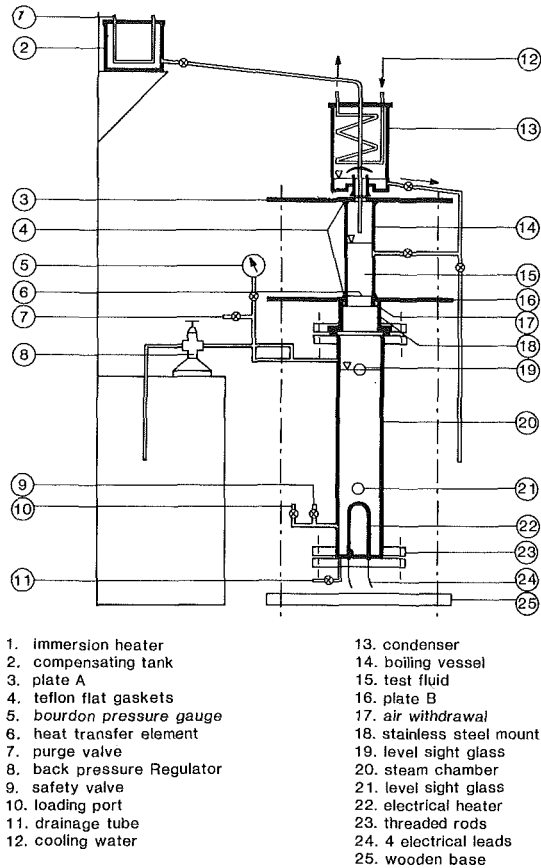|		
		and the condensing process, respectively
T, T_A, T_c	=	temperature, limiting temperature for liquid–solid contact, thermodynamic critical temperature
T_{hn}, T_{sat}, T_w	=	homogeneous nucleation temperature, saturation temperature, wall temperature
$\alpha_f, \alpha_g, \alpha_h$	=	thermal diffusivities of the saturated liquid, the vapor in the film, and the heater, respectively
β, β_a, β_r	=	contact angle; advancing and retreating contact angles
Δq	=	difference between the film transition heat flux and the pure film boiling heat flux that would exist without any liquid–solid contact
$\Delta T, \Delta T_A$	=	$(T_w - T_{sat}); (T_A - T_w)$
λ_d	=	most "dangerous" Taylor wavelength, $2\pi\sqrt{3\sigma/g(\rho_f - \rho_g)}$
ν	=	kinematic viscosity of the vapor
ρ_f, ρ_g	=	saturated liquid and vapor densities, respectively
σ	=	surface tension
τ	=	characteristic period of Taylor wave motion during film boiling

Fig. 2 The present reconstruction of the classical "Berenson experiment"

1. immersion heater
2. compensating tank
3. plate A
4. teflon flat gaskets
5. bourdon pressure gauge
6. heat transfer element
7. purge valve
8. back pressure Regulator
9. safety valve
10. loading port
11. drainage tube
12. cooling water
13. condenser
14. boiling vessel
15. test fluid
16. plate B
17. air withdrawal
18. stainless steel mount
19. level sight glass
20. steam chamber
21. level sight glass
22. electrical heater
23. threaded rods
24. 4 electrical leads
25. wooden base

condition. Notice that this means that if Klimenko is correct, $Nu \neq fn(\Delta T)$, and q is directly proportional to ΔT, except as the temperature dependence of physical properties influences the relationship. This contradicts the conventional wisdom as expressed in equation (3) and, in fact, we find the physical mechanisms upon which equation (3) is based to be more convincing. Nevertheless, we shall subsequently see that the functional dependence of Klimenko's equation provides more accurate means for extrapolating film boiling data than does equation (3).

Present Aims. The objective of the present study is to measure boiling curves in a Berenson-type apparatus, with an emphasis on the transitional boiling region. We seek to do this with a lowered thermal resistance so as to gain improved access to the transition region, and to do so with a controlled set of surface finishes. We shall then seek to provide a workable description of film transition boiling and to locate its onset.

Experiment

Apparatus. The present experiment is shown schematically in Fig. 2 and described in full detail by Ramilison (1985). It consists of an upper vessel containing a boiled liquid, which is heated through a copper plate by condensing water in a high-pressure chamber below. The plate is 6.35 cm in diameter and made of 99.99 percent copper, 1.524 cm thick. It is flush with the glass sidewalls of the upper chamber, and over 3 λ_d in diameter (for each of the boiled fluids) to guarantee a good approximation to an infinite flat plate geometry. The apparatus was well insulated during the tests.

The plate is supported by a 2.5-mm-thick stainless steel bridge that almost thermally isolates it from the lower chamber. The thermal resistance of the copper plate is 0.000252 m²-°C/W (exclusive of the condensing film). This is 1/6th of the value in Berenson's experiment. It is equipped with four thermocouples at different locations on the top which verified the unidimensionality of heat flow and gave the basis for specifying the temperature at the bottom of the plate. (The bottom temperature was needed subsequently to predict the condensation resistance.)

Three surfaces were prepared for use in each of the four boiled liquids: reagent grade acetone, Freon-113, n-pentane, and benzene. The surfaces were prepared in the following ways:

1 A *rough surface* was obtained by wrapping a #80 emery cloth around a 1-in.-dia shaft and using five strokes in one direction, five strokes at right angles to that direction, etc., until the surface was judged reproducible.

2 A *mirror-polished surface* was prepared by passing through a series of increasingly fine emery papers, and doing the final polish with 0.05μ alumina until the surface served as an optically flawless mirror.

3 A *Teflon-coated surface* was made by commercially coating a previously mirror-polished heater (on the top only) with a 1 mil layer of polytetrafluorethylene. The coating was inspected to verify that it was completely smooth and free of any flaws.

Procedure. The heat flux in the tests was obtained in either or both of two ways. Before each test, the apparatus was operated with no boiled liquid in the upper chamber. This established the heat loss of the insulated container as a function of the temperature of the condensing water. The heat transfer was then determined by subtracting the heat loss from the electrical supply to the water chamber. The heat flow was also computed by condensing the boiled vapor to a temperature as close to saturation as possible, and weighing it. The latter method could only be used accurately at relative higher heat fluxes where it was used to verify the energy-input-minus-loss method discussed above.

The transition-film boiling heat fluxes discussed here were all obtained by the energy-input-minus-loss method. The probable error in the resulting q was found by Ramilison to range downward from a maximum value of 3.8 percent.

The present film and transition-film boiling data were all reached from the film boiling side. First, we established the film boiling heat flux by going to the peak nucleate boiling heat flux, increasing the heat flux slightly, and then stabilizing the system at the highest-heat-flux film-boiling condition. Then we varied the power to pass through decreasing ΔT. This process continued until the system abruptly reverted to nucleate boiling.

The heater surface temperature T_w was measured by a thermocouple less than 1 mm below the surface of the copper block. This gave temperatures within about a tenth of a degree Celsius of the surface temperature at film-transition boiling conditions. The temperature difference ΔT was obtained as the difference between T_w and T_{sat} for the boiled liquid.

The temperature difference, $(T_{cond.stm.} - T_{sat})$ (recall equation (2)), was controlled by regulating the pressure in the lower chamber. This was done by adjusting both the regulating valve and the electric heat supply to the chamber, a process that involved a good deal of technique as described by Ramilison.

Contact Angles. The interpretation of the results of this work required a knowledge of the advancing and retreating contact angles, β_a and β_r, for the various surfaces and liquids used. Measurements of β_r were obtained with the tilting plate method, using the actual heaters as the tilting plates and making the observations at T_{sat}. Since the tilting plate normally involves wetting the surface, we had to modify it to obtain β_a. The heaters had to be set at a given angle, immersed, the shape of the miniscus noted, the heater withdrawn and completely dried out, the angle reset, and the plate re-immersed, until the

Table 1 Complete boiling heat transfer data from the present tests

Point No.	ΔT °C	Heat flux $(W/m^2)10^{-3}$
acetone, teflon-coated		
1	23.6	201.8
2	20.1	137.5
3	21.6	174.4
4	25.8	258.8
5	28.4	306.5
6	32.2	369.5
7	35.7	387.3
8	38.7	396.2
9	142.2	28.6
10	15.4	95.3
acetone, mirror polished		
1	31.5	257.7
2	27.6	172.4
3	29.3	216.6
4	35.3	291.9
5	37.3	310.0
6	22.9	97.4
7	14.8	52.4
8	25.9	127.1
9	98.1	17.8
acetone, rough		
1	13.0	217.4
2	11.7	154.2
3	11.0	72.4
4	10.2	47.7
5	14.0	240.5
6	16.1	327.0
7	17.7	350.7
8	19.4	366.2
9	108.1	19.8
n-pentane, teflon-coated		
1	29.7	224.1
2	27.6	180.8
3	22.9	60.9
4	25.4	130.7
5	36.4	293.6
6	31.9	269.4
7	35.5	287.2
8	119.9	23.7
benzene, teflon-coated		
1	37.9	254.5
2	45.2	334.1
3	52.2	351.3
4	32.9	167.0
5	29.3	107.7
6	40.8	288.2
7	26.4	60.3
8	19.1	34.9
9	113.3	23.7

Point No.	ΔT °C	Heat flux $(W/m^2)10^{-3}$
acetone, teflon-coated		
1	37.3	393.3
2	39.5	399.7
3	136.3	26.9
4	130.1	41.4
5	112.7	141.1
6	71.2	291.0
7	49.9	379.1
8	53.4	370.5
9	69.4	304.5
10	95.1	218.4
acetone, mirror polished		
1	26.9	171.8
2	115.2	22.4
3	98.3	18.5
4	90.4	16.1
5	83.6	15.9
6	74.8	18.0
7	118.6	22.7
8	70.7	18.9
9	67.1	19.9
acetone, rough		
1	14.6	313.0
2	107.2	19.4
3	99.3	17.7
4	86.9	15.8
5	82.1	14.9
6	73.9	15.0
7	68.9	16.3
8	60.8	19.4
9	52.2	23.1
10	116.9	21.4
n-pentane, teflon-coated		
1	24.3	129.7
2	100.3	20.9
3	95.0	21.3
4	89.8	22.6
5	84.2	24.9
6	122.0	24.2
7	80.4	25.6
benzene, teflon-coated		
1	34.5	167.7
2	111.6	23.3
3	101.1	21.1
4	95.2	21.3
5	91.1	22.6
6	83.7	23.9
7	114.3	24.1
8	120.3	24.8
9	107.8	22.0
10	80.6	24.6

Point No.	ΔT °C	Heat flux $(W/m^2)10^{-3}$
n-pentane, mirror polished		
1	34.6	193.9
2	28.4	150.8
3	31.2	166.6
4	24.9	111.3
5	37.9	213.8
6	22.1	84.4
7	36.6	205.1
8	109.8	21.1
n-pentane, rough		
1	12.9	215.0
2	121.0	23.5
3	110.3	21.5
4	101.7	18.9
5	92.1	16.5
6	83.9	15.4
7	75.7	16.3
8	69.4	17.7
9	63.5	19.0
10	57.2	20.0
11	52.1	21.5
12	46.8	24.8
Freon-113, teflon-coated		
1	32.5	216.6
2	29.4	174.9
3	26.9	135.7
4	24.7	99.5
5	22.4	66.2
6	19.7	37.2
7	35.2	237.7
8	34.7	235.2
9	31.6	207.7
10	113.4	20.9
Freon-113, mirror polished		
1	33.5	169.8
2	36.0	195.4
3	26.9	123.6
4	21.7	67.9
5	16.7	48.5
6	31.8	157.7
7	34.7	192.4
8	117.8	21.4
Freon-113, rough		
1	15.3	217.4
2	11.8	101.2
3	12.9	141.7
4	10.6	72.1
5	9.1	38.6
6	13.9	178.9
7	18.0	221.5
8	13.3	169.9
9	121.2	21.9

Point No.	ΔT °C	Heat flux $(W/m^2)10^{-3}$
n-pentane, mirror polished		
1	31.5	166.9
2	120.4	23.7
3	110.4	21.4
4	102.4	19.4
5	94.2	18.9
6	88.9	18.6
7	81.8	19.1
8	77.4	19.8
9	72.0	21.9
10	66.6	25.5
11	61.3	28.7
n-pentane, rough		
1	8.1	105.5
2	12.3	246.5
3	14.8	261.8
4	9.0	135.6
5	10.0	171.4
6	7.5	63.4
7	13.2	251.4
8	10.2	201.3
9	100.4	18.2
Freon-113, teflon-coated		
1	32.0	208.2
2	112.4	20.6
3	99.3	19.2
4	93.2	18.8
5	85.9	19.5
6	80.7	19.9
7	76.4	22.9
8	122.1	21.6
9	119.1	21.0
Freon-113, mirror polished		
1	26.9	123.2
2	107.5	19.3
3	100.1	17.2
4	88.6	15.6
5	84.5	15.1
6	79.7	15.1
7	73.2	16.0
8	66.1	18.4
9	65.4	18.7
10	63.6	19.7
Freon-113, rough		
1	12.6	139.9
2	121.7	21.6
3	114.2	19.6
4	104.4	18.5
5	95.6	16.2
6	85.6	14.6
7	76.7	13.2
8	68.3	12.4
9	61.3	12.1
10	54.9	12.8
11	47.1	14.6
12	41.4	16.3

liquid surface intersected it without being perceptibly bent in either direction. The observations of both contact angles were judged accurate within ±5 percent.

Results and Discussion

Results. The complete heat transfer data and contact angle measurements from the present tests are given in Tables 1 and 2, respectively. Each set of data in Table 1 is ordered in chronological sequence. The heat transfer data were plotted in two ways by Ramilison (1985): as full boiling curves, and as expanded plots in the transition film boiling range. Since the complete data are given in Table 1, we include the complete curves only for acetone and Freon-113 (Figs. 3 and 4) and the expanded curves only for *n*-pentane and benzene (Figs. 4 and 6).

Typical "accessibility lines" are drawn in Figs. 3 and 4. The fact that they are not all the same reflects the fact that each is based on a different condensing heat transfer coefficient, inferred from the measured heat flux.

Nucleate Boiling and Burnout. The nucleate boiling regime exhibits the well-known sensitivity of heat flux on surface finish, although it is interesting to note that the curves for the teflon-finished surfaces are only slightly steeper than those for the mirror-finish data.

The present burnout data and those of Berenson were compared with the hydrodynamic peak heat flux prediction of Lienhard et al. (1973). The present rough surface data were consistently between 93 and 98 percent of the prediction. The

Table 2 Contact angle values and temperatures at the onset of the transition-film boiling region

Liquid	Surface Finish	Contact Angle +5°		T_A °C	T_A °C	$\dfrac{T_A - T_{sat}}{T_{h.n.} - T_{sat}}$
		β_r	β_a			
acetone	Teflon	0	5	200.2	190.0	0.96
	Mirror	13	40		142.8	0.59
		15	45		131.4	0.55
Freon-113	Teflon	8	30	177.5	161.0	0.82
	Mirror	10	40		144.9	0.67
	Rough	13	50		132.0	0.58
normal pentane	Teflon	8	25	164.1	148.3	0.84
	Mirror	10	35		138.8	0.80
	Rough	15	45		128.8	0.64
benzene	Teflon	15	40	249.0	189.4	0.56

highly polished surfaces consistently gave peak heat fluxes that lay between 81 and 87 percent of the prediction. The teflon-coated surfaces gave values that exceeded the prediction by 4 to 10 percent. Berenson found that a rough oxidized surface could give values almost 20 percent above the prediction.

While surface roughness clearly exerts only a second-order influence on burnout, it is an influence that is not yet understood and which merits further study.

Stable Film Boiling. The stable film boiling data lie in a range in which radiation heat transfer contributes virtually nothing to the total *q*. In this range both our data and those of
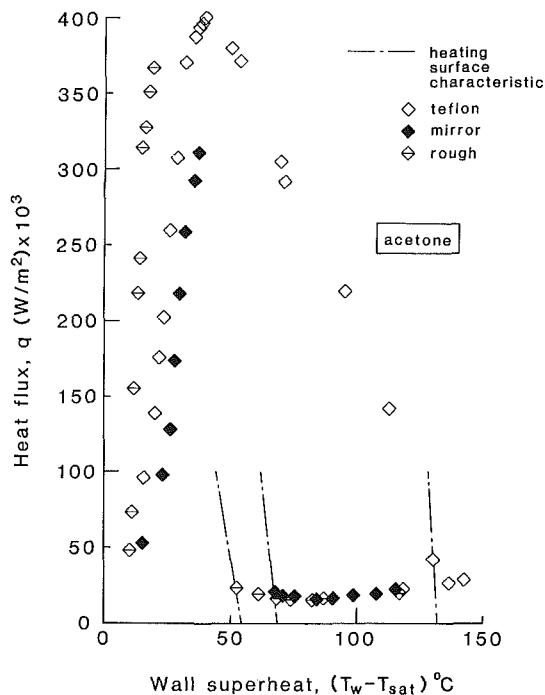
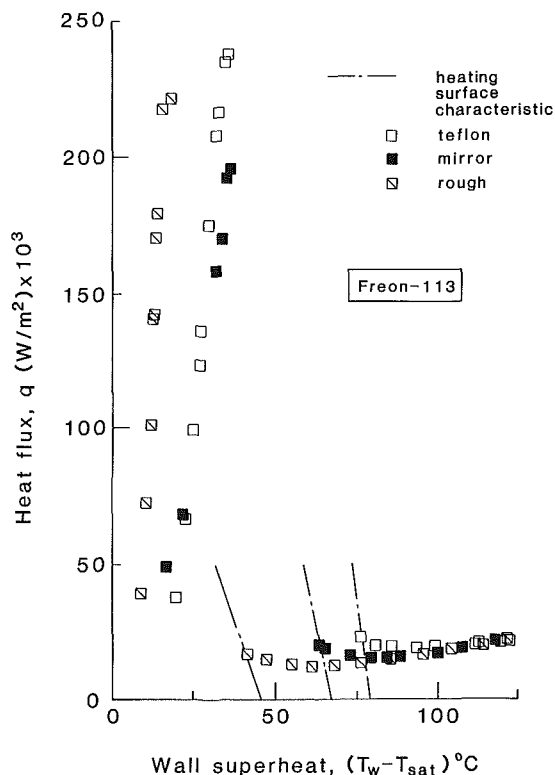Fig. 3 Boiling curves for acetone boiling on teflon-coated, mirror-finished, and "rough" surfaces

Fig. 4 Boiling curves for Freon-113 boiling on teflon-coated, mirror-finished, and "rough" surfaces

Berenson are almost perfectly represented – within a constant – by Klimenko's turbulent film boiling correlation (equation (15)) for $Ja > 0.5$. This expression tells us that the only temperature dependence of the heat transfer coefficient arises in the temperature dependence of the viscosity and thermal diffusivity of the vapor.

However, we had to replace Klimenko's empirical constant of 0.0086, which had originally been established with a good
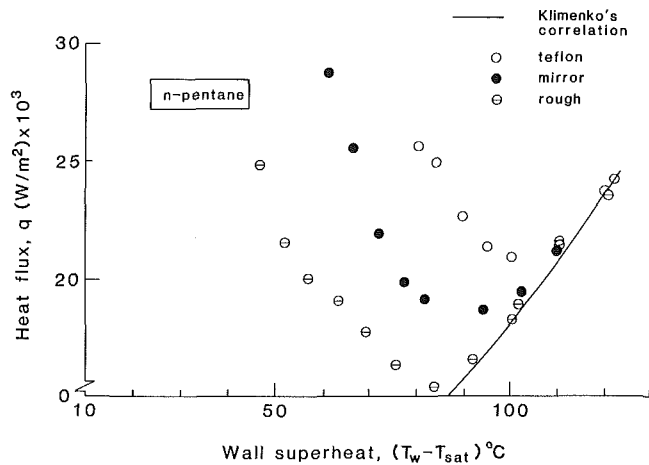
Fig. 5 Film and film-transition regions for n-pentane boiling on teflon-coated, mirror-finished, and rough surfaces
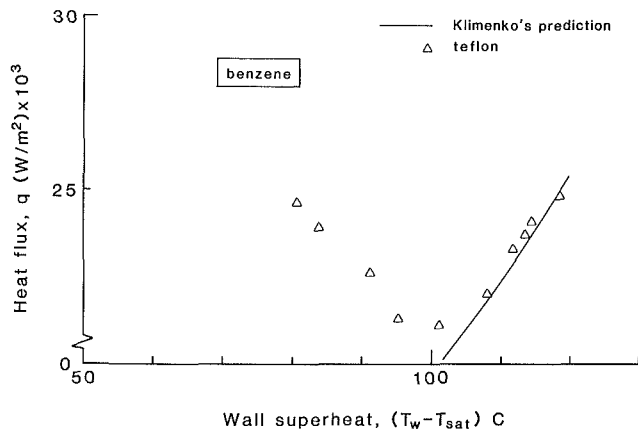
Fig. 6 Film and film-transition regions for benzene boiling on a teflon-coated surface

deal of data scatter based on film boiling in different geometries, with specific values for each liquid. The values used were: 0.0057 for Freon-113 and n-pentane; 0.0066 for acetone; and 0.0154 for benzene. The film boiling curve fit is shown graphically in Figs. 5 and 6.

While the details of Klimenko's formulation are probably not perfect, it nevertheless provides us with a very nearly perfect basis for fitting the existing data. We therefore believe that his rationale merits further study.

Film-Transition Region. The data separated fairly abruptly from the film boiling extrapolation as the surface temperature was lowered below a certain point A, which differs in each configuration. This separation doubtless represents the point at which the liquid–vapor interface begins to make contact with the heater. We accordingly define q_A and ΔT_A at that point, where $\Delta T_A \equiv (T_A - T_w)$. The film-transition boiling region then lies to the immediate left of point A. It is worth noting that q_{min} is less than q_A, and always within 12 percent of it in our experiments.

In the present work, point A was deemed to occur at the point at which the film boiling data first reached a value that was 1.05 times the Klimenko data fit.

The data for acetone on a teflon-coated surface, and only these data, fail to pass into the transition-film boiling region at all. Both contact angles in this case (see Table 1) represent almost perfect wetting. Consequently the q–ΔT data in Fig. 3 do not diverge from the film boiling curve; they leave it very abruptly. This behavior signifies a direct jump to transition-film boiling.
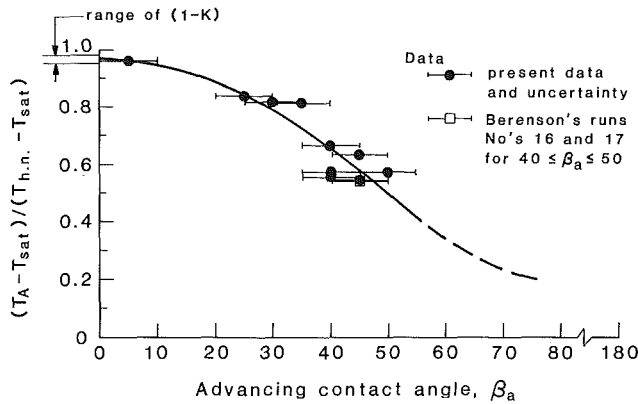
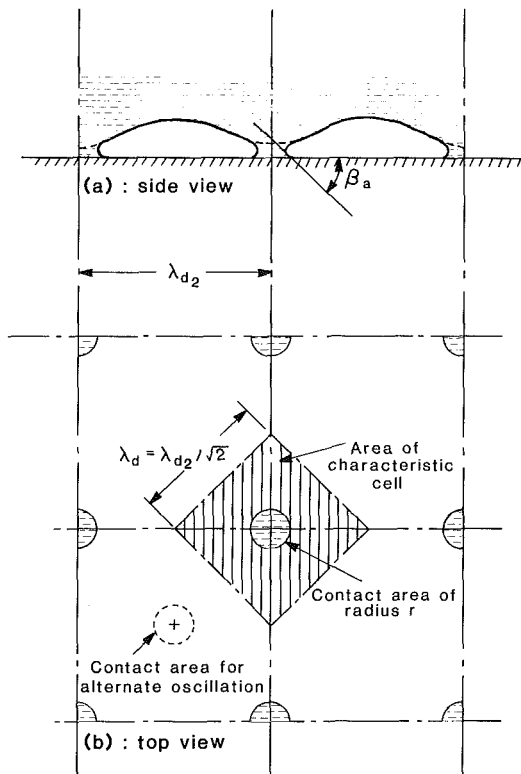**Fig. 7 Variation of the onset of transition boiling with the advancing contact angle**

Fig. 8 Model of contact of the liquid–vapor interface with the heater during film-transition boiling

The film-transition boiling curves in each case passed from point A to the left through a minimum and back up to a point at which neighboring points could no longer be reached. It is important to note that, at the last attainable film-transition boiling point, the "accessibility lines" were not tangent to the film-transition boiling curve. If the reason for our inability to measure further in this region had merely been a loss of accessibility, then they *would* have been tangent.

What we therefore witness must be a collapse of the film-transition process. It is our belief that this collapse occurs because, as the extent of surface contact increases, we reach a point at which the surface no longer dries out between contacts with the interface. When this occurs, the contact angle changes from its relatively high advancing value β_r. The system must then leave film-transition boiling and find a new equilibrium in either nucleate transition or nucleate boiling where behavior is dictated by β_r. (When Witte and Lienhard originally discussed the two possible modes of transition boiling, they suggested that the interface might contact the surface

tangentially, in the film-transition mode. The recognition of the role of the two contact angles makes it unnecessary to postulate this form of contact.)

A Recent Corroborative Experiment. Chowdhury and Winterton (1985) gave boiling curves obtained by quenching a vertically oriented finite cylinder in water and methanol. They did this for several values of contact angle as given by the sessile drop method. While these experiments cannot be compared quantitatively with ours, they very clearly show that T_A decreases strongly with increasing β.

A Model for the Film-Transition Boiling Heat Flux

Limit of Liquid–Solid Contact. We envision film-transition boiling as involving limited liquid–solid contact. Therefore, we must first consider the temperature at which the first contact can occur. It is well-understood (see, e.g., Yao and Henry, 1978) that, based on the contact of two semi-infinite regions

$$\frac{T_{\text{wall}} - T_{\text{contact}}}{T_w - T_{\text{sat}}} = \frac{k_f/\alpha_f^{1/2}}{k_f/\alpha_f^{1/2} + k_h/\alpha_h^{1/2}} \equiv K \tag{6}$$

The limiting value of the contact temperature should then be the absolute limiting homogeneous nucleation temperature T_{hn}, which has been shown by Lienhard (1982) to be well approximated by

$$T_{hn} = [0.923 + 0.077(T_{\text{sat}}/T_c)^9]T_c \tag{7}$$

In Fig. 7 we indicate the fraction of the limiting liquid superheat at which the first liquid contact occurs. Bearing in mind that $(T_A - T_{\text{sat}})/(T_{\text{hn}} - T_{\text{sat}})$ cannot ever exceed $(1 - K)$ for the system, we note that as β_a approaches zero — or perfect wetting — T_A approaches the temperature required by perfect homogeneous nucleation. (Notice that $(1 - K)$ is given as a narrow range rather than as a single value, owing to the slight temperature variation of the thermal properties.) At increasing values of β_a, it becomes harder for the liquid to make contact, and easier to carry film boiling down to lower temperatures.

A Model for Correlating the Transition-Film Boiling Heat Flux. The liquid–vapor interface in film boiling takes the form of a cyclically collapsing, two-dimensional, square array of Taylor-unstable waves as shown in Fig. 8. The size of a characteristic cell in this grid is $\lambda_d = 2\pi\sqrt{3\sigma/g(\rho_f - \rho_g)}$ where λ_d is the most rapidly collapsing one-dimensional Taylor wave given by Bellman and Pennington (1955). The two-dimensional wave exceeds λ_d by a factor of $\sqrt{2}$ (see Sernas, 1969).

The liquid–solid contact area can be represented as a fraction of the area of the cell, $(r/\lambda_d)^2$, where r is the radius of the frustrum of the cone of liquid that contacts the surface. The duration of the contact t_c will be a fraction of the characteristic period of the Taylor wave (see, e.g., Zuber)

$$\tau \sim [\sigma/g^3(\rho_f - \rho_g)]^{1/4} \tag{8}$$

Next we wish to relate the heat flux added to the film-boiling heat flux by transient contact Δq to the local transient heat flux to the liquid resulting from liquid–solid contact. Δq is related to $q_{\text{transient}}$ by the simple energy balance

$$\lambda_d^2(\tau)(\Delta q) \sim r^2(t_c)q_{\text{transient}} \tag{9}$$

But $q_{\text{transient}}$ is given by the semi-infinite region expression

$$q_{\text{transient}} = \frac{k_h(T_{\text{sat}} - T_{\text{contact}})}{(\alpha_h \tau)^{1/2}} = \frac{k_h(T_w - T_{\text{sat}})}{(\alpha_h \tau)^{1/2}} K \tag{10}$$

where we use equation (6) to eliminate T_{contact}. If we put this back into equation (9) we obtain an expression for Δq in terms of the unknowns t_c and τ.

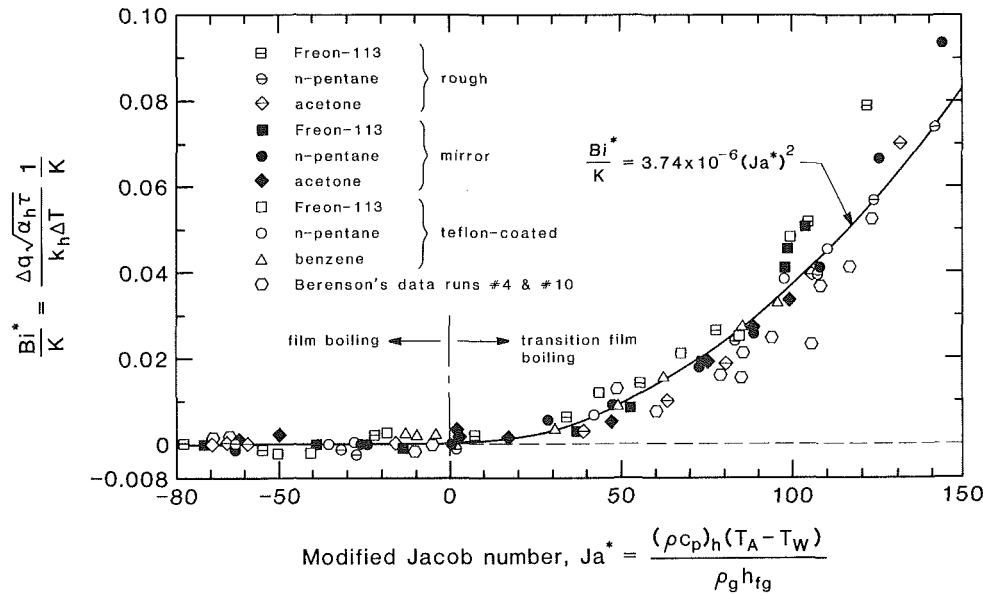To eliminate t_c and τ we make two physical assumptions:

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Fig. 9 Correlation for transition film boiling heat transfer on a horizontal flat plate

1 The fractional area of the contact circle increases in direct proportion to the fractional duration of contact

$$t_c/\tau \sim (r/\lambda_d)^2 \qquad (11)$$

2 Since the energy storage in the metal as a consequence of contact must be directly proportional to the additional latent heat contributed per unit cell, the fractional contact area $(r/\lambda_d)^2$ can be proportioned as follows:

$$(r/\lambda_d)^2 \sim \frac{(\rho c_p)_h(T_A - T_w)}{\rho_g h_{fg}} = \frac{(\rho c_p)_h \Delta T_A}{\rho_g h_{fg}} \qquad (12)$$

When we combine equations (10), (11), and (12) with equation (9) we obtain

$$Bi^* = \text{const } (K)(Ja^*)^2 \qquad (13)$$

where

$$Bi^* \equiv \frac{\Delta q(\alpha_h \tau)^{1/2}}{\Delta T k_h} \text{ and } Ja^* \equiv \frac{(\rho c_p)_h \Delta T_A}{\rho_g h_{fg}} \qquad (14)$$

We compare equation (13) with the film and film-transition boiling data from Table 1, in Fig. 9. With the constant fixed at $3.74 (10)^{-6}$, the equation brings all but 7 of our data, and those of Berenson's data that can be used, together within an absolute error of 0.01 in Bi^*.

Conclusions

Transition boiling has proven over the years to be a treacherous mine field. Therefore our conclusions should be qualified to some extent. We are very confident that:

1 Part of the region in which $dq/d\Delta T$ is positive, which has appeared in the past to have been pure film boiling with no liquid-solid contact, now seems almost certainly to be "film-transition" boiling with significant contact.

2 The boundary between the pure-film and film-transition regions can be located – at least for a flat plate – using the correlation for T_A given in Fig. 7.

3 The expression

$$Bi^* = 3.74(10)^{-6}(K)(Ja^*)^2 \qquad (13a)$$

can be used to correlate film-transition and film boiling once T_A is known.

The following item is a strong conjecture rather than a conclusion:

4 We are fairly confident that the jumps that we and so many others observe from film-transition to nucleate-transition boiling occur because the control of the process is shifted from β_a to β_r, or vice versa. (It is certain that these jumps did not occur by virtue of the mere loss of accessibility in our experiments.)

This is a confirmation of prior work rather than a conclusion:

5 The burnout heat flux definitely suffers a secondary dependence on the surface condition.

Acknowledgments

References

Bellman, R., and Pennington, R. H., 1955, "Effects of Surface Tension and Viscosity on Taylor Instability," *Q. App. Math.*, Vol. 22, pp. 1605-1610.

Berenson, P. J., 1960, "Transition Boiling Heat Transfer From a Horizontal Surface," M.I.T. Heat Transfer Lab. Tech. Rept. No. 17.

Chang, Y. P., 1959, "Wave Theory of Heat Transfer in Film Boiling," ASME JOURNAL OF HEAT TRANSFER, Vol. 81, p. 112.

Chowdhury, S. K. R., and Winterton, R. H. S., 1985, "Surface Effects in Pool Boiling," *Int. J. Heat Mass Transfer*, Vol. 28, No. 10, pp. 1881-1889.

Hesse, G., 1973, "Heat Transfer in Nucleate Boiling, Maximum Heat Flux and Transition Boiling," *Int. J. Heat Mass Transfer*, Vol. 16, pp. 1611-1627.

Klimenko, V. V., 1981, "Film Boiling on a Horizontal Plate – New Correlation," *Int. J. Heat Mass Transfer*, Vol. 24, pp. 69-79.

Lienhard, J. H., and Dhir, V. K., 1980, "On the Prediction of the Minimum Pool Boiling Heat Flux," ASME JOURNAL OF HEAT TRANSFER, Vol. 102, No. 2, pp. 457-460.

Lienhard, J. H., Dhir, V. K., and Riherd, D. M., 1973, "Peak Pool Boiling Heat-Flux Measurements on Finite Horizontal Flat Plates," ASME JOURNAL OF HEAT TRANSFER, Vol. 95, No. 4, pp. 477-482.

Lienhard, J. H., 1982, "Corresponding States Correlations for the Spinodal and Homogeneous Nucleation Temperatures," ASME JOURNAL OF HEAT TRANSFER, Vol. 104, No. 23, pp. 379-381.

Ramilison, J. R., 1985, "Transition Boiling Heat Transfer and the Film Transition Regime," Ph.D. Dissertation, Mechanical Engineering Department, University of Houston, Oct. 1985.

Sernas, V., 1969, "Minimum Heat Flux in Film Boiling – A Three Dimensional Model," *Proc. 2nd Can. Cong. App. Mech.*, Univ. of Waterloo, 1969, pp. 19-23.

Witte, L. C., and Lienhard, J. H., 1982, "On the Existence of Two 'Transition' Boiling Curves," *Int. J. Heat Mass Transfer*, Vol. 25, No. 6, pp. 771-779.

Yao, S., and Henry, R. E., 1978, "An Investigation of the Minimum Film Boiling Temperature on Horizontal Surfaces," ASME JOURNAL OF HEAT TRANSFER, Vol. 100, No. 2, pp. 260-267.

Zuber, N., 1959, "Hydrodynamic Aspects of Boiling Heat Transfer," AEC Report AECU-4439, Physics and Mathematics.