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THE DERIVATION AND APPLICATION OF CRITERIA FOR THE THERMAL STABILITY OF HEAT TRANSFER MEDIA

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ABSTRACT

This article derives the generic criterion for the thermal stability of heat transfer fluids:

$$(dQ_{in}/dT_f - \dot{m}C) < dQ_{out}/dT_f$$

If this criterion is not satisfied, the fluid temperature will not be stable at T_f, and oscillatory behavior or hysteresis will result.

The generic criterion is used to derive parametric criteria, and the parametric criteria are used to analyze the thermal stability of steam heated pool boilers such as those used by Berenson (1960) and by Ramilison (1985). The analysis indicates that this type of boiler is unstable *throughout* the transition region of the pool boiling curve. This result is at odds with the widely accepted view.

NOMENCLATURE

A	surface area, m^2
C	specific heat, J/kg K
h	heat transfer coefficient, kW/m^{2}K
k	thermal conductivity, kW/m K
$\dot{m}$	mass flow rate, kg/s
q	heat flux, kW/m^2
Q	heat flow rate, kW
Q_{stored}	heat storage rate within the control volume, kW
t	thickness or time, m or s
T	temperature, K
ΔT_f	a vanishingly small perturbation of T_f, K

Subscripts

bf	boiling fluid
bi	boiling interface
bp	boiler plate
f	fluid
i	interface
in	into
out	out of
sf	heat source fluid
si	interface on the heat source side

BACKGROUND

"Thermal stability" is the tendency for vanishingly small temperature perturbations to decrease with time. If heat transfer equipment lacks thermal stability, the result will be oscillatory behavior or hysteresis, both of which are generally undesirable.

The necessary and sufficient condition for thermal stability at a heat transfer interface is

$$dq_{in}/dT_i < dq_{out}/dT_i \qquad \text{Criterion (1)}$$

where q is heat flux, T is temperature, "in" and "out" refer to into and out of the interface, and "i" refers to the interface. If Criterion (1) is not satisfied, the interface temperature will exhibit oscillatory behavior or hysteresis. The criterion for interface thermal stability was derived by Adiutori (1964), Stephan (1965), and Kovalev (1968).

Criterion (1) states that an interface will be stable at temperature T_i if, and only if, the indicated inequality is satisfied. The left side of Criterion (1) describes how heat flux into the interface responds to interface temperature; the right side describes how heat flux out of the interface responds to interface temperature.

Criterion (1) is widely regarded as the necessary and sufficient condition which, if satisfied at all heat transfer interfaces, will result in thermally stable operation of the equipment. However, Criterion (1) is *NOT* sufficient to ensure stable operation of the equipment because it does not address the thermal stability of heat transfer media--i.e. does not address fluid thermal stability.

The only criterion for fluid thermal stability found in the literature is the parametric criterion for fluid thermal stability in a two phase, forced convection system by Adiutori (1965).

THE DERIVATION OF THE GENERIC CRITERION FOR THE THERMAL STABILITY OF HEAT TRANSFER MEDIA

It is self evident that, in order for heat transfer equipment to operate in a thermally stable manner, the temperature must be stable everywhere in the equipment--ie at all points within the heat transfer walls and heat transfer fluids. Criterion (1) describes the conditions required for thermal stability at wall/fluid interfaces, but it has nothing to do with the thermal stability of heat transfer fluids.

The generic criterion for the thermal stability of heat transfer fluids was derived by drawing a control volume around an arbitrary heat transfer fluid as shown in Figure (1), and then determining the conditions which cause the fluid temperature to be stable. In order to simplify the derivation, the following reasonable assumptions were made:

- The fluid temperature is uniform. Therefore $T_{out} = T_f$.
- The fluid flow is steady-state. Therefore $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$.
- The inlet and outlet fluids are of the same single phase. (However, the control volume may contain several phases.) Therefore temperature uniquely determines the enthalpy of the fluid streams. (If either fluid stream contained two phases, or if the fluid streams were of different phase, it would be necessary to consider phase change enthalpy and fluid quality.)

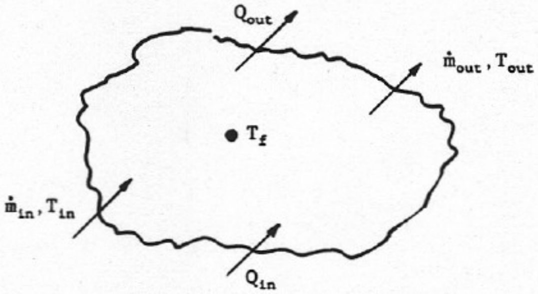

FIGURE 1 CONTROL VOLUME AROUND AN ARBITRARY HEAT TRANSFER FLUID

The fluid thermal stability at temperature T_f was appraised by considering a steady-state condition, and determining whether a small perturbation in fluid temperature would tend to increase or decrease with time. Stability results if the perturbation decreases with time. Instability results if the perturbation increases with time.

Since the unperturbed system is initially at steady-state, the heat storage rate in the control volume is zero, and the system is initially described by Eq (1):

$$Q_{stored}(T_f) = Q_{in}(T_f) - Q_{out}(T_f) - \dot{m}C(T_f - T_{in}) = 0 \qquad (1)$$

The effect of a vanishingly small perturbation of fluid temperature (ΔT_f) is determined by differentiation of Eq (1) with respect to T_f, resulting in Eq (2):

$$Q_{stored}(T_f + \Delta T_f) = \Delta T_f(dQ_{in}/dT_f - dQ_{out}/dT_f - \dot{m}C) \qquad (2)$$

The analysis proceeds by noting the following:

- Stability requires that the perturbation, ΔT_f, decrease with time.
- ΔT_f would decrease with time only if ΔT_f and dT_f/dt were opposite in sign.
- Q_{stored} and dT_f/dt are obviously of the same sign. Therefore stability requires that Q_{stored} and ΔT_f be of opposite sign (so that ΔT_f will decrease with time).
- Equation (2) indicates that Q_{stored} and ΔT_f are of opposite sign only if Criterion (2) is satisfied.

$$(dQ_{in}/dT_f - \dot{m}C) < dQ_{out}/dT_f \qquad \text{Criterion (2)}$$

Note that Criterion (2) describes the conditions which cause perturbations in fluid temperature to decrease with time. Therefore it is the generic criterion for the thermal stability of heat transfer fluids--i.e. the generic criterion for fluid thermal stability. If Criterion (2) is not satisfied, the fluid temperature will not be stable at T_f, and the result will be oscillatory behavior or hysteresis, depending on the nature of the $Q(T_f)$ functions in Criterion (2).

The generic form of Criterion (2) does not readily reveal the manner in which design parameters affect the thermal stability of heat transfer fluids. However, as shown below, Criterion (2) can be used to derive fluid thermal stability criteria in terms of design parameters.

APPLYING STABILITY CRITERION (2) TO THE HEAT SOURCE FLUID IN A POOL BOILER

Criterion (2) can be used to derive the thermal stability criterion for the heat source fluid in the common type of pool boiler shown in Fig. (2).

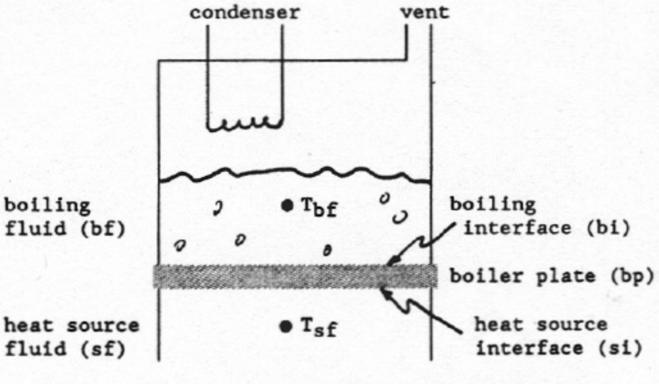

FIGURE 2 A COMMON TYPE OF POOL BOILER

The left side of Criterion (2) cannot be evaluated on the basis of the information in Figure (2). However, the right side of Criterion (2) can be evaluated by noting from Figure (2) that

$$T_{sf} - T_{bf} = \Delta T_{si} + \Delta T_{bp} + \Delta T_{bi} \qquad (3)$$

Differentiation of Eq (3) with respect to q results in Eq (4):

$$dT_{sf}/dq = d\Delta T_{si}/dq + d\Delta T_{bp}/dq + d\Delta T_{bi}/dq \qquad (4)$$

Inversion of Eq (4) results in Eq (5):

$$dq/dT_{sf} = (d\Delta T_{si}/dq + d\Delta T_{bp}/dq + d\Delta T_{bi}/dq)^{-1} \qquad (5)$$

The assumption of uniform heat flux in the boiler plate results in Eq (6):

$$Q_{out} = \int q_{bp} dA_{bp} = q_{bp}A_{bp} = qA_{bp} \qquad (6)$$

Combining Eqs (5) and (6) results in Eq (7):

$$dQ_{out}/dT_{sf} = A_{bp}(dq/dT_{sf}) = A_{bp}/(d\Delta T_{si}/dq + d\Delta T_{bp}/dq + d\Delta T_{bi}/dq) \qquad (7)$$

Combining Criterion (2) and Eq (7) results in Criterion (3a):

$$(dQ_{in}/dT_{sf} - \dot{m}C) < A_{bp}/(d\Delta T_{si}/dq + d\Delta T_{bp}/dq + d\Delta T_{bi}/dq)$$

Criterion (3a)

Notice that Criterion (3a) is written in terms of q rather than h and k. However, it is readily transformed to the h and k form by substituting hΔT for q at the interfaces, and kΔT/t for q in the boiler plate. The h and k transformation of Criterion (3a) results in Criterion (3b):

$$(dQ_{in}/dT_{sf} - \dot{m}C) < A_{bp}/((h_{si} + \Delta T_{si}dh_{si}/d\Delta T_{si})^{-1} + t_{bp}/k_{bp} + (h_{bi} + \Delta T_{bi}dh_{bi}/d\Delta T_{bi})^{-1})$$

Criterion (3b)

It is important to note that Criteria (3a) and (3b) differ only in form--Criterion (3a) is written in terms of q, and Criterion (3b) is written in terms of h and k. Other than form, Criteria (3a) and (3b) are identical.

(In the remainder of this article, stability criteria are presented only in the q form. However, the criteria are readily transformed to the h and k form by the substitutions noted above.)

Criteria (3a) and (3b) are thermal stability criteria for the heat source fluid in the pool boiler shown in Figure (2). Notice that, although these criteria describe the conditions which are necessary for stability, they do not quantitatively describe the behavior which results from instability. However, there is little practical need to predict the behavior of unstable systems because unstable systems are generally unacceptable.

The practical need lies in understanding the causes of instability, and being able to design against instability. As illustrated below, Criteria (3a) and (3b) answer both of these needs for pool boilers.

APPLYING CRITERION (3a) TO THE HEAT SOURCE FLUID IN FIGURE 3

A common type of pool boiler is shown in Fig. 3.

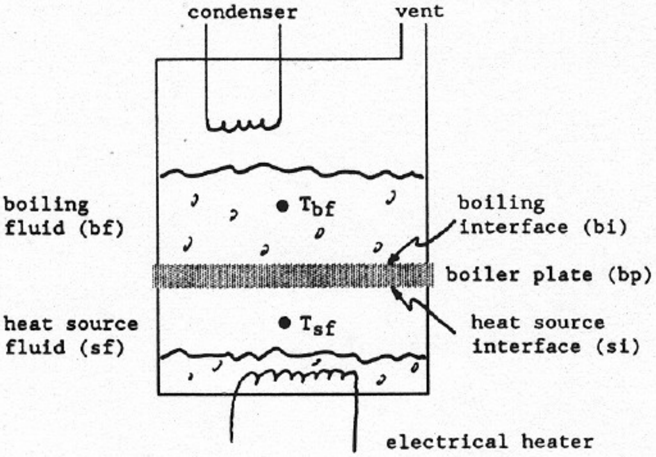

FIGURE 3 A TYPE OF POOL BOILER COMMONLY USED IN BOILING RESEARCH

This type of pool boiler has been used in boiling research for several decades. For example, this type was used in the experiment by Berenson (1960, 1962), and the experiment by Ramilison(1985). (See also Ramilison and Lienhard (1987).) Note that the heat source fluid is electrically heated and unvented.

In the boilers by Berenson (1960) and Ramilison (1985), the heat source fluid was steam condensing on the bottom of the boiler plate. The steam was generated by an electrical heater immersed in a pool of water at the bottom of the heat source chamber.

Criterion (3a) is applied to the heat source fluid in Fig. (3) in the following way:

- Assume that the heater's temperature coefficient of electrical resistivity is zero. This reasonable approximation causes the heater power to be independent of heater temperature, and thus the first term in Criterion (3a) equals zero:

$$dQ_{in}/dT_f = 0 \qquad (8)$$

- Since there is no net fluid flow through the heat source chamber, the second term in Criterion (3a) equals zero:

$$\dot{m}C = 0 \qquad (9)$$

- Combining Criterion (3a) with Eqs (8) and (9), and eliminating A_{bp}, gives Criterion (4).

$$d\Delta T_{bi}/dq > -(d\Delta T_{si}/dq + d\Delta T_{bp}/dq) \qquad \textbf{Criterion (4)}$$

Criterion (4) is the thermal stability criterion for the heat source fluid in the boiler shown in Fig. (3). In order for the boiler to operate in a steady-state manner at a heat source temperature of T_{sf}, Criterion (4) must be satisfied.

It is important to note that thermally stable operation of the boiler requires that ALL heat transfer interfaces and fluids be thermally stable. Therefore, although Criterion (4) is necessary and sufficient to establish the thermal stability of the heat source fluid acting as a *component*, it is not sufficient to establish the overall thermal stability of the boiler *system*.

THE THERMAL STABILITY CRITERION FOR THE BOILING INTERFACE IN FIGURE 3

In order to address the thermal stability of the pool boiler in Fig. (3), it is necessary to appraise the thermal stability of the boiling interface acting as a component--i.e. to appraise the interface stability which would result if the boiler plate and boiling fluid were coupled to a constant temperature heat source fluid. The appraisal is accomplished with the aid of Criterion (1).

The left side of Criterion (1) is determined by first noting that inspection of Fig. (3) results in Eq (10).

$$T_{sf} = T_{bf} + \Delta T_{bi} + \Delta T_{bp} + \Delta T_{si} \qquad (10)$$

Differentiation of Eq (10) with respect to q, and the observation that the temperature of the boiling fluid is independent of q and thus $dT_{bf}/dq = 0$, result in Eq (11).

$$dT_{sf}/dq = d\Delta T_{bi}/dq + d\Delta T_{bp}/dq + d\Delta T_{si}/dq \qquad (11)$$

Because the component analysis is based on a constant temperature heat source fluid, Eq (12) applies.

$$dT_{sf}/dq = 0 \qquad (12)$$

Combining Eqs (11) and (12), and rearranging, results in Eq (13).

$$d\Delta T_{bi}/dq = -(d\Delta T_{si}/dq + d\Delta T_{bp}/dq) \qquad (13)$$

Inverting Eq (13) results in Eq (14).

$$dq_{in}/d\Delta T_{bi} = -(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1} \qquad (14)$$

Combining Eq (14) and Criterion (1) results in Criterion (5).

$$-(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1} < dq_{out}/dT_{bi} \qquad \textbf{Criterion (5)}$$

Criterion (5) is a thermal stability criterion for the boiling interface in Fig. (3).

Criterion (5) is transformed to a more convenient form by first noting that inspection of Fig (3) results in Eq (15).

$$T_{bf} + \Delta T_{bi} = T_{bi} \qquad (15)$$

Differentiation of Eq (15) with respect to q, and the observation that the boiling fluid is vented (and thus the temperature of the boiling fluid is independent of q, and $dT_{bf}/dq = 0$), result in Eq (16).

$$d\Delta T_{bi}/dq = dT_{bi}/dq \qquad (16)$$

Combining Criterion (5) and Eq (16) results in Criterion (6).

$$-(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1} < dq_{out}/d\Delta T_{bi} \qquad \textbf{Criterion (6)}$$

Criteria (5) and (6) are thermal stability criteria for the boiling interface in Fig. (3). Note that, except for form, the two criteria are identical.

THE THERMAL STABILITY OF THE BOILER IN FIGURE 3

In order for the boiler in Fig. 3 to operate in a thermally stable manner, all heat transfer interfaces and fluids must exhibit thermal stability. Therefore, in order to determine whether the boiler will exhibit stable behavior at a particular operating point, it is necessary to apply Criterion (1) to all heat transfer interfaces in the boiler, and Criterion (2) to all heat transfer fluids.

Notice that the upper chamber of the Fig. (3) boiler is vented. Therefore perturbations in the temperature of the boiling fluid will decrease with time because the vent constrains the fluid to remain at the saturation temperature corresponding to the ambient pressure. In other words, the vent stabilizes the temperature of the boiling fluid. However, if the upper chamber were not vented, it would be necessary to appraise the thermal stability of the boiling fluid with Criterion (2).

In essence then, the boiler in Fig. (3) will be thermally stable if the heat source fluid and the boiling interface are thermally stable. (The interface at the lower surface of the boiler plate is obviously thermally stable because condensing interfaces do not exhibit the negative values of $dq/d\Delta T$ which normally cause thermal instability.)

Therefore the necessary and sufficient condition for the thermal stability of the Fig. (3) boiler is that Criteria (4) *AND* (6) be satisfied. Inspection of Criteria (4) and (6) indicates that:

(1) If $dq/d\Delta T_{bi}$ is greater than zero (as in the nucleate and the film boiling regions), Criteria (4) and (6) are both satisfied because $d\Delta T_{si}/dq$ and $d\Delta T_{bp}/dq$ are both positive. Therefore the boiler is thermally stable in the nucleate and the film boiling regions.

(2) If $dq/d\Delta T_{bi}$ is less than zero (as in the transition region), Criterion (6) is satisfied only if $dq/d\Delta T_{bi}$ is GREATER THAN $-(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1}$.

(3) If $dq/d\Delta T_{bi}$ is less than zero (as in the transition region), Criterion (4) is satisfied only if $dq/d\Delta T_{bi}$ is LESS THAN $-(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1}$.

(The validity of Item (3) is evident on noting that, if $dq/d\Delta T_{bi}$ is less than zero, Criterion (4) can be rewritten in the form of Criterion (7).)

$$-(d\Delta T_{si}/dq + d\Delta T_{bp}/dq)^{-1} > dq/d\Delta T_{bi} \qquad \text{Criterion (7)}$$

It is important to note that Items (2) and (3) are *mutually exclusive*, and therefore there is *NO* negative value of $dq/d\Delta T_{bi}$ which satisfies BOTH Criteria (4) and (6). We therefore reach the important conclusion that

> *The boiler in Fig. (3) is thermally UNstable THROUGHOUT the transition region of the pool boiling curve.*

This result is contrary to the widely accepted view that the boiler in Fig. (3) is thermally stable in the transition region if Criterion (1) is satisfied at the boiling interface.

GRAPHICAL DESCRIPTION OF THE THERMAL STABILITY PERFORMANCE OF THE POOL BOILER IN FIGURE (3)

The thermal stability performance of the pool boiler in Fig. (3) can be described graphically in terms of instability envelopes defined by parametric criteria. For example, if the pool boiling curve in Fig. (4) is assumed, the instability envelopes shown in Fig. (5) are defined by Criteria (4) and (6).

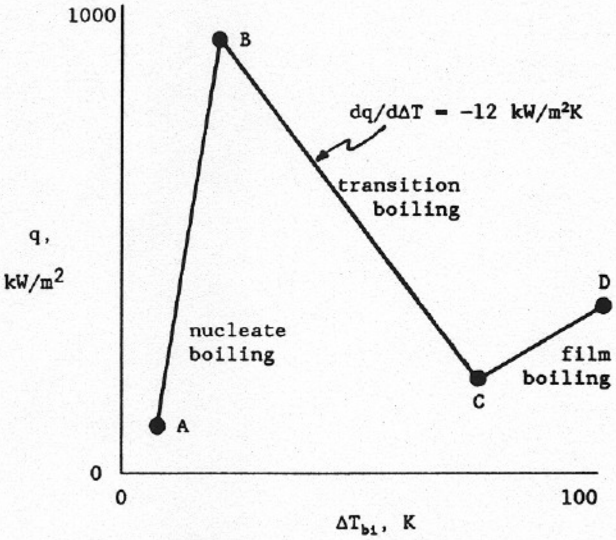

FIGURE 4 IDEALIZED POOL BOILING CURVE

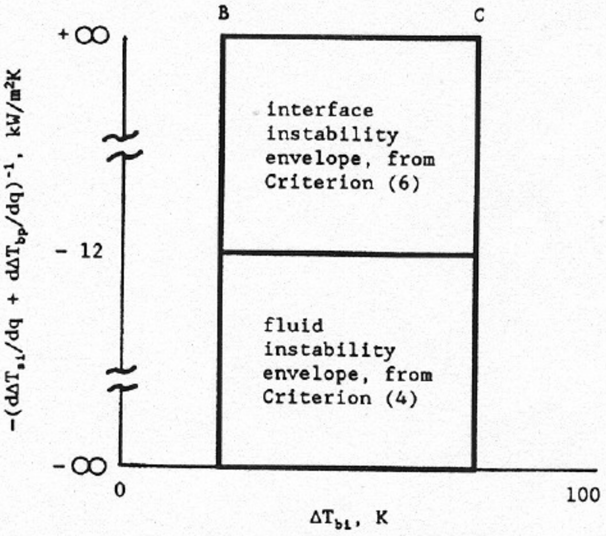

FIGURE 5 THERMAL INSTABILITY ENVELOPES FOR THE BOILER IN FIGURE (3), BASED ON THE BOILING CURVE IN FIGURE (4)

Notice that Fig. (5) indicates the following:

- The boiler is thermally stable throughout the nucleate and the film boiling regions.
- In the transition region, the boiling interface is unstable when the heat source fluid is stable, and the heat source fluid is unstable when the interface is stable. Therefore the boiler is thermally unstable throughout the transition region, since there is no condition at which both the boiling interface and the heat source fluid are thermally stable.

CONTROLLED-STATE VS. STEADY-STATE OPERATION

In spite of the fact that the Fig. (3) boiler is thermally unstable throughout the transition region of the pool boiling curve, this type of boiler has often been used to obtain allegedly steady-state data in the transition region. (For example, both Berenson (1962) and Ramilison and Lienhard (1987) reported steady-state data points obtained in the transition region with a Fig. (3) type boiler.)

The answer to this seeming anomaly is that the thermal stability of the heat source fluid can be augmented by manual control of the fluid temperature, and this may make it possible to operate in a more or less steady manner, even though the heat source fluid is thermally unstable. In this "controlled-state" operation, the power to the heater is manually controlled to maintain the unstable fluid temperature within acceptable limits.

It therefore seems reasonable to conclude that steady-state transition region data reported in the literature is actually controlled-state data if it was obtained with a Fig. (3) type boiler.

In order to optimize the manual or automatic control of the heat source fluid temperature in a Fig. (3) type boiler, the principal requirement is that the heater response be rapid so that excursions in fluid temperature can be corrected promptly. The main design objectives for rapid heater response are:

- The heat capacity of the electrical heater should be minimized.

- The thermal resistance of the electrical heater should be minimized.

Both objectives are met if the electrical heater is a fine gauge wire.

TRANSITION REGION OPERATION OF BERENSON'S (1960) BOILER

Berenson's (1960) boiler was of the type shown in Fig. (3). The boiler plate was a copper disc 5.7 cm thick; the heat source fluid was water which condensed on the lower surface of the boiler plate. The water was heated by an electrical heater immersed in a pool of liquid in the heat source chamber. The electrical heater was a fine gauge wire, and the power input to the heater was manually controlled.

Berenson (1960) does not state whether or not the boiler could operate in a truly steady-state manner in the transition region--i.e. whether it could operate in a steady, "hands off" manner in the transition region. He gives only the following description of the boiler operating procedure:

> *The power input was varied to maintain the output of the thermocouples in the copper block constant, while a thermocouple placed in the side insulation was monitored. Steady-state is reached when the variation of the temperature in the insulation with time was negligible. It normally took between 15 to 30 minutes to reach steady-state operation when moving from one point to another.*

Figure (6) contains data for two runs reported by Berenson (1962). Note that transition region data were obtained in Run 7 in spite of fluid thermal instability, and were not obtained in Run 17, presumably because of interface thermal instability.

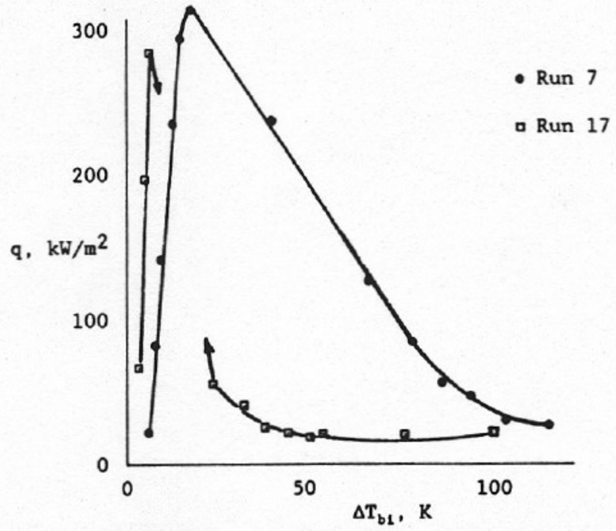

FIGURE 6 BERENSON (1960) DATA REPLOTTED ON LINEAR COORDINATES *(Note transition region data in Run 7, and essential lack of transition region data in Run 17.)*

Adiutori (1991) notes that the boiling data reported by Berenson were bounded by

$$dq/d\Delta T = -3.8\ \mathrm{kW/m^2K}$$

Since −3.8 kW/m²K corresponds to the estimated limit imposed on Berenson's boiler by Criterion (1), it is reasonable to conclude that controlled-state operation of Berenson's boiler was possible throughout the envelope of fluid thermal instability. Thus it was possible to obtain data everywhere outside the envelope of interface thermal instability.

TRANSITION REGION OPERATION OF RAMILISON'S (1985) POOL BOILER--PRESSURE REGULATOR INACTIVE

Ramilison (1985) and Ramilison and Lienhard (1987) describe an experiment with a pool boiler of the type used by Berenson. Ramilison and Lienhard state:

> *The "Berenson" flat-plate transition-boiling experiment has been re-created with a reduced thermal resistance in the (boiler plate), and an improved access to those portions of the transition boiling regime that have a steep negative slope.*

(The reduced thermal resistance was the result of decreasing the thickness of the boiler plate from 5.7 cm to 1.5 cm.)

Ramilison's boiler included an adjustable pressure regulator on the lower chamber. The regulator was used in only one run, and the results of that run are discussed in the next section.

With the regulator inactive, Ramilison reported boiling curve data in a region bounded by

$$dq/d\Delta T = -0.6\ \mathrm{kW/m^2K}$$

This limiting slope is not nearly as steep as the limiting slope in Berenson's experiment, in spite of the fact that Ramilison's limiting slope was expected to be steeper because reduced thermal resistance in the boiler plate was expected to give "improved access to those portions of the transition boiling regime that have a steep negative slope". In other words, Berenson's data included transition region data obtained at negative slopes much steeper than those reported by Ramilison, in spite of the fact that the opposite result was expected.

This anomaly is explained by noting that:

- Both boilers were thermally unstable throughout the transition region.

- In order to obtain data within the transition region, it was necessary to operate the boilers in the controlled-state--i.e. it was necessary to manually control the electrical heater so as to maintain the unstable temperature of the heat source fluid within acceptable limits.

- Berenson's boiler could be operated in the controlled-state throughout the fluid instability envelope because the electrical heater was a fine gauge wire, the optimum design for controlled-state operation.

- Ramilison's boiler could not be operated in the controlled-state in much of the fluid instability envelope because the electrical heater was relatively massive, as indicated in the following from Ramilison (1985):

> *The chamber heater was composed of two water immersion heaters (#22), rated at 1000 and 2000 watts, respectively. They had high watt density incoloy sheath elements, brazed to a 3.81 cm brass screw plug. . . . The four power leads from the heater were 16 gauge copper wire . . .*

In summary, with the pressure regulator inactive, the massive electrical heater in Ramilison's boiler prevented controlled-state operation in much of the fluid instability envelope. Therefore Ramilison's boiler could not be made to operate in the regions of steep negative slope earlier investigated by Berenson, in spite of the fact that Ramilison's boiler was expected to be better in this regard than Berenson's boiler (due to the reduced thermal resistance in the boiler plate).

TRANSITION REGION OPERATION OF RAMILISON'S (1985) BOILER--PRESSURE REGULATOR ACTIVE

With the pressure regulator active, the heat source fluid in Ramilison's boiler was thermally stable because the saturation temperature was fixed by the pressure regulator. Therefore, since the heat source fluid was thermally unstable in the transition region with the regulator inactive, activating the regulator would be expected to markedly improve boiler stability in the transition region. The end result would be that boiler operation would then be limited only by interface thermal stability.

In the one run in which the pressure regulator was active, the data reported by Ramilison were bounded by

$$dq/d\Delta T = -3.6 \text{ kW/m}^2\text{C}$$

Notice that this represents a six fold improvement relative to the value with the pressure regulator inactive. This improvement verifies the conclusion that Ramilison's boiler could not be operated in the controlled-state throughout much of the transition region.

It should be noted that the pressure regulator had only one effect on the boiler--it stabilized the temperature of the heat source fluid, thus eliminating fluid instability, and making it possible to operate the boiler everywhere except within the interface instability envelope.

The fact that the transition region performance of the boiler was greatly improved by the pressure regulator demonstrates the importance of fluid thermal stability, and validates the thermal stability theory presented in this article.

CONCLUSIONS

- The widely accepted view that Criterion (1) is the necessary and sufficient criterion for the thermal stability of heat transfer equipment is not true.
- The thermal stability of heat transfer media must also be addressed in order to correctly appraise the thermal stability of heat transfer equipment.
- Criterion (2) is the generic criterion for the thermal stability of heat transfer media.
- Criteria (3) through (7) are parametric stability criteria which are useful for appraising the thermal stability of pool boilers.
- Steam heated pool boilers such as the type used by Berenson (1960) and Ramilison (1985) are thermally unstable *throughout* the transition region.
- The design of the electrical heater in Berenson type pool boilers is an important design consideration. The optimum design is a fine gauge wire.

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