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Maximum allowable heat flux for a submerged horizontal tube bundle

Donald M. McEligot

Idaho National Engineering Laboratory /
Lockheed Martin Idaho Technologies
Idaho Falls, Idaho 83415-3890
and
University of Arizona, Tucson, Arizona

For application to industrial heating of large pools by immersed heat exchangers, the socalled maximum allowable (or "critical") heat flux is studied for unconfined tube bundles aligned horizontally in a pool without forced flow. In general, we are considering boiling after the pool reaches its saturation temperature rather than sub-cooled pool boiling which should occur during early stages of transient operation. A combination of literature review and simple approximate analysis has been used. To date *our main conclusion is that estimates of* q''_{chf} *are highly uncertain* for this configuration.

1. Background

The horizontal sections in a tubular heat exchanger in a large pool are comparable to the bundle in a horizontal kettle reboiler in the chemical processing industry [Niels, 1979]. Applications include "stab-in" heat exchangers in the petroleum industry and other pool heaters. However, in a large open pool the flow is not confined as it is in a shell-and-tube heat exchanger, steam generator or kettle reboiler; hence, velocities do not necessarily increase in the vertical direction due to vapor generation and density reduction in the same way.

The classic text by Kern on process heat transfer [1950] suggests "the maximum allowable flux for the vaporization of water ..... using forced or natural circulation is

30,000 Btu/(hr)(ft^2). . . . . . The objects of the limitations above are the elimination of all vapor blanketing capabilities"(his page 460).

Palen and Small [1964] provide guidance for the design of kettle and internal reboilers. An internal reboiler is essentially a U-tube heat exchanger inserted through the side of a larger tank; hence, they are sometimes called "stab-in" reboilers. Palen and Small note that practice is to avoid exceeding a flux of about 12,000 to 15,000 Btu/(hr)(ft^2) but then provide a graphical correlation of plant reboiler data that suggests higher values. Their correlation is presented as their Figure 2, included here as Figure 1. (A later paper by Palen, Yarden and Taborek [1972] indicates that their proprietary data show these estimates to be conservative, but it is not clear how conservative they are.)

2. Phenomenological considerations

Typical values of critical heat flux for infinite, horizontal flat plates in saturated pool boiling are believed to be of the order of 3 x 10^5 Btu/hr-ft^2-F for water at one atmosphere (an order of magnitude higher than Kern's suggestion for bundles). One might ask -- *why might the critical heat flux be less for a large bundle ?*

The generally accepted hydrodynamic theory [Bonilla and Perry, 1941; Kutateladze, 1952; Zuber, 1959; Lienhard, 1988] describes a cause of burnout or vapor blanketing of flat plates and individual circular cylinders for single component fluids. (McEligot [1964; Lienhard, 1988] extended the correlation to handle dilute binary solutions.) Its idea is that the vapor blanketing that causes burnout or critical heat flux occurs when the removal of vapor above the surface is limited by a breakdown in the flow of the vapor through the pool (due to a hydrodynamic Kelvin-Helmholtz instability). The hydrodynamic problem is indicated in Figure 2. Zuber's dissertation [1959] provided an approximate analysis which quantified this theory for an infinite flat plate; more readily available descriptions of the approach are provided by Sun and Lienhard [1970] and Lienhard and Dhir [1973]. We can adapt the results of Zuber to demonstrate one possible reason for a reduction in critical heat flux for a large horizontal bundle.

We consider a large horizontal bundle with the upper tube array shown in cross sectional view in Figure 3. The equivalent (fictitious) horizontal plane is sketched above the bundle and we identify as a typical cell the regions corresponding to one vertical row of tubes. For the horizontal plane, the heat flux causing the vapor generation may be called q''_{hp} and its limiting value, when the vapor removal process becomes unstable, is given by Zuber [1959] as

$$q''_{hp,Z} \approx 0.13\,\mathrm{Ku} = 0.13\,\rho_v^{1/2}\,h_{fg}\,[\sigma\,(\rho_l - \rho_v)]^{1/4}$$

By an energy balance, one sees that the heat transfer rate for a typical cell is given as

$$q_{hp} = q''_{hp}\, p_h\, L = \rho_v\, Q_v\, h_{fg} = \rho_v\, Q'_v\, L\, h_{fg}$$

where Q'_v is the vapor volume flow rate per unit length. At the critical condition then this quantity would be given as

$$Q'_{v,c} = q''_{hp,Z}\, p_h \,/\, (\rho_v\, h_{fg})$$

For the present explanation we hypothesize that, for the bundle, the vapor removal process is limited at the same vertical vapor flow rate per unit cell as the horizontal plate. The heat transfer area in the typical cell is then $N_{vr}\, \Pi\, D_t\, L$, where N_{vr} is the number of tubes in a vertical row, so the energy balance may be written as

$$q_b = q''_t\, N_{vr}\, \Pi\, D_t\, L = \rho_v\, Q_v\, h_{fg} = \rho_v\, Q'_v\, L\, h_{fg}$$

Here q''_t or q''_b represents an average heat flux for the tubes in the bundle. By substituting $Q'_{v,c}$ and rearranging, one obtains for the critical heat flux of a bundle the relationship

$$(\, q''_{b,c} \,/\, q''_{hp,Z}\,) \approx (\, p_h \,/\, D_t\,) \,/\, (\, \Pi\, N_{vr}\,)$$

Therefore, *under this hypothesis*, for a fixed geometry *the maximum allowable heat flux would decrease as the number of tubes in a vertical row increases.* That is, the critical heat flux or vapor blanketing heat flux is predicted to be less for a bundle than for a horizontal flat plate as by Zuber. However, the graphical correlation of Palen and Small and other data suggest that higher heat fluxes are feasible.

3. Palen and Small correlation and its applicability

The procedure recommended by Palen and Small [1964], for design of horizontal bundles used as reboilers, is "based more on experience and empirical correlation of plant data than on theory." In the case of maximum allowable heat flux or vapor blanketing however, their limitation was developed by modifying the Zuber correlation, apparently using an approach comparable to that of section 2 above.

The recommended maximum heat flux is taken as a function of a dimensional physical property factor Ψ and a dimensionless tube density factor Φ (Figure 1),

$$\Psi = \rho_v\, h_{lv}\, [\, g\, \sigma\, (\rho_l - \rho_v) \,/\, \rho_v^2\,]^{1/4}$$

$$\Phi = (D_b\, L \,/\, A_{surf}) = D_b\, L \,/\, (N\, \pi\, D_{tube}\, L)$$

The physical meaning of this geometrical factor is that it is simply the ratio of the (one-sided) surface area of a plane through the bundle to the surface area of all the tubes in the bundle. Palen, Yarden and Taborek [1972] later noted that it can be related to a measure of "the ratio of the maximum amount of flow area for liquid entrance into the bundle to the maximum amount of surface for vapor generation." Rearranging the definitions, one can relate Φ to the grouping in the previous section as

$$(p_h / D_t) / (\Pi N_{vr}) = (p_h/p_v)(N/N_{vr}^2)\,\Phi$$

For a square pitch and a square bundle the grouping on the left becomes equal to Φ. If the plane is considered to be horizontal, the use of Φ as a correlating factor implies application of the hypothesis of section 2 to the overall bundle, i.e., an averaged approach rather than treating the central vertical row.

The range of data used to develop their graphical correlation included pitch-to-diameter ratios of about 1.3 to 2. The range of Φ was not given, but in a figure in the paper by Palen, Yarden and Taborek [1972] implies that it may have been approximately $0.002 < \Phi < 0.1$. The fluids involved were hydrocarbons at pressures of about 1, 3.4 and 20 atmospheres and property factor Ψ was from about 3600 to 11,000 in their units. For water at one atmosphere and 100 C, Ψ would be about 15,000 which is higher than the range of the data.

The graphical correlation of Figure 1 suggests that, for low Φ , maximum allowable heat fluxes would be greater than those predicted by the approximate relation derived in section 2. (One sees the basis of this statement by projecting the single tube intercept to lower values of Φ at a slope of unity, i.e., linear.) The difference is a factor of 1.8 (approximately). In their later paper, Palen, Yarden and Taborek [1972] summarized results for a wider range of fluids, including water, and concluded that the correlation of Palen and Small is "very conservative." However, they indicate that the better estimates "cannot be presented quantitatively on account of the proprietary nature of HTRI's (Heat Transfer Research Institute) research work."

4. Other approaches and considerations

This discussion has mostly concentrated on the correlation for critical heat flux proposed by Palen and Small for horizontal bundles in kettle reboilers (which differ from the unconfined geometry of a pool). This correlation diverges from the more familiar ones for single tubes [Sun and Leinhard, 1970; Leinhard and Dhir, 1973] as a bundle becomes larger, i.e., $\Phi = (D_b L / A_{surf}) = D_b L / (N \pi D_{tube} L)$ decreases. As shown in Figure 4, that divergence is a measure of our current uncertainty. It appears that this correlation may provide a reasonable lower limit for *unconfined bundles* .

However, there are other measurements - again for *confined* bundles - which have higher values.

Most of the limited data found for critical heat flux on horizontal bundles involve some degree of forced flow as a consequence of the geometry and/or flow system.

Leroux and Jensen [1992] concentrated on examining critical heat flux on a single tube in a channel-confined array of unheated tubes. Vertical mass flux and local quality of their working fluid (Refrigerant R-113) were controlled so their data may be useful to check the performance of thermal hydraulic codes if they were applied for local predictions within a detailed geometric description of a tube bundle. These data do not appear to be helpful for resolving the uncertainty in q''_{chf} between correlations (Figure 4) when treating large bundles.

Nucleate boiling of R-113 in an apparent pool was studied by Marto and Anderson [1992] with a small, short bundle of three vertical columns of five tubes each. Pitch-to-diameter ratio was about 1.2 and the heated region was about ten diameters long; material was copper. *Critical heat flux was not studied,* but the narrow bundle of staggered tubes was exercised at levels to about forty per cent of $q''_{chf,Zuber}$ without evidence of a departure from nucleate boiling. An approximate estimate of the tube density factor, as if the bundle were "large," is $\Phi \approx 0.15$ but the narrow configuration probably permits vapor to escape to the sides easily. At this value of Φ the data would not provide information to discriminate between the correlations of Palen and Small and Zuber or Lienhard and Dhir.

Fujita et al. [1984, 1986] measured nucleate boiling of R113 on a variety of horizontal tube bundles in an apparatus which resembles a kettle reboiler. The bundles had one or three (staggered) vertical columns of tubes with a small ratio of tube-pitch-to-apparatus-diameter so the bundles might be considered to be nearly unconfined. The configuration and heat flux levels were comparable to those of Marto and Anderson but the pitch does not appear to be listed for the experiments with all tubes heated. *Critical heat flux was not studied.*

In a near Hele-Shaw cell configuration, Leong and Cornwell [1979] have constructed an experiment representing a reboiler bundle with 241 tubes. The tube density factor was $\Phi \approx 0.02$; again the fluid was R-113. While their studies were constrained to nucleate boiling, they did note "there was no indication of any dry-out in spite of the highest heat flux approaching the burnout flux of a single tube under pool boiling conditions." However, in a later investigation with the same apparatus, Shüller and Cornwell [1984] did measure dryout conditions on the shell side. At about 45 per cent of the Zuber prediction of q''_{chf} for R-113 at one atmosphere, over 20 per cent of the tubes showed evidence of partial dry-out. In their Figure 8, there is indication that a tube in the middle of the bundle reached a *critical heat flux at only ~14* *per cent of q"chf,Zuber* (Figure 5). This latter value is in approximate agreement with the correlation of Palen and Small.

Shüller and Cornwell note further that continued testing at 100 kw/m^2 (~ 0.45 q"chf,Zuber) eventually damaged the reboiler rig. A related rig was constructed to obtain further results for dry-out of reboilers at higher heat fluxes. The experimental results with this later "Tube Column Rig" may be misleading; they are shown in their Figure 11 and they imply that the critical heat flux may be within about 25 per cent of that predicted by Lienhard and Dhir [1973]. However, this apparatus employs forced flow (but the value of the flow rate is not given). Further, the short tubes are copper which could be expected to have significant conduction heat losses; the earlier apparatus used stainless steel.

Chan and Shoukri [1984] measured nucleate boiling and burnout for a 3 x 3 tube bundle in a pool of R113 refrigerant. They found that *q"chf* appeared on a bottom tube and it was reduced to *about eighty per cent of q"chf,Zuber* (Figure 5). Details of the dimensions are not clear but the tube density factor Φ was apparently 0.12 or more.

5. Concluding remarks

This treatment has shown pedagogically that it would not be unreasonable for the critical heat flux of a horizontal bundle to be lower than that predicted by the popular Zuber correlation. The uncertainty in the appropriate value grows as the bundle size becomes larger (Φ decreases) as shown in Figure 5.

In the open literature there are only a few investigations of critical heat flux with geometries and conditions relevent to large industrial designs. These studies seem to have been invariably with fluids other than water (mostly R-113), to take advantage of lower power requirements.

Some measurements of dry-out by Shüller and Cornwell and by Chan and Shoukri follow the trends predicted by Palen and Small, while other investigations are inconclusive. Other data by Cornwall and colleagues appear to contradict the correlation of Palen and Small (but some of these latter measurements are with forced flow and possibly significant conduction heat losses).

Most laboratory studies of critical heat flux use electrical resistance heating for convenience. Consequently, the heat flux is controlled. In many industrial applications the heat flux will be determined by the temperature difference between the fluid inside the tubes and the pool temperature on the secondary side in conjunction with the related thermal resistances. Beyond predicting expected values of the critical heat flux, it is also necessary to investigate the consequences of exceeding it and causing dryout or vapor blanketing in this situation, while the primary fluid inlet temperature is held nearly constant. A question that should be addressed is how the overall performance of the heat exchanger varies as individual tubes reach q''_{chf} and shift to a form of film boiling. Transverse and axial propagation of the vapor blanketing through the heat exchanger need to be considered. It appears that both outlet temperature and mass flow rate of the fluid inside the tubes and their local distributions will be affected, the approximate magnitudes of these effects should be quantified.

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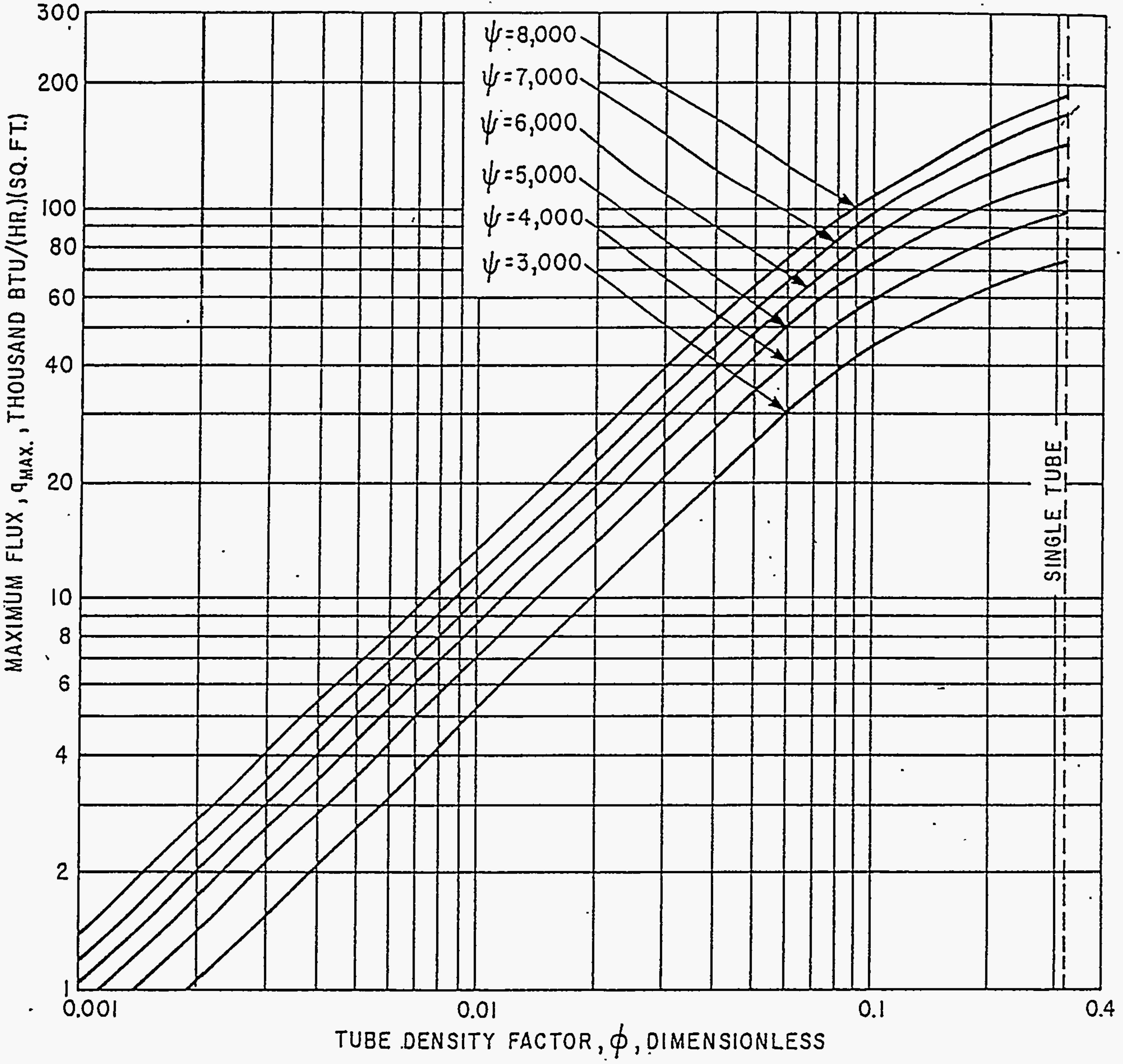

FIGURE 2—When using the estimate from this curve, a safety factor of 0.7 also should be used.

Figure ·1. Maximum bundle heat flux for a horizontal kettle or internal ("stab-in") reboiler [Palen and Small, Hydrocarbon Processing, 1964]

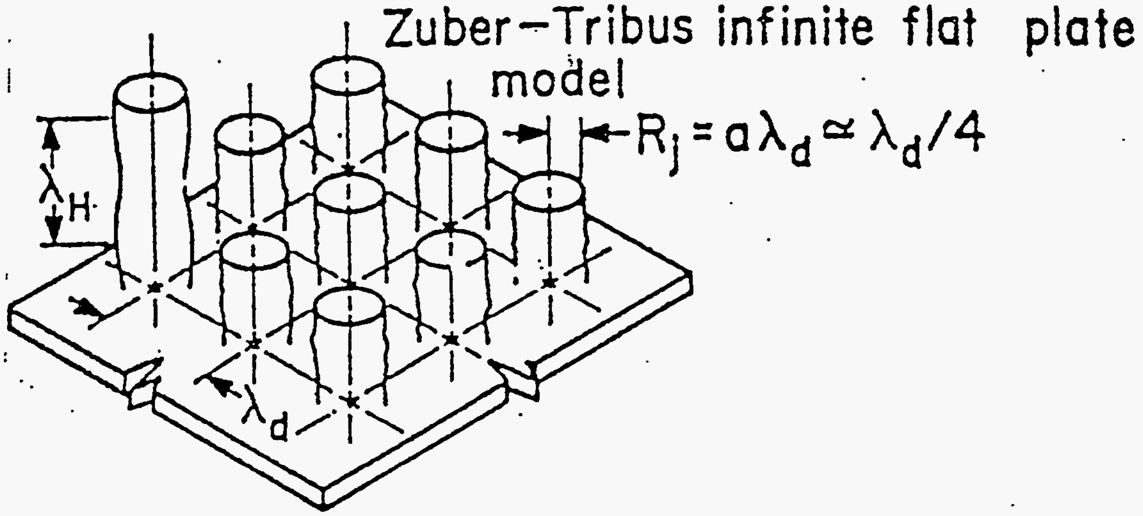

Figure 2. Conceptual vapor-removal configuration near the critical heat flux on an infinite horizontal plane in accordance with the model of Zuber [Lienhard and Dhir, 1973].

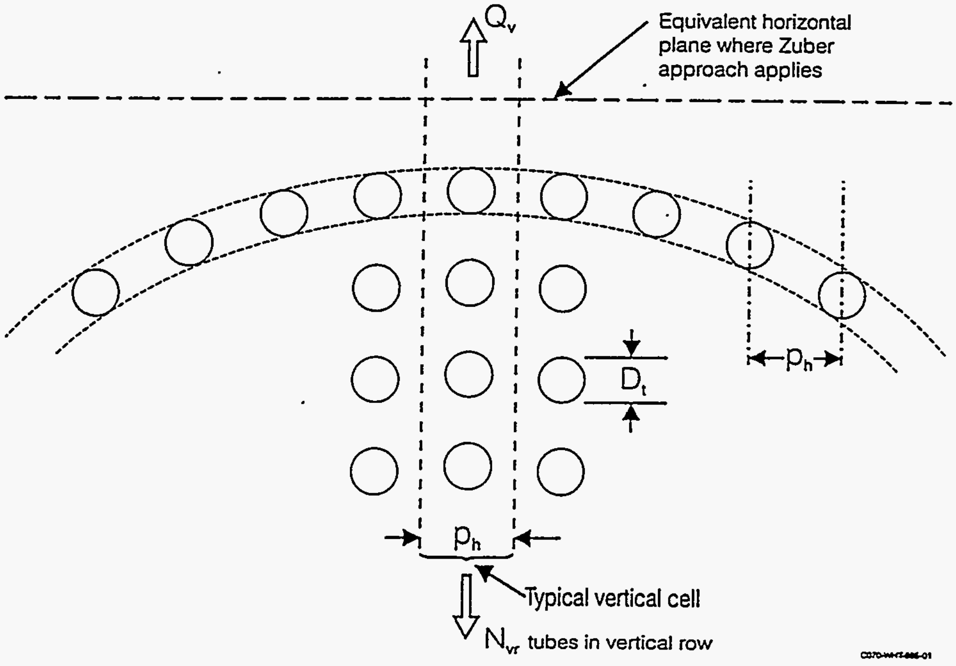

Figure 3. Construction relating tube bundle heat flux to equivalent heat flux / vapor flux (enthalpy flux) of an infinite horizontal plane.

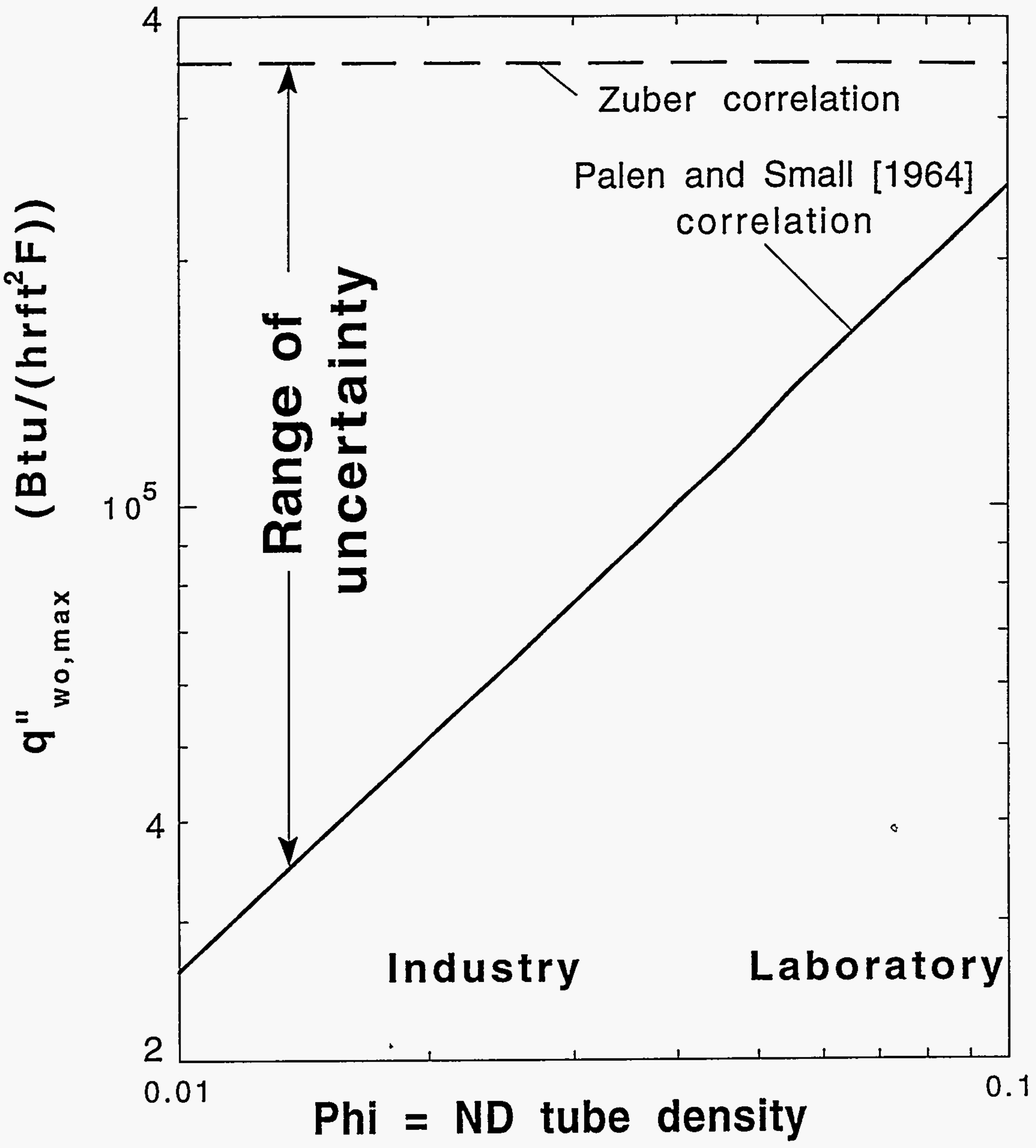

Figure 4. Comparison of maximum heat fluxes predicted by Zuber correlation and Palen and Small [1964] correlation extrapolated to conditions of water at 100 C and 1 atmosphere.

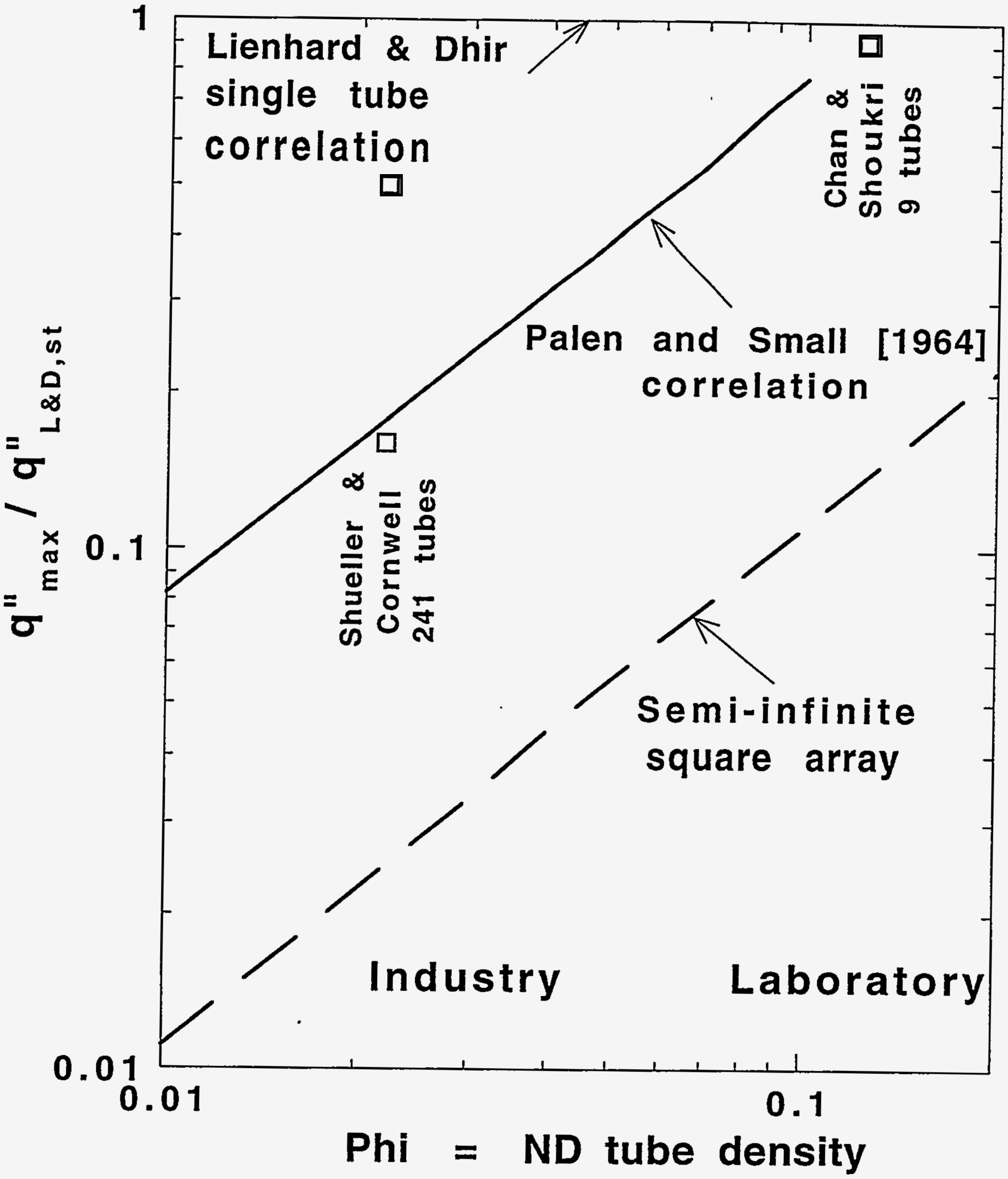

Figure 5. Comparison of empirical correlations of maximum allowable heat flux for horizontal tube bundles and limited data available [Shüller and Cornwell, 1979; Chan and Shoukri, 1984].