Transition Boiling Heat Transfer During Reflooding Transients

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INTRODUCTION

Transition boiling heat transfer is characterized by a heat flux which declines as the heater wall temperature increases. Steady state transition boiling is also characterized by alternate periods of high and low heat transfer caused by intermittent wetting of the heated surface. In flow boiling, the reason for intermittent wetting depends on the volume fraction of vapor present. At high vapor volume fractions, annular flow exists during what is generally called the nucleate boiling region, and a thin liquid film is present on the surface. The remainder of the passage is filled with vapor carrying entrained droplets. Above the nucleate boiling region there is no liquid film, and heat is transferred to droplet-laden vapor. In the narrow transition boiling region between nucleate boiling and heat transfer to steam, the liquid film is present only part of the time. The intermittent wetting produces significant wall temperature oscillations.

Recent phenomenologically based modeling of steady state transition boiling heat transfer at high vapor fractions has been successful in predicting the magnitude of both temperature oscillations and heat transfer rates. After a brief review of the steady state model, this note shows how the results of the steady state analysis for vertical surfaces may be used to obtain heat transfer rates during reflooding transients.

Steady State Transition Boiling Behavior at High Vapor Fractions

Kao and Weisman (1985) concluded that during steady state transition boiling at high vapor fractions, intermittent wetting of a vertically oriented heater surface is primarily due to the vertical oscillation of the liquid film on the surface. That is, the upper edge of the liquid film moves up and down in a direction parallel to the vertical heater surface. The length of the wetted region thus periodically expands and contracts. The authors justified their conclusion by their visual observations and temperature oscillation data as well as the wall temperature measurements of France et al. (1982).

Kao and Weisman used their vertically oscillating liquid-film model to develop a prediction for steady state transition boiling at high vapor fractions. They expressed the total heat flux, q''_t, as a sum of convective and boiling components

$$q''_t = fq''_{wet} + (1 - f)h_c\,(\Delta T_{sat}) \qquad (1)$$

The value of q''_{wet} was taken as being nearly equal to the critical heat flux. The critical heat flux was then predicted by using the results of Griffith et al. (1978). These results showed that in flow boiling at low mass velocities, the ratio of q''_{crit} to the critical heat flux in pool boiling was a function of the volumetric vapor fraction.

Kao and Weisman found that the wetted area heat flux decreased slightly as the wall temperature increased. They concluded that

$$q''_{wet} = q''_{crit}\exp\left[-1.6 \times 10^{-3}\,(\overline{T}_w - \overline{T}_{w,wet})\right] \qquad (2)$$

Further, it was found that f, the wetted area fraction, was a function of $(T_w - T_{w,wet}) \times (q''_s/q''_{wet})$. When steady state transition boiling heat transfer coefficients were predicted using the foregoing model, generally good agreement was obtained.

TRANSIENT BEHAVIOR

A phenomenon of considerable practical importance is the bottom reflooding, or quenching, of a nuclear reactor core during a hypothetical loss-of-coolant accident. Transition boiling behavior is a significant component of the accident analysis since the actual quench front is in the transition boiling region. The rate at which the quench front advances up the core is substantially influenced by behavior in this region. Therefore, in this note we reexamine the University of Cincinnati transient transition boiling data and develop a phenomenologically based estimate of transient transition boiling heat transfer using the steady state model.

In the reflooding experiments of Wang (1981), hot mercury flowed through the central tube. The tube was cooled by water flowing in the outer annulus at a rate so low that only the lower portion of the tube was wetted. A step increase in flow then allowed the rewet front to move up the tube. Heat transfer coefficients and rewetting rates observed during these tests were previously reported by Wang et al. (1982).

In those runs where the entering water had little subcooling, rewetting of the upper thermocouples was relatively slow. The rewetting occurred some time after the exit quality had reached its new equilibrium value. In a typical run, calculations indicated that the exit quality had reached its new lower value in about 3 s while rewetting of the upper thermocouple did not occur until 12 s after the transient was initiated. In some runs it was possible to observe the liquid film on the surface of the hot tube. After the step change in flow rate, the liquid film slowly advanced up the tube. The arrival of the film at a given thermocouple approximately coincided with a rapid decrease in temperature at that point. The liquid film appeared to advance more or less steadily without the periodic vertical oscillations seen in steady state. Of course, the edge of the liquid film was not smooth and there was a small scale random oscillation of the edge. The temperature measurements confirmed the lack of substantial vertical oscillations of the front since the large size temperature oscillations seen in the steady state runs were not observed here.

Wang et al. postulated that during annular flow, the slow advance of the rewetting front (advance of thin water film on heated tube) was controlled by the rate at which heat is transferred to the liquid film in the rewet region. They wrote a heat balance around the rewetting front region in a manner similar to that suggested by Yadigaroglu and Arrieta (1978). The Wang et al. heat balance had the form

$$\begin{pmatrix}\text{Stored heat}\\ \text{released by steel}\end{pmatrix} + \begin{pmatrix}\text{Stored heat}\\ \text{released by Hg}\end{pmatrix} + \begin{pmatrix}\text{Heat transported}\\ \text{by flowing Hg}\end{pmatrix} = \begin{pmatrix}\text{Heat transferred}\\ \text{to coolant}\end{pmatrix} \quad (3)$$

The rate of heat transfer to the coolant was obtained by writing an approximate correlation of the experimentally observed transition boiling heat transfer coefficients during transients as

$$q'' = 1.6 \times 10^{6} \exp[-0.014\,(\Delta T_{sat})] \quad (4)$$

and integrating this over the temperature range corresponding to the change from dry to wetted conditions. With this approach, good agreement was obtained with observed rewetting rates between 0.3 and 3.5 cm/s.

REEXAMINATION OF TRANSIENT BEHAVIOR

If the wetted area heat transfer rates estimated from the steady state transition boiling data are applicable during transients, then the heat transfer rate prediction of Eq. 4 would only be a rough approximation. We would expect that, at the lower values of (ΔT_{sat}), the heat transfer rates would correspond to those of a fully wetted region. These high heat transfer rates should then be followed by a region of rapidly declining heat transfer corresponding to the narrow region in which the edge of the rewetting front fluctuates. At high values of (ΔT_{sat}), we would expect a low heat transfer rate corresponding to that attainable in the presence of droplet-laden steam.

The actual heat transfer rates observed by Wang (1981) during two typical transient experiments (runs T706 and T801) are plotted vs. (ΔT_{sat}) in Figure 1. Also shown is a plot of Eq. 4 used by Wang et al. to estimate the transient heat transfer rates in the transition region. It is obvious that Eq. 4 is only an approximation of the experimental observations. The observed heat transfer rates do indeed show a region of high heat transfer followed by a narrower region of rapidly declining heat transfer.

The shaded region in Figure 1 represents the wetted area heat fluxes predicted on the basis of Eq. 2. A region is used instead of a line because the quality, and hence q''_{crit}, varies somewhat with both run number and time. It may be seen that these predictions are in moderately good agreement with the observed heat transfer rates at the lower values of (ΔT_{sat}). Thus the predictions of wetted area heat transfer based on steady state observations appear to agree with the wetted heat transfer rates observed during the transient.

In describing the quenching of a hot rod, some authors distinguish between the quench and rewet temperatures. They define the quench temperature as that at which rapid cooling begins, generally via conduction to the wetted areas. The rewet temperature is defined as the temperature at which permanent contact between liquid and heater wall is reestablished. With this terminology, the beginning of heat transfer to a fully wetted wall would occur at the rewet temperature. Bennett et al. (1966) have suggested that the rewet temperature may be taken as $(T_{sat} + 100°C)$. However, the data of Wang et al. seem to indicate that $(T_{crit} + 100°C)$ may be a somewhat more consistent approximation. This is in agreement with the test runs of Figure 1 where T_{crit} was a little over 20°C above saturation and rewetting took place at about 120°C above saturation. (The value of T_{crit} is computed as the temperature given by the nucleate boiling heat flux correlation of McAdams et al. (1949) when the heat flux is equal to q''_{crit}.)

Although the full description of the heat transfer in the rewet region is complicated, a simple approximation appears adequate for design purposes. Since the average heat transfer rate in the partly wetted region is only about 30% of that in the fully wetted region, and since the partly wetted region is small, it is suggested that heat transfer to the liquid film be ignored in the partly wetted region. The transition boiling heat transfer would then be approximated as being equal to q''_{wet} (from Eq. 2) between T_{crit} and the rewet temperature $(T_{crit} + 100°C)$. This approximation would be conservative in that it would lead to an underestimate of the rate at which the rewet front advances. If this approximation were to be used instead of Eq. 4 to predict the heat transfer rate in the rewet-velocity calculation of Wang et al. (1982), the total heat transfer rate would be about 80% of that used by Wang et al.

In the dry region immediately above the rewet front, the rate of heat transfer was significantly above that which could be attributed to convection to steam alone. Since wall tem-

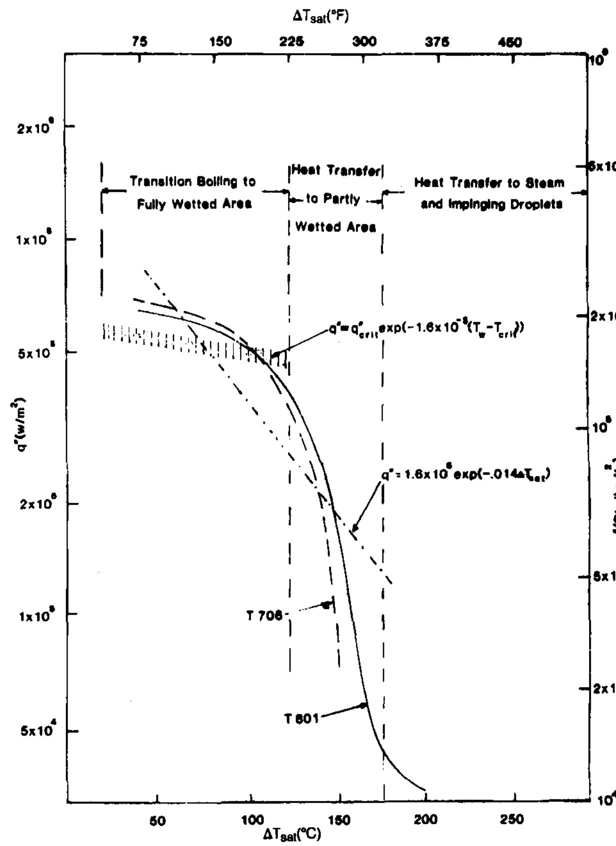

Figure 1. Heat transfer rates during reflooding transients (water at 1.7 bar = 170 kPa).

peratures were relatively low, it appears likely that there was significant heat transfer from the wall to impinging liquid droplets. Estimates of this heat transfer with the Ganic-Rohsenow (1978) correlation were in the same range as Wang's (1981) experimental observations.

CONCLUSION

Reexamination of transient rewetting of vertical surfaces at high void fractions indicates some significant differences between steady state and transient reflood behavior. The vertical oscillation of the liquid film on the heater surface is absent during reflood. However, the heat transfer rate between rewet and the temperature at which the critical heat flux occurs is consistent with estimates of transition boiling heat transfer to the wetted region derived on the basis of steady state data. Use of the steady state expression (Eq. 2) for the heat transfer rate in this region appears to provide a convenient design approach. Heat transfer rate calculations for the steam heat transfer region immediately above the quench front should allow for droplet wetting of the surface.

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NOTATION

f = wetted fraction
q'' = heat flux, w/m^2
h_c = convective heat transfer coefficient, w/m^{2}°C
T = temperature, °C
$\bar{T}$ = mean temperature, °C
ΔT_{sat} = $T_w - T_{sat}$

Subscripts and Superscripts

crit = at critical heat flux conditions
t = total
w = wall surface
sat = saturation
wet = wet
s = standard conditions

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