Upstream Critical Heat Flux and Its Design Implications

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ABSTRACT
While most critical heat flux (CHF) studies focus on relatively straightforward geometries, actual equipment applications are complex. This paper summarizes literature which provides insights into the effects of selected inlet conditions on CHF and the occurrence of upstream CHF. Vertical smooth bore tube CHF tests found that the concept of “local conditions hypothesis”, though not universally defensible, provides an adequate basis for applying CHF data to design. Upstream CHF indications have been found to be associated with a minimum in the CHF versus quality curve which has been attributed to the transition from intermediate flow regimes to annular flow regimes. Design implications are discussed including: 1) for vertical smooth bore tubes, upstream CHF is generally not observed except at very high masses where specific data are required - at lower mass fluxes, special design procedures are needed where nonuniform circumferential heating is present, 2) for inclined smooth bore tubes, design specific data are needed as upstream CHF observations are more prevalent, 3) for vertical and inclined multi-lead ribbed bore tubes (common in the power industry), minimum mass fluxes are specified to avoid upstream CHF, and 4) coiled and serpentine tubes are discussed.

Introduction
Critical heat flux (CHF) is an important parameter in the design and successful operation of a broad range of industrial equipment such as utility boilers, biomass and waste-to-energy steam generators, hydrocarbon or refrigerant evaporators and advanced solar central receivers. In such equipment, the occurrence of CHF conditions (transition from relatively high heat transfer rates associated with nucleate or forced convective boiling to the poorer heat transfer resulting from transition or film boiling) can lead to overheating of heat transfer surfaces, reduced equipment performance or chemical concentration and accelerated corrosion often leading to mechanical failure. While most reported experimental studies have dealt with relatively straightforward physical arrangements, complex geometries and inlet flow conditions are more frequently the “rule and not the exception” in practice. These complex situations can have a significant impact on the CHF design limits. They may result in a reduction in CHF or in unexpected “upstream” CHF indications where substantial temperature excursions occur upstream of the outlet of the heated channel while inlet and outlet sections of the channel maintain convective boiling conditions.

Exit CHF in vertical tubes: Effect of selected inlet flow conditions
Steam generating equipment generally uses relative large diameter long vertical smooth bore tubes to absorb heat and convert water into steam for power and process applications. However, there are also frequent tube bends creating openings in the furnace wall panels (for burners, sootblowers, observation ports) and transitions in tube diameters and internal surface geometries (such as inserting ribbed bore...
(rifled) tubes which suppress CHF in high heat flux zones). Extensive testing of these boiler conditions have been conducted with long (> 5.3 m) electrically heated vertical test sections at operating pressures of 15 to 20 MPa and mass fluxes of 300 to 1700 kg/m²s [1–3]. During such testing with uniform axial heating, the initial temperature excursions indicative of CHF predominately occur at the outlet of the heated length. To evaluate the effect of inlet conditions on CHF indications occurring at the outlet of the tubes, three different inlet geometries have been used in testing: 1) 90-degree long radius elbows, 2) 39 L/D (length to diameter ratio) unheated smooth bore tube inlet section and 3) 39 L/D unheated multi-lead ribbed bore tube inlet section. Flow modeling has shown (Kitto [3]) that fully developed single phase and two-phase flow patterns for multi-lead ribbed bore tubes are obtained for L/Ds between 24 and 36. Similar results for rifled tubes were found by Zarnett and Charles [4].

Sample results for outlet or exit CHF indications for these tests are shown in Figure 1 for an electrically heated large diameter (38 mm ID) vertical smooth bore tube test section with a 5.39 m heated length. The heat flux distribution is uniform axial and non-uniform circumferential as described by Kitto and Wiener [2] and Kitto [3] and typical of boiler furnace wall panels. Single-phase and two-phase inlet flow conditions were used. As shown in Figure 1, inlet geometries and inlet flow conditions tested did not have a significant effect on test section exit (or outlet) CHF indications for high pressure, upward steam-water flow in the large diameter tubes. Similar results were found with longer test sections and uniform circumferential and axial heating by Watson et al. [1], as well as for two tube lengths under similar conditions by Humphries et al. [5]. These test results support the concept of the “local conditions hypothesis” for CHF where temperature excursions indicative of CHF are a function of the local bulk steam quality in the tube axial location and independent of the inlet conditions. Though not universally defensible, the “local conditions hypothesis” has been found to provide an adequate basis for representing and applying the CHF test results to design for the conditions tested. However, as discussed below, the possibility of upstream CHF under certain conditions (where the temperature excursions indicative of CHF occur toward the inlet or middle of the test section) may modify the design process.

**Upstream CHF**

In experimental investigation of CHF, the heat flux is increased or the mass flux is reduced or the inlet enthalpy is increased until a temperature excursion indicative of CHF is observed. In most cases where uniform axial and circumferential heat flux distributions are tested, these temperature excursions are initially observed at the outlet of the test section as discussed above. However, a fairly broad range of investigators have found that under certain conditions, the initial temperature excursion may occur in the middle or near the inlet of the test section heated length while the outlet and inlet test section temperatures remain unchanged. Kitto [3] and Groeneveld [6] provide brief summaries of upstream CHF phenomena while this paper provides a broader review and assessment. Table 1 provides an overview of the investigators broken down into some broad categories for design consideration [1, 3, 5, 7–23].

**Vertical tubes with high mass flux**

Upstream CHF in vertical tubes was initially reported in the early 1960s by Waters et al. [7] and confirmed by Matzner et al. [8]. The upstream CHF behavior was characterized by: 1) mass fluxes greater than 2200 kg/m²s, 2) a slow temperature rise, 3) the ability to move the temperature indications toward the inlet or outlet by adjusting the inlet enthalpy, 4) reproducibility, 5) no observed flow oscillations, 6) growth of the temperature excursion zone by further increasing the test section heat flux (power input) and 7)

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| CD | CD boundary in Figure 4 |
| CHF | critical heat flux |
| D | diameter, m |
| FT | furnace tube |
| G | mass flux, kg/m²s |
| ID | inside diameter, mm |
| L | length, m |
| L/D | length-to-diameter ratio |
| P | pressure, Pa |
| q’ | heat flux, W/m² |
| q’’ | critical heat flux, W/m² |
| SBW | steam-by-weight, percent |
| x | quality, percent |
| xcr | quality at critical heat flux, percent |

| Greek symbols |
|---------------|
| $\phi_{CD}$ | heat flux boundary in Figure 4, W/m² |
| $\phi_{FT}$ | heat flux furnace tube in Figure 4, W/m² |
occurring at relatively low qualities in the range of 10–30%. Other researchers [9–16] identified in Table 1 also found similar upstream CHF conditions at high mass fluxes. Yokoya, et al. [16], performed testing of upstream CHF conditions using Freon-115, confirming and expanding the earlier research and also finding that the CHF was higher at the upstream indication for CHF at the same qualities at the exit of the test section (somewhat different than other researchers listed).

The CHF versus local quality curve and associated heat transfer/flow phenomenon were used by Waters et al. [7] and Groeneveld [11] to explain this behavior. A generalized CHF versus quality curve is shown in Figure 2. A local minimum in the curve exists where increasing test section power (horizontal line in the figure) can produce upstream observations depending upon the inlet conditions. Groeneveld [6, 11] suggests that the local minimum corresponds to a froth regime occurring as a result of intense mixing near the tube wall at high mass fluxes. Upstream CHF is postulated to occur as a consequence of the deterioration of heat transport properties near the tube wall. Under the high velocity froth regime, the local wall voidage, to which CHF is sensitive, is high because of the more homogeneous flow pattern across the tube section. At higher qualities, the local wall voidage falls as the flow pattern shifts to the annular regime and at lower qualities the total vapor content (voidage) falls with the homogeneous flow reducing the near wall voidage. The minimum of the CHF versus quality curve is established by the transition to annular flow.

From a design standpoint, predictions of high mass flux upstream CHF in vertical smooth tubes is problematic as current general models, such as Groeneveld [24], do not adequately predict the minimum in the CHF vs quality curve. If equipment operation is expected under such high mass flux conditions (see Table 1), experimental data will be required. At lower mass fluxes, upstream CHF behavior has generally not been observed in vertical tubes except for the case discussed below involving nonuniform circumferential heating.

**Vertical tubes with low mass flux**

In general, upstream CHF has not been observed in vertical tubular geometries at low mass fluxes (<2200 kg/m²s) especially with uniform circumferential heating. However, Table 1 identifies special cases where low mass flux upstream CHF indications have been reported.

The earliest is by Aladyev et al. [17]. While included here for completeness, the test apparatus design included an inlet accumulator and other design elements which resulted in flow oscillations which were directly associated with the upstream CHF indications and which thus bring their usefulness into question. Waters et al. [7] attempted to duplicate these conditions by adding an accumulator at the inlet of their test section, and were not able to duplicate the oscillations or the experimental results. Thus, the results of this work are not considered useful or reliable for design purposes.

The next two vertical tube low mass flow studies listed in Table 1 (Humphries et al. [5] and Kitto [3]) explored the effects of nonuniform circumferential heating on CHF in vertical tubes – a physical arrangement common to utility and industrial boiler walls panels as well as large concentrating solar receivers. For the majority of test conditions in both studies, CHF indications occur at the test section outlet as is common for uniform circumferential heating (see Figure 1). However, under a range of relatively low quality conditions, upstream CHF indications were found to occur if a swirl flow pattern is present at the inlet of the heated test section - resulting from closely coupled bends in the case of Humphries et al. [5] or a
Kitto was able to eliminate the upstream indications by replacing the ribbed bore spool piece with a smooth bore tube. The upstream CHF observations reported by Kitto were associated with: 1) low mass fluxes \( (540 - 1360 \text{ kg/m}^2\text{s}) \), 2) a relatively fixed location for the initial indication (82 to 106 L/Ds from the exit of the ribbed tube spool piece), 3) a secondary swirling flow pattern existing at the test section inlet, and 4) peak heat flux levels at the upstream indication which are more appropriate for uniform circumferential heating (see Figure 3). As discussed in the paper, the inlet swirling motion decays along the length of the smooth bore with a reduction in angular momentum of around 60 to 75% at the upstream CHF indications. Neither Humphries et al. [5] nor Kitto [3] found instances where the heat flux at the upstream temperature excursion was less than the uniformly heated tube CHF value within the error band of the data. The mechanism proposed for the upstream CHF indication is a destructive interference

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**Table 1. Upstream CHF observations summary.**

| Author(s)               | Year | Reference | Inside diameter (mm) | Fluid     | Pressure (MPa) | Mass flux \( \times 10^3 \) kg/m\(^2\)s | Quality (%) |
|-------------------------|------|-----------|---------------------|-----------|---------------|----------------------------------------|-------------|
| **Vertical smooth bore tube – high mass flux** |      |           |                     |           |               |                                        |             |
| Waters et al.           | 1964 | [7]       | 11.2                | Water     | 6.9 & 10.3    | 4.9 – 7.0                             | 10 – 32     |
| Matzner et al.          | 1965 | [8]       | 10.2                | Water     | 6.9           | 6.8 – 9.5                             | 9 – 28      |
| Bertoletti et al.       | 1966 | [9]       | 15                  | Water     | 5.0           | 3.9                                    | 13          |
| Hassid et al.           | 1966 | [10]      | 15                  | Water     | 5.0           | 2.2 – 3.8                              | 17 – 20     |
| Groeneveld              | 1974 | [11]      | 7.8                 | Freon-12  | 0.7 – 1.5     | 4.1 – 8.1                             | 8 – 45      |
| Menlo (Note 1)          | 1977 | [12]      | 12.6                | Freon-12  | 1.1           | > 3.7                                 | 10 – 23     |
| Merlo & Ahmad (Note 1)  | 1979 | [13]      | 5.3                 | Freon-12  | 1.1           | 3.1                                    | 12 – 20     |
| Katto & Ashida          | 1982 | [14]      | 5                   | Freon-12  | 2.0 – 3.4     | 2.7 – 6.9                             | –           |
| Katto & Yokoya          | 1982 | [15]      | 5                   | Freon-12  | 2.0 – 3.4     | > 3.8                                 | –           |
| Yokoya et al.           | 1996 | [16]      | 5                   | Freon-115 | 1.4 – 3.0     | 3.27 & 6.54                           | 0 – 20      |
| **Vertical smooth bore tube – low mass flux** |      |           |                     |           |               |                                        |             |
| Aladyev et al. (Note 2) | 1961 | [17]      | 8                   | Water     | 10.0          | 0.4                                   | 0 – 30      |
| Humphries et al. (Note 3)| 1984 | [5]       | 53                  | Water     | 18.0          | 0.4                                   | 10 – 25     |
| Kitto (Note 3)          | 1986 | [3]       | 38                  | Water     | 18.6          | 0.95                                  | 0 – 13      |
| **Horizontal or inclined smooth bore tube** |      |           |                     |           |               |                                        |             |
| Waters et al. (Note 4)  | 1964 | [7]       | 11.2                | Water     | 10.3          | 4.8 – 6.7                             | 10 – 32     |
| Watson et al. (Note 5)  | 1974 | [1]       | 38.1                | Water     | 18.6          | 1.4 – 1.6                             | 5 – 25      |
| Merlo                   | 1977 | [12]      | 12.6                | Freon-12  | 1.1           | > 0.7                                 | 0 – 25      |
| Jensen & Bergles        | 1981 | [18]      | 7.6                 | R-113     | 0.94          | < 1.0                                 | < 0         |
| Kanazaka et al.         | 1986 | [19]      | 17.8                | Water     | 8.9           | 0.48                                  | < 0         |
| Ami et al. (Note 6)     | 2014 | [20]      | 20                  | Water     | 0.4           | > 0.06                                | < 20        |
| **Coiled tube**         |      |           |                     |           |               |                                        |             |
| Jensen & Bergles        | 1981 | [18]      | 7.6                 | R-113     | 0.94          | 0.6 – 5.5                             | 0 – 20 to 5 |
| **Multi-lead ribbed bore tube** |      |           |                     |           |               |                                        |             |
| Watson et al. (Note 7)  | 1974 | [1]       | 39.4                | Water     | 18.6          | < 0.54                                | Note 6      |
| Iwabuchi et al. (Vertical) | 1982 | [21]      | 17.7                | Water     | 20.6          | 0.8 – 1.0                             | 35 – 70     |
| **Serpentine smooth bore tube** |      |           |                     |           |               |                                        |             |
| Robertson               | 1973 | [22]      | 19                  | Water     | 5.2 & 6.9     | 0.4 – 1.0                             | 22 – 50     |
| Fisher & Yu (Note 8)    | 1975 | [23]      | 40                  | Freon-12  | 1.0 & 3.6     | 0.6 – 2.2                             | 5 – 35      |

**Notes:**
1. Water equivalent pressure approximately 6.9 Mpa.
2. Flow oscillations were observed by Aladyev et al. [17] due to the design of the test apparatus leaving validity of the data questionable.
3. See text for discussion of nonuniform circumferential heating effects.
4. High mass flux test.
5. 50-degree inclination from horizontal.
6. Nonuniform circumferential heating, top and bottom peak.
7. Vertical (Quality: 35–62% plus 7.5 and 30 degree inclined from the horizontal (Quality: 0–20%).
8. Water equivalent: 6.7 and 18.0 Mpa.

**Figure 2.** Heat flux versus quality curve illustrating upstream CHF.
between the decaying inlet induced swirl flow pattern and the relatively weak circumferential flow caused by the one-sided heating. The highest quality at which upstream CHF was observed (“A” in Figure 3) or minimum in the CHF versus quality curve is associated with the transition to full annular flow based upon the flow regime map discussed in the paper.

Two design options seem possible to avoid such upstream CHF conditions. The first option is to use the peak circumferential heat flux with uniformly heated CHF data (most conservative). The second involves using a more nuanced concept shown in Figure 4 from Humphries et al. [5]. In this case, the peak equipment heat flux would be used for design with uniformly circumferential heating CHF data down to $\phi_{CD}$ shown in Figure 4 and then nonuniform circumferential heating CHF data for lower heat flux conditions. Note that Kitto’s [3] evaluation indicated that $\phi_{CD}$ in Figure 4 would correspond to the point where the transition to full annular flow would occur in the vertical smooth bore tubes.

**Inclined/horizontal tubes**

A number of studies in Table 1 have identified upstream CHF in inclined and horizontal tubes. Waters et al. [7] performed tests in horizontal tubes at high mass fluxes (similar to the vertical tests discussed above). At such high mass fluxes, the CHF data for vertical and horizontal tubes tend to merge, and Waters et al. [7], in fact, identified upstream CHF at similar conditions to those observed in the vertical tube.

Watson et al. [1] identified upstream CHF in tubes inclined 50-degrees from the horizontal at lower mass fluxes (1.4–1.6 Mg/m²s). The temperature excursions were observed on the top of the uniformly heated inclined tube. The upstream temperature excursions could be expanded by increasing the applied heat flux or moved toward the inlet or outlet of the test section by changing the inlet enthalpy. In addition, similar CHF indications could be identified at the test section outlet by matching the flow rate and local steam quality. These observations were attributed by the authors to the transition from a density stratified two-phase flow pattern found in inclined or horizontal tubes to an annular flow pattern using flow regime maps when this transition occurred near the test section inlet or mid-section. At lower mass fluxes, the authors indicate that the buoyancy forces become more significant and contribute to a variety of stratified flow patterns in inclined tubes where the voidage concentrates toward the top of the tube (producing stratified flow, plug flow, wavy flow, etc.) and significantly reducing CHF compared to vertical flows. A transition to annular flow in horizontal tubes results in a significant increase in the CHF as voidage is more concentrated in the core of the flow pattern. Though the flow pattern transition is different than that observed by Waters et al. [7], the implied CHF versus quality curve is similar to that shown in Figure 2.

Merilo [12] also studied CHF conditions in horizontal tubes at both high and low mass fluxes. At high mass fluxes, the observations were similar to those observed by Waters et al. [7], while at low mass fluxes the behavior was similar to that found by Watson et al. [1]. Jensen and Bergles [18] and Kanzaka et al. [19] also observed a minimum in the CHF versus quality curves and upstream CHF indications in horizontal tubes even at bulk subcooling (bulk quality less than 0%). As with Watson et al. [1], Jensen and Bergles [18] attributed this to buoyancy and local wall void concentrating at the top of the horizontal tube even during subcooled boiling conditions. Ami et al. [20] explored CHF at low pressures and mass fluxes in inclined tubes with uniform and nonuniform circumferential heating. At the high end of their mass flux range (>60kg/m²s for top peak heat flux and >75 kg/m²s for bottom peak) upstream CHF
indications were observed which were attributed to the transition region from churn flow to annual flow. Thus from a design perspective, two cases exist for inclined or horizontal tubes:

1. High Mass Flux: For mass fluxes greater than 2200 kg/m²s, upstream CHF is possible because of the froth flow to annual flow pattern transitions as discussed by Groeneveld [6, 11].

2. Low Mass Flux: For lower mass fluxes, upstream CHF behavior can be found as a result of the transition from intermediate flow patterns (density stratified two-phase flow or churn flow) to annular flow.

In either case, predictions of upstream CHF in inclined smooth tubes are problematic as current general models do not adequately predict the minimum in the CHF vs quality curve. If equipment is designed with inclined or horizontal tubes, experimental data would be required.

**Coiled tubes**

Jensen and Bergles [18] explored CHF in horizontal coiled tubes and identified upstream CHF conditions during many of the tests. In coiled tubes, the flow regime quickly becomes annular at very low local qualities because of the centrifugal forced caused by the separation of the phases and the liquid being concentrated on the tube wall. A secondary circumferential flow results (see Figure 5). At very low mass fluxes and large coil diameters, buoyancy forces overcome the inertial and centrifugal forces allowing local voidage to concentrate at the top of the tube (similar to horizontal tube flow). However for any but the lowest mass fluxes, the secondary circular flow produced by the coiled tube dominates. Even at moderate subcooled bulk conditions, local wall voidage is sufficient to induce some of this circulation. Figure 6 shows the generalized CHF versus quality schematic provided by the authors to describe their data, including a "forbidden zone" where data could not be obtained. The authors found that this behavior varied with mass flux and the ratio of the tube-to-coil diameters. As with the other upstream CHF studies discussed above, a minimum in the heat flux versus quality curve exists as the flow transitions from subcooled bubbly/intermediate flow to full annual flow.

From a design perspective, if coiled tubes are operated at moderate subcooling or low inlet qualities and upstream CHF needs to be avoided for process or thermal considerations, the design heat flux would have to be set below the minimum of the CHF versus quality curve (including a margin of safety). The minimum in the curve would have to be defined from experimental studies over the range of conditions (fluid, temperature and pressure) and geometries (tube and coil diameter) for the specific application since current models do not adequately define this minimum.
Ribbed bore tubes

Watson et al. [1] reported results of tests with multi-lead ribbed bore (or rifled) tubes at high pressures and identified upstream CHF indications in both vertical and incline orientations. Ribbed tubes have the significant benefit of suppressing CHF conditions until higher heat flux and high quality local conditions than smooth bore tubes as shown in Figures 7 and 8 which plot CHF data by mass flux versus quality for a constant pressure and heat flux. The improvement in performance is a function of mass flux. For mass fluxes below a "limiting" value, the enhancement in CHF is modest. However, above the limiting mass flux, fully developed swirl flow exists in the ribbed tube and CHF indications occur at 86% quality and are almost independent of mass flux and tube orientation. For the vertical tube test data shown in Figure 7, the limiting mass flux is 0.54 Mg/m²s while for Figure 8, the value is 0.68 Mg/m²s. As noted on these figures, a number of upstream CHF indications were recorded in the area of the limiting mass flux. For the vertical tube, the authors postulate that the upstream CHF indications were caused by intermediate two-phase flow patterns (slug, or churn or limited annular) with low liquid deposition rates, which eventually give way to fully annular flow with the strong swirl flow pattern characteristic of multi-lead ribbed tubes. For the 5 and 30 degree inclined ribbed tubes, the authors postulate that a density stratification flow regime (for inclined tubes) exists in the subcooled and low quality region —5% to 25% causing the CHF indications while at higher qualities, the density stratified flow transitions to full annular flow. Though not extensively discussed, Iwabuchi et al. [21] observed similar behavior in vertical ribbed tubes for the operating conditions listed in Table 1.

From a design perspective, upstream CHF indications in ribbed bore tubes can generally be avoided by maintaining the flow rate (including safety margin) above the limiting mass flux established by experimental testing.

Serpentine tubes

Robertson [22] reported CHF data from water flowing inside serpentine tubes (horizontal tubes connected by
180-degree bends in the vertical plane). CHF temperature indications and temperature fluctuations were observed on the top of the horizontal sections generally at the outlet of the horizontal run. Temperature fluctuations always preceded the CHF indications. These conditions led to material deposition in the upper surface of the test section during some test runs (poor water control during these runs) which mirror the conditions found in the operating equipment (leading to tube failures). Upstream CHF observations were made producing the CHF versus quality curves shown in Figure 9 with the distinct minimum for many of the test conditions (summarized in Table 1). These upstream indications could be eliminated by decreasing the pressure or increasing the mass flux. Based upon horizontal flow regime maps, the minimum in the CHF versus quality curve and the temperature fluctuations were tied to the transition from annular (with little or no droplet entrainment) to annular-dispersed flow. The design recommendation was made to avoid the annular flow regime by increasing the mass flux (potentially using smaller diameter tubes) or if the process permits, reducing the operating pressure. It was also noted that 180-degree heated bends are susceptible to overheating (on the concave surface) at very low qualities and moderate to high heat fluxes corresponding to bubbly flow pattern. At higher qualities with the annular dispersed flow regime, the secondary circumferential flow pattern in heated bends redistributes the liquid to the tube walls (see Figure 5 for coils) reducing the occurrence of the temperature excursions.

Fisher and Yu [23] observed similar behavior (including upstream CHF) in a Freon-12 cooled serpentine test section. CHF temperature excursions were observed on the top of the tube with temperature fluctuations preceding CHF. Slug flow was identified as at least part of the reason for the temperature fluctuations.

As recommend by Robertson [22], from a design perspective upstream CHF conditions should be avoided by operating the serpentine sections in annular-dispersed flow by adjusting mass flux (and/or operating pressure) to maintain the annular-dispersed flow regime. If heated bends are part of the design, test data would be required to determine the maximum heat flux that can be tolerated without overheating.

**Summary & conclusions**

1. The vertical smooth bore tube CHF tests with exit indications found that the concept of “local conditions hypothesis” for CHF (a function of the local bulk quality), though not universally defensible, provides an adequate basis for representing and applying the CHF test results to design for typical conditions.

2. Upstream CHF indications from many investigators have been found to be associated with a minimum in the CHF versus quality curve (Figure 2) under a variety of geometries, fluids and test conditions. This minimum has been attributed to the transition from intermediate flow regimes (such as slug, plug, churn, frothy, wavy, and stratified) to full annular or dispersed-annular flow regimes. For a range of operating conditions, CHF was found to be lower at the intermediate flow regimes than during full annular or dispersed-annular flow regimes resulting in a discontinuity or minimum in the CHF versus quality curve. It was generally found that reducing the operating pressure (if acceptable for the process application) can potentially reduce or eliminate the upstream CHF indications.

3. The effect of mass flux on upstream CHF is more complex. At lower mass fluxes, increasing the mass flux (perhaps smaller diameter tubes) can...
reduce or eliminate the upstream CHF indications. However at high mass fluxes (> 2200 kg/m²s), the high mass flux contributes to the deterioration in heat transfer properties and that therefore increasing mass flux here is not useful for design.

4. Upstream CHF indications were also observed in multi-lead ribbed bore (or rifled) tubes, and occurred as a result of flow pattern transition to the full swirling flow induced by the internal ribs. These occurrences can be avoided by designing the equipment minimum mass flux to be greater than the limiting mass flux for the specific tube inside diameter, rib geometry, and tube orientation at operating pressure.

5. While advancements are being made in the CHF predictive models and show promise, predicting upstream CHF behavior remains a challenge. The use of experimental data with test conditions similar to the expected operating conditions are still required to assure that upstream CHF data incorporated into the design process (such as with the approaches discussed above for the CHF in nonuniform circumferentially heated vertical tubes at low mass fluxes) or designs can be adapted to avoid upstream CHF occurrences.

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Disclosure statement

No potential conflict of interest was reported by the author.

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