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**KEYWORDS:** *critical heat flux, subcooled boiling, correlation*

# EVALUATION OF SUBCOOLED CRITICAL HEAT FLUX CORRELATIONS USING THE PU-BTPFL CHF DATABASE FOR VERTICAL UPFLOW OF WATER IN A UNIFORMLY HEATED ROUND TUBE

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*A simple methodology for assessing the predictive ability of critical heat flux (CHF) correlations applicable to subcooled flow boiling in a uniformly heated vertical tube is developed. Popular correlations published in handbooks and review articles as well as the most recent correlations are analyzed with the PU-BTPFL CHF database, which contains 29 718 CHF data points. This database is the largest collection of CHF data (vertical upflow of water in a uniformly heated round tube) ever cited in the world literature. The parametric ranges of the CHF database are diameters from 0.3 to 45 mm, length-to-diameter ratios from 2 to 2484, mass velocities from 0.01 × $10^3$ to 138 × $10^3$ kg/$m^2$·s, pressures from 1 to 223 bars, inlet subcoolings from 0 to 347°C, inlet qualities from −2.63 to 0.00, outlet subcoolings from 0 to 305°C, outlet qualities from −2.13 to 1.00, and CHFs from 0.05 × $10^6$ to 276 × $10^6$ W/$m^2$. The database contains 4357 data points having a subcooled outlet condition at CHF. A correlation published elsewhere is the most accurate in both low- and high-mass velocity regions, having been developed with a larger database than most correlations. In general, CHF correlations developed from data covering a limited range of flow conditions cannot be extended to other flow conditions without much uncertainty.*

## I. INTRODUCTION

Critical heat flux (CHF) is an important limit when designing heat transfer equipment in which evaporation is occurring. Exceeding this heat flux limit causes the replacement of liquid adjacent to the heat transfer surface with a vapor blanket. This blanket acts as a barrier to heat flow from the heat dissipating device, resulting in catastrophic failure (burnout) of the device. The nuclear power industry has been at the forefront of research efforts aimed at understanding pool- and flow-boiling CHF, particularly in relation to the design and safe operation of water-cooled nuclear reactors. Insufficient cooling during an overpower transient or a loss-of-coolant accident may cause CHF, leading to a core meltdown and subsequent release of radioactive material into the environment.

Subcooled flow boiling has great potential for accommodating the high heat fluxes in such diverse applications as fusion and fission reactors, manufacturing and materials processing, advanced space thermal management systems, accelerator targets, avionic "cold plates," X-ray anodes, and high-density multichip modules in supercomputers and other modular electronics. The design engineer utilizes empirical CHF correlations to ensure that the extreme operating conditions in these applications maintain heat fluxes in the nucleate boiling regime safely below CHF. Unfortunately, existing CHF correlations have been developed from data covering a limited range of flow conditions and, consequently, cannot be extended to other flow conditions without uncertainty.

The objectives of the current study are as follows:

1. compile all known CHF data for vertical upflow of water in a uniformly heated round tube from the world literature
2. determine the accuracy of existing CHF correlations[1-24] applicable to subcooled conditions at the location of CHF
3. recommend a correlation for predicting CHF in subcooled flow boiling.

## II. THE PU-BTPFL CHF DATABASE

### II.A. Compilation of CHF Data

Experiments to determine the CHF for flow in round tubes have been carried out in many countries over the past 50 yr. Previously, the largest (4372 data points) and most well-known CHF database for vertical upflow of water in a uniformly heated tube was published by Thompson and Macbeth.[25] Upon examination of this database, several problems became apparent:

1. Almost 30% of the database (1246 data points) was obtained from other published databases[2,26] and not from the authors of the data. Consequently, crucial information from the original data source was omitted from Thompson and Macbeth.

2. Careful examination of the original publications containing the data illuminated the severe faults of the Thompson and Macbeth database (listed in historical order):

    a. 23 data points[27] were tabulated with nominal values of pressure and length that, in some cases, were significantly different (>10%) from the actual values.

    b. 32 data points[28] were obtained with upflow in a tube inclined at 45 deg.

    c. 141 data points[29,30] were not identified as being obtained with substantial amounts of nitrogen gas in the flow loop, which reduced CHF by 50 to 80%. Furthermore, CHF was identified as the test condition that caused the test section to glow near the outlet. Also, some of these data were obtained with severe flow rate and pressure fluctuations and intermittent flow reversal.

    d. 12 data points[31] were obtained with various amounts of dissolved hydrogen in the water.

    e. 13 data points[32] were tabulated in Firstenberg et al.[26] with a column labeled as outlet quality when, in fact, it was the inlet quality.

    f. 7 data points[33] were not true CHF data points.

    g. 16 data points[33] were obtained with vertical downflow.

    h. At least 214 additional data points[34,35] were tabulated with an incorrect pressure or length. Note that not all data in Thompson and Macbeth were compared with the original source to identify all data incorrectly tabulated by Thompson and Macbeth.

3. The references cited by Thompson and Macbeth were in some cases incomplete, inaccurate, or omitted. The authorship of 342 data points could not be determined.

4. Some data were identified as premature CHF (322 points), inconsistent with other data (30 points), or low-velocity data with lower CHF than comparable data (39 points) without explanation. In addition, some data that violated an energy balance were not noted.

These issues prompted the authors of the current study to conduct an extensive literature search and compile all tabulated CHF data from the original sources. Furthermore, the validity of each data point was assessed on a point-by-point basis.

More recently, several subcooled CHF correlations[18,21-24] were designed using the ENEA CHF database,[36] which contains only subcooled CHF data for various flow configurations. Of the 1865 subcooled CHF data points in the ENEA CHF database, 832 data points were not obtained with vertical upflow in a uniformly heated round tube (rectangular channel, 47; annular channel, 69; downflow in an annulus with the inner surface heated, 376; horizontal flow in a tube, 299; vertical downflow in a tube, 39; flow in a nonuniformly heated channel, 2). Detailed examination of the ENEA CHF database illuminated several notable imperfections:

1. Data were incorrectly identified as being obtained with vertical upflow in a uniformly heated tube:

    a. 226 data points[13,37,38] were obtained with horizontal flow in a tube.

    b. 39 data points[39] were obtained with vertical downflow in a tube.

    c. 2 data points[40] were obtained with flow in a nonuniformly heated channel.

2. A total of 376 data points[41] indicated as being obtained simply with an annular channel were obtained with downflow in an annulus with the inner surface heated. Furthermore, CHF for these data was defined as the visual observation of an incandescent spot on the inner surface and not by physical destruction or sudden change in resistance of the test section.

3. A total of 117 data points[42] were tabulated with an incorrect heated length (40% too large); 31 of these data points were also tabulated with an incorrect CHF value.

Since >50% of the data in the ENEA CHF database was incorrectly tabulated or not obtained with vertical upflow in a uniformly heated round tube, correlations developed or verified using the entire ENEA CHF database should be reevaluated using a thoroughly inspected database developed for a single-flow configuration such as that compiled in this study.

Table I lists the parametric ranges associated with the valid data in the PU-BTPFL (Purdue University—Boiling and Two-Phase Flow Laboratory) CHF database. CHF data contained in this database that were excluded from further analysis included data identified

TABLE I

Summary of the PU-BTPFL CHF Database for Vertical Upflow of Water in a Uniformly Heated Tube*

| | | Tube Dimensions | | | | Inlet Condition | | Outlet Condition | | CHF |
|---|---|---|---|---|---|---|---|---|---|---|
| | Valid CHF Data | $D \times 10^3$ (m) | $L/D$ | $G \times 10^{-3}$ (kg/m$^2$·s) | $P \times 10^{-5}$ (N/m$^2$) | $\Delta T_{sub,i}$ (°C) | $x_i$ | $\Delta T_{sub,o}$ (°C) | $x_o$ | $q_m \times 10^{-6}$ (W/m$^2$) |
| Low mass velocity region | 3 311 | 0.7<br>44.7 | 2<br>684 | 0.34<br>10 | 1<br>218 | 12<br>343 | −3.03<br>−0.04 | 0<br>288 | −2.25<br>0.00 | 0.5<br>57 |
| High mass velocity—small diameter region | 1 043 | 0.3<br>6.0 | 2<br>109 | 10<br>134 | 1<br>196 | 12<br>347 | −2.36<br>−0.03 | 0<br>305 | −2.13<br>0.00 | 6<br>276 |
| Subcooled CHF data | 4 357 | 0.3<br>45 | 2<br>684 | 0.34<br>134 | 1<br>218 | 12<br>347 | −3.03<br>−0.03 | 0<br>305 | −2.25<br>0.00 | 0.5<br>276 |
| PU-BTPFL CHF data | 28 009 | 0.3<br>45 | 2<br>2484 | 0.01<br>134 | 1<br>218 | 0<br>347 | −3.03<br>0.00 | 0<br>305 | −2.25<br>1.00 | 0.05<br>276 |

*Note:

1. Valid CHF data indicate the number of CHF data points minus the number of premature CHF data, data in violation of an energy balance, and additional unreliable data.

2. The upper (lower) number in each cell of the parameter columns represents the smallest (largest) value of the parameter for the acceptable CHF data in that category. The parameter ranges for the outlet conditions were calculated using the inlet condition (if known) and an energy balance. Saturated fluid properties were evaluated at the outlet pressure (if known).

3. The low mass velocity region consisted of CHF data subcooled at the outlet with $G < 10\,000$ kg/m$^2$·s. The high mass velocity—small diameter region consisted of CHF data subcooled at the outlet with $G \geq 10\,000$ kg/m$^2$·s and $D \leq 6$ mm. Three data points from the high mass velocity region were omitted because $D = 12.8$ mm.

by the original authors as having oscillating or unstable flow conditions, vapor flashing, or other unexplained phenomena at the instant of CHF (1273 points); data that violated an energy balance (see Sec. II.B) (256 points); data that yielded an outlet quality >1 (148 points); data that yielded an inlet temperature <0°C (24 points); and other data considered unreliable (8 points). CHF data obtained with the following experimental conditions were unconditionally excluded from the PU-BTPFL CHF database:

1. nonaqueous fluids or deuterium oxide (heavy water)
2. additives introduced into the fluid to enhance heat transfer
3. noncircular (e.g., rectangular, annular, rod bundle) channel or parallel-flow channel (two channels connected to same inlet plenum)
4. nonuniform axial or circumferential heat flux
5. vertical downflow
6. horizontal flow
7. flow in an inclined tube
8. swirl flow promoter (e.g., twisted tape insert) within tube or upstream of tube inlet
9. cooling of the exterior surface of the tube in addition to flow within the tube
10. steam-water mixture at tube inlet (liquid distribution over the entrance cross section will depend on the method used for introducing the steam-water mixture, which may consequently influence CHF conditions)
11. applied magneto-electrical field or acoustical energy
12. abnormal test section inlet or outlet (e.g., orifice plate, inlet expansion, outlet contraction)
13. internal surface alterations to increase roughness and enhance heat transfer
14. significant amounts of dissolved gas (e.g., hydrogen, nitrogen) in the fluid.

In addition, CHF data presented with an unspecified length or diameter and data presented only in graphical form were excluded.

### II.B. Assessment of CHF Data

The first law of thermodynamics requires that the energy content of a unit mass of fluid at the channel outlet (outlet enthalpy) equal the energy content at the inlet (inlet enthalpy) plus the energy added as the unit mass passes through the heated channel (heat input divided by mass flow rate):

$$h_o = h_i + 4\,\frac{L}{D}\,\frac{q_m}{G} \ . \tag{1}$$

CHF data were tabulated in a spreadsheet as shown in the original data source. If the tabulated inlet condition was inlet quality or subcooling (see Nomenclature for definitions), then the inlet temperature was calculated using equations[43] for saturation temperature, saturated liquid enthalpy, and latent heat of vaporization. The enthalpy of subcooled liquid was approximated by the saturated liquid enthalpy at the subcooled temperature. All calculations performed in the current study utilized saturated fluid properties based on outlet pressure if known. If the outlet quality or subcooling was tabulated instead of an inlet condition, then the outlet enthalpy was determined and inlet enthalpy calculated using energy balance (1). Once the inlet enthalpy was determined, inlet temperature was calculated from the equation for saturated liquid enthalpy using the secant method of iteration. Finally, each CHF data point in the PU-BTPFL CHF database was represented by the following set of data: tube inside diameter, heated length, mass velocity, outlet pressure (or inlet pressure if outlet pressure was unknown), inlet temperature, and experimental CHF.

If both inlet and outlet conditions were tabulated in the original source, outlet quality was calculated using energy balance (1) and the inlet temperature in the PU-BTPFL CHF database. This calculated outlet quality was compared with outlet quality determined from the outlet condition tabulated in the original data source. If these outlet qualities differed by more than 0.05 (0.10 if pressure was >75% of critical pressure), then an energy balance was violated, and the data point was discarded from further analysis. This process filtered the data for typographical errors committed by the original authors or inaccurate thermophysical properties utilized by the original authors.

Table I also lists the parametric ranges associated with the 4357 valid subcooled CHF data points within the PU-BTPFL CHF database, which is the focus of this study. A large contribution to the subcooled CHF data was the 489 data points published by Ornatskii and co-workers.[7,12,42,44] Inlet conditions were not tabulated, and an energy balance utilizing the outlet subcooling yielded inlet temperatures as low as −34°C with 24 data points below 0°C! This impossible condition raises some doubt as to the accuracy of the tabulated outlet subcooling and, hence, the validity of all data published by Ornatskii and co-workers.

Another anomaly was discovered in the 268 CHF data points published by Celata and co-workers.[36,45-47] Celata[48] indicated that measured inlet and outlet temperatures at the instant of CHF were utilized to calculate CHF using the following energy balance:

$$q_m = \frac{GD}{4L} c_{pf}(T_o - T_i) \ , \tag{2}$$

where $c_{pf}$ was evaluated at the average of inlet and outlet bulk temperatures so that Eq. (2) approximates Eq. (1). Outlet temperature was measured downstream of the heated section after the fluid was mixed using a twisted tape over a length of 4 cm inside the tube. Mixing of the fluid was considered suitable by the investigators after a thermocouple traversed across the channel cross section (2.5 to 8.0 mm in diameter) indicated insignificant variations in temperature. The rationale behind this procedure was that significant heat losses precluded the calculation of power as the product of voltage across and current through the test section.[45,47] However, heat losses to the environment should be negligible compared with heat dissipated to a high-velocity, subcooled flow. Celata[48] later indicated that tabulated values of power[46,47] were simply not reliable even though there was no mention of measurement inaccuracies.

Celata's rationale for using a sensible energy balance instead of the more accurate and more widely used (in fact, to the best of the authors' knowledge, the data from Celata and co-workers were the only data in the PU-BTPFL CHF database obtained using this method) direct measurement of current and voltage ignores the following possibilities:

1. The mixing length downstream of the heated section (4 cm) was comparable to the length of the heated section (10 cm for the majority of tests), providing additional surface area for heat loss if, indeed, heat losses were significant for their apparatus.

2. Insufficient mixing of the fluid or incomplete condensation of vapor generated in the heated section will lead to inaccurate temperature measurements.

Both situations combine to produce a measured temperature of the flow core lower than the outlet temperature based on thermodynamic equilibrium, resulting in a calculated CHF lower than the actual value. Incidentally, CHF calculated from Eq. (2) and tabulated by Celata et al.[46,47] was from 30% higher to 30% lower than CHF calculated from measured power. In fact, calculations performed in the current study indicated that 22 of 43 CHF values[46] and 10 of 78 CHF values[47] were larger than the maximum possible heat flux based on the tabulated power! Other data from Celata and co-workers[36,45] did not contain power measurements and, hence, could not be inspected for this irregularity.

A significant fraction of CHF data obtained by Vandervort et al.[23] was labeled as premature CHF with the justification that capillary tubes ($D \leq 2.5$ mm) had a smooth internal surface creating nucleation instabilities, that tube burnout occurred in the upstream portion of the tube, and that measured CHF was lower than CHF predicted by their correlation. These phenomena were not reported by Celata et al.,[46,47] who obtained measurements under similar operating conditions.

The remainder of the PU-BTPFL CHF database (saturated outlet condition) is being closely examined for evidence of other irregularities that may corrupt the integrity of the database. Parametric trends of the CHF data will be analyzed to verify that data from one source observes the trends exhibited by data from other sources obtained with similar operating conditions. This analysis will help to identify entire data sets having premature CHF because of flow instabilities inherent in the experimental flow loop. Currently, only the CHF data from Ornatskii and co-workers and Celata and co-workers and the nonpremature CHF data from Vandervort et al. can be identified as data that must be used with caution.

### II.C. Identification of Mass Velocity Regions

Recent assessments of CHF correlations[22,49] were conducted without regard for the parametric range specified by the correlation. In other words, the accuracy of a correlation was determined in a global manner using an entire database containing a wide range of flow conditions. Consequently, these authors unfairly discriminated against correlations applicable to flow conditions where a low concentration of experimental data existed. In an effort to assess and compare the predictive ability of the correlations with fairness in this study, the subcooled CHF data were examined to identify regions of high and low mass velocity and pressure.

Figure 1 shows the 4357 subcooled CHF data points in the PU-BTPFL CHF database plotted in the mass velocity-pressure plane. Visual inspection identified a mass velocity $G$ of $10 \times 10^3$ kg/m$^2$·s as a boundary between high and low concentrations of data (especially for pressures >20 bars). Further examination revealed that for $G \geq 10 \times 10^3$ kg/m$^2$·s, the largest tube diameter $D$ was 6 mm (0.24 in.), except for three data points[50] obtained with $D = 12.8$ mm and $P = 69$ bars (2 at $G = 13.7 \times 10^3$ kg/m$^2$·s and 1 at $G = 18.6 \times 10^3$ kg/m$^2$·s). These three data points were omitted from further analysis to preserve the physics associated with high mass velocity subcooled boiling in small diameter tubes. Table I lists the parametric ranges associated with the data in the low mass velocity and high mass velocity–small diameter regions. Regions of high and low pressure were not identifiable in this initial assessment and may be defined after further analysis.

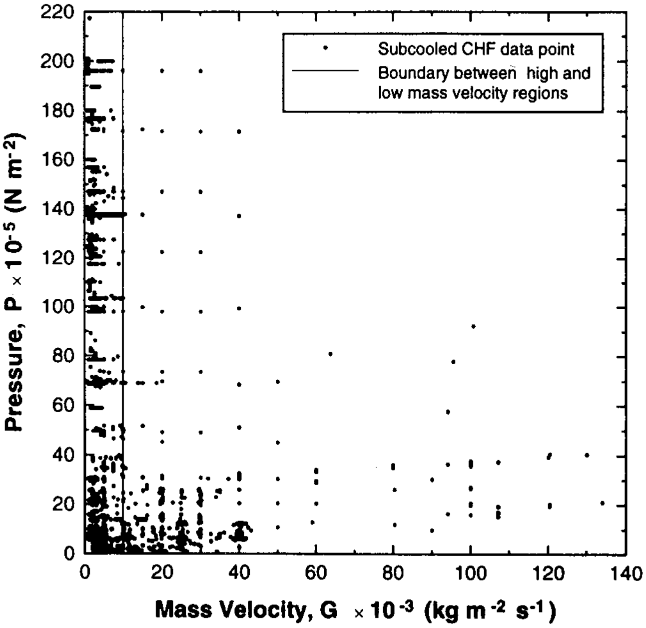

Fig. 1. Subcooled CHF data in the mass velocity-pressure plane.

## III. FLOW BOILING CHF CORRELATIONS

### III.A. Compilation of Correlations

Hundreds of CHF correlations have been published in the archival literature during the past 50 yr. The authors of this study are in the process of collecting all CHF correlations applicable to flow in uniformly heated round tubes. The current study considers the most popular and recently published correlations[1-24] applicable to subcooled CHF and presents a methodology for accurately evaluating the predictive ability of these correlations. Correlations not applicable to water (including Freon scaling correlations) or uniformly heated round tubes cooled by internal axial flow were eliminated from consideration. Also, the original version of a correlation later revised or proven unreliable by the author of the correlation or co-workers at that author's institution were rejected, and only the revised correlation was retained for further analysis in the current study. Correlations were not discarded based on limited experimental conditions or a minimum number of data sources or data points utilized to develop the correlation. The earliest archival publication of a CHF correlation is cited in the list of references unless the authors subsequently refined or extended the parametric range of the correlation.

### III.B. Types of Correlations

CHF correlations generally assume one of the following forms: dimensional correlation based purely on a statistical analysis of the data, nondimensional correlation based on dimensionless groups applicable to flow boiling, or a correlation based on superposition of a pool-boiling CHF model or correlation and a single-phase forced convection correlation. The latter correlation may seem the most attractive at first; however, it speculates that the physical mechanism that initiates CHF in pool boiling is hydrodynamically identical to that in flow boiling, which may or may not be true.

Correlations can also be classified as either an upstream conditions correlation (UCC) based on independent variables such as inlet quality (or subcooling) and heated length,

$$q_m = f(D, L, G, P, x_i) \,, \tag{3}$$

or a local conditions correlation (LCC) based on a dependent variable such as outlet quality (or subcooling),

$$q_m = f(D, G, P, x_o) \ . \tag{4}$$

Equation (4) can be obtained by substituting energy balance (1) into Eq. (3) and assuming that the effect of heated length on local conditions is small (valid except for small $L/D$). Evaluating a UCC is rather straightforward since the quantities on the right side of Eq. (3) are known a priori by the design engineer. On the other hand, an LCC can be evaluated using either of the two methods discussed in the next section.

### III.C. Methods of Evaluating LCCs

CHF correlations based on local conditions [e.g., Eq. (4)] are developed from experimental data using the following procedure:

1. Outlet enthalpy for each data point is calculated using energy balance (1) and the measured CHF and inlet temperature.

2. Outlet quality is calculated using the definition of thermodynamic equilibrium quality and the calculated outlet enthalpy.

3. The unknown constants in the correlation are determined using nonlinear regression, which uses the outlet quality calculated from experimental data to minimize the sum of the squares of the error between measured and predicted CHF [i.e., root-mean-square (rms) error is minimized].

Figure 2 shows the linear relationship between heat flux and thermodynamic equilibrium quality at the outlet as dictated by an energy balance. Also shown is a typical CHF correlation having a negative slope since CHF generally increases as quality decreases with all other parameters ($D$, $L$, $G$, and $P$) fixed.[51] The predictive ability of a CHF correlation can be assessed using experimental data and either the direct substitution method (DSM) or energy balance method (EBM).

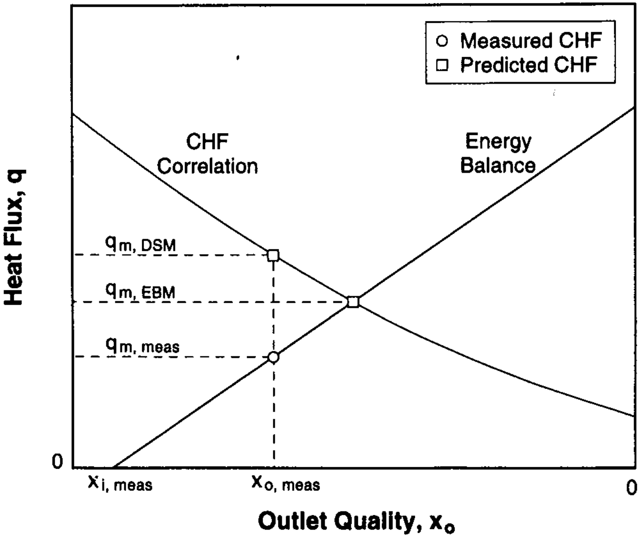

Fig. 2. CHF predicted using an LCC and either the DSM or EBM.

The DSM predicts CHF by simply substituting an outlet quality into an LCC. If the outlet quality is calculated from measured CHF and inlet temperature using an energy balance, then the DSM yields an rms error identical to that obtained when the correlation was developed, assuming that the same database is utilized. The EBM predicts CHF using an inlet temperature and numerical iteration to simultaneously satisfy an energy balance and an LCC. This iterative method requires outlet quality to be calculated from an estimated CHF and measured inlet temperature using an energy balance. This outlet quality is substituted into the correlation, the predicted CHF is compared with the estimated CHF, an improved estimate of CHF is determined, a new outlet quality is calculated from the improved estimate of CHF and an energy balance, and the process is repeated until the CHF values converge. As shown in Fig. 2, the rms error calculated using EBM will always be lower than that obtained using DSM (Ref. 52). In other words, the numerical coupling of a correlation with an energy balance (i.e., EBM) transforms an LCC into a UCC and lowers the rms error below that obtained when the correlation was developed, giving the engineer a false sense of improved accuracy. Furthermore, the EBM yields an outlet quality at CHF substantially different from that calculated from the experimental data unless measured and predicted CHF are identical.

Celata[48] and Inasaka and Nariai[49] preferred the EBM simply because the method yielded a lower rms error when compared with experimental data. The rationale behind the decision of Bricard and Souyri[52] and the authors of the current study to exclusively use the DSM when analyzing correlations was that CHF in subcooled flow boiling is a local phenomenon independent of the inlet condition. In other words, an LCC must correctly interpret the relationship between local quality and CHF. However, from a design perspective, either method may be utilized as long as the quoted accuracy of the correlation has not been biased by the EBM. For example, suppose that an engineer is designing a heat dissipating device that utilizes subcooled flow boiling. The channel cross section, mass velocity, pressure, and inlet temperature must be selected such that the maximum heat flux during operation is safely below CHF. The outlet quality corresponding to this maximum heat flux is calculated using an energy balance and estimates of the design parameters. Then, the outlet quality is substituted into an LCC applicable to the flow configuration to predict CHF. Finally, the engineer compares CHF predicted using this DSM with the maximum operating heat flux to decide if the design parameters must be modified for safe operation of the device. The EBM could also be utilized in this situation by simultaneously solving for outlet quality and CHF using an energy balance and an LCC. The predicted CHF is again compared with the maximum operating heat flux and the design process repeated until safe operation of the device is ensured.

### III.D. Identification of Ultra-High Mass Velocity Correlations

Recently, subcooled flow boiling of water at high mass velocity has been investigated as a means of removing the ultra-high heat fluxes associated with the thermal hydraulics of fusion reactors.[22,24,49,53,54] Of course, the successful use of this cooling technique requires that the CHF be avoided. Figure 3 shows the parametric ranges in the mass velocity-pressure plane of the few CHF correlations applicable to the ultra-high mass velocities ($G > 20 \times 10^3$ kg/m$^2 \cdot$s) required by some reactor components. Although these correlations extend beyond $20 \times 10^3$ kg/m$^2 \cdot$s, a majority of the data was obtained at lower mass velocities, thus biasing the accuracy of the correlation toward lower mass velocities. Furthermore, the bulk of data obtained at ultra-high mass velocities[7,12,23,36,42,44,46,47] is questionable (see Sec. II.B), which raises additional doubt as to the validity of the correlations derived using these data.

## IV. STATISTICAL ASSESSMENT OF CORRELATIONS

### IV.A. Methodology

The current study utilized the following methodology in assessing the predictive capabilities of the CHF correlations:

1. If the parametric range of a correlation was not explicitly stated in a reference, an attempt was made to ascertain the parametric range by inspecting the data (if discussed or cited in the reference) utilized to develop the correlation. In some cases, only limited information on the parametric range was given or determined (e.g., only the pressure range was given by Zenkevich[4]). Experimental data were utilized to determine if a specific data point was within the parametric range of a correlation.

2. Thermophysical properties were evaluated at the temperature specified by the correlation using equations developed by the authors from published data.[55,56] If this information was omitted, then $c_{pf}$, $\mu_f$, and $\rho_f$ were all evaluated at the saturation temperature corresponding to the pressure (if $x_o \geq 0$) or bulk liquid temperature at the outlet (if $x_o < 0$). In all cases, $\mu_g$, $\rho_g$, and $\sigma$ were evaluated at the saturation temperature.

3. The DSM was utilized to predict CHF from LCCs.

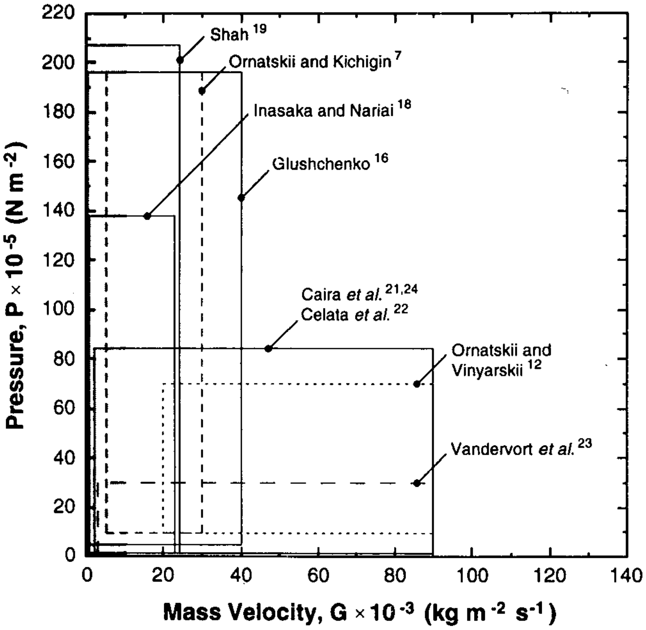

Fig. 3. Subcooled CHF correlations applicable to the high mass velocity-small diameter region with a mass velocity upper limit of at least $20 \times 10^3$ kg/m$^2 \cdot$s.

4. Mean absolute and rms errors of the correlations were calculated using

mean absolute error

$$= \frac{1}{N} \sum \frac{|q_{m,pred} - q_{m,meas}|}{q_{m,meas}} \times 100\% \tag{5}$$

and

rms error

$$= \left[ \frac{1}{N} \sum \left( \frac{q_{m,pred} - q_{m,meas}}{q_{m,meas}} \right)^2 \right]^{1/2} \times 100\% \ , \tag{6}$$

where $N$ is the number of CHF data points.

5. Negative qualities were always evaluated using enthalpy subcooling instead of the product of liquid specific heat and temperature subcooling.

6. Since the outlet was subcooled, bulk liquid temperature at the outlet was evaluated from the outlet enthalpy determined using energy balance (1).

### IV.B. Results

Table II lists the mean absolute and rms errors for each correlation when compared with all subcooled CHF data and CHF data in the low mass velocity-region, high mass velocity-small diameter region, and parametric range specified by the correlation. The mass

TABLE II

Performance of Subcooled CHF Correlations Using the PU-BTPFL CHF Database*

| | Subcooled CHF Data in PU-BTPFL CHF Database (4357 Points) | | Low Mass Velocity Region (3311 Points) | | High Mass Velocity-Small Diameter Region (1043 Points) | | Subcooled CHF Data Within Parametric Range Specified by Correlation | | |
|---|---|---|---|---|---|---|---|---|---|
| Correlation | Mean Absolute Error (%) | rms Error (%) | Mean Absoute Error (%) | rms Error (%) | Mean Absolute Error (%) | rms Error (%) | Number of Data Points | Mean Absolute Error (%) | rms Error (%) |
| Longo[1] | 53.0 | 70.6 | 47.6 | 64.3 | --- | --- | 20 | 10.6 | 13.6 |
| DeBortoli et al.[2] | 754.8 | 2812.4 | 290.0 | 808.0 | --- | --- | 672 | 13.5 | 17.1 |
| Gambill and Greene[3] | 68.6 | 72.8 | 74.2 | 77.5 | --- | --- | 123 | 47.9 | 53.6 |
| Zenkevich[4] | 34.9 | 46.0 | 33.3 | 45.0 | --- | --- | 3872 | 32.7 | 42.5 |
| Bernath[5] | 43.1 | 66.2 | 30.4 | 43.1 | --- | --- | 853 | 22.3 | 28.6 |
| Jacobs and Merrill[6] | 734.8 | 4339.3 | 875.0 | 4971.8 | --- | --- | 671 | 18.8 | 26.7 |
| Ornatskii and Kichigin[7] | 36.9 | 45.3 | 40.7 | 48.8 | 24.7 | 31.7 | 220 | 13.6 | 18.5 |
| Gambill[8] | 44.4 | 56.6 | 45.7 | 59.8 | 40.5 | 44.8 | 4243 | 44.2 | 56.6 |
| Tong et al.[9] | 30.4 | 46.5 | 31.6 | 49.3 | --- | --- | 1561 | 19.0 | 26.5 |
| Wilson and Ferrell[10] | 36.3 | 56.5 | 37.4 | 57.7 | --- | --- | 553 | 12.7 | 15.9 |
| Griffel and Bonilla[11] | 41.7 | 56.3 | 37.6 | 55.9 | 55.0 | 57.6 | 602 | 16.7 | 21.5 |
| Ornatskii and Vinyarskii[12] | 143.7 | 219.9 | --- | --- | 73.1 | 106.9 | 96 | 5.2 | 7.7 |
| Skinner and Loosmore[13] | 47.9 | 73.0 | 53.4 | 80.4 | 30.6 | 41.4 | 140 | 127.4 | 160.9 |
| Tong[14] | 42.7 | 71.3 | 45.1 | 77.1 | --- | --- | 1594 | 22.8 | 31.7 |
| Tong[15] | 107.0 | 179.6 | 88.1 | 172.6 | --- | --- | 659 | 15.6 | 18.3 |
| Glushchenko[16] | 34.5 | 43.3 | 35.0 | 43.5 | 32.4 | 42.4 | 1302 | 21.6 | 28.4 |
| Bowring[17] | 29.4 | 42.7 | 21.9 | 33.3 | 53.5 | 63.9 | 2512 | 20.4 | 33.3 |
| Inasaka and Nariai[18] | 55.4 | 100.0 | 44.2 | 81.6 | 91.0 | 143.8 | 1888 | 28.8 | 37.2 |
| Shah[19] | 33.9 | 76.6 | 38.0 | 86.5 | 20.8 | 27.1 | 3607 | 36.3 | 83.1 |
| Boyd[20] correlation no. 1 | 54.8 | 59.8 | 58.6 | 63.0 | 42.7 | 48.1 | 0 | | |
| Boyd[20] correlation no. 2 | 146.3 | 369.1 | 130.1 | 379.5 | 181.2 | 345.7 | 0 | | |
| Caira et al.[21] | 18.0 | 25.5 | 16.5 | 22.1 | 22.6 | 34.4 | 1218 | 17.5 | 22.4 |
| Celata et al.[22] | 39.4 | 51.1 | 39.9 | 53.3 | 38.1 | 43.5 | 1218 | 45.2 | 48.8 |
| Vandervort et al.[23] | 64.2 | 82.5 | 77.5 | 86.0 | 48.8 | 78.1 | 675 | 39.7 | 49.8 |
| Caira et al.[24] | 77.9 | 131.8 | 94.8 | 149.5 | 24.3 | 40.2 | 1218 | 16.2 | 26.8 |

*Note:

1. A dash in a column indicates that the correlation is not applicable to that mass velocity region.

2. The following correlations predicted negative values of CHF when data were outside the parametric range specified by the correlation:

   a. Jacobs and Merrill[6]: 96 points (96 in the low velocity region)

   b. Boyd[20] correlation no. 2: 1396 points (1285 in the low velocity region and 108 in the high velocity region)

   c. Vandervort et al.[23]: 2230 points (2170 in the low velocity region and 57 in the high velocity region).

3. Boyd[20] published two correlations based on a data set having a limited parametric range. None of the data in the PU-BTPFL CHF database were within this parametric range.

4. The correct constants for the Caira et al.[24] correlation were obtained from Caruso.[57]

velocity range specified by each correlation was examined to determine the mass velocity region(s) relevant to the correlation. Correlations applicable to the low mass velocity region ($G < 10 \times 10^3$ kg/m$^2 \cdot$s) typically had an upper limit of $10.9 \times 10^3$ kg/m$^2 \cdot$s or lower. Some correlations applicable to the low mass velocity region extended well above $10.9 \times 10^3$ kg/m$^2 \cdot$s, the next lowest upper limit being $18.6 \times 10^3$ kg/m$^2 \cdot$s.

Thus, the division between the high and low mass velocity regions for the correlations was defined as $10.9 \times 10^3$ kg/m$^2$·s. If the lower limit of a correlation was below $10.9 \times 10^3$ kg/m$^2$·s, then the correlation corresponded to the low mass velocity region. Likewise, if the upper limit was above $10.9 \times 10^3$ kg/m$^2$·s, it corresponded to the high mass velocity–small diameter region. A dash in a cell in Table II indicates that the correlation does not correspond to that mass velocity region. The following discussion mainly emphasizes the mean absolute error since this value treats the error from each data point equally. On the other hand, rms error assigns greater weight to those predictions exhibiting larger deviations from the experimental CHF.

Figure 4 shows a bar chart of the mean absolute error for the correlations when compared with data within the parametric range of the correlation. The number within each bar indicates the number of data points within the parametric range for that particular correlation. Correlations[3,13,22,23] that were developed using data obtained only by the authors of the correlation tended to have larger errors since a significant amount of data from other authors was within the parametric range. These dimensional correlations (except Celata et al.[22]) were based purely on a statistical analysis of the data and may not accurately predict the effect of certain parameters on CHF. In general, a single data set having relatively few data points may not provide sufficient variation of the independent parameters within a parametric range to accurately predict CHF. Exceptions to these large errors occurred when the parametric range was limited to include data only from the authors of the correlation.[1,7,12] Larger errors were also obtained with the multifluid correlations developed by Gambill[8] and Shah,[19] which were not optimized to predict CHF for water. All correlations besides those mentioned earlier and Zenkevich[4] had a mean absolute error <30% when compared with data in the parametric range of that correlation. Zenkevich provided a parametric range only for pressure, and thus, a significant amount of data not applicable to the correlation was probably introduced into the analysis.

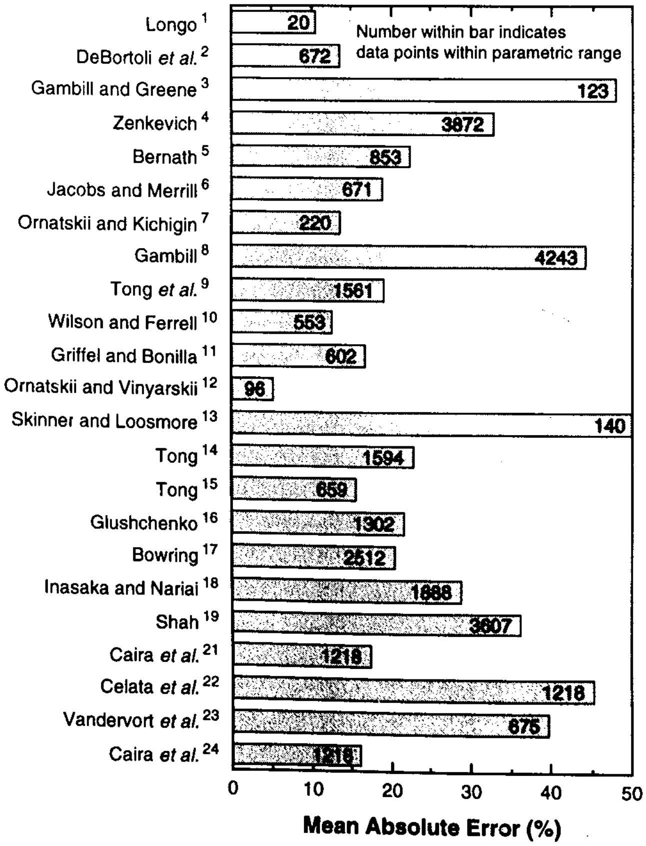

Fig. 4. Mean absolute error of the correlations for subcooled CHF data within parametric range specified by each correlation.

Caira et al.[24] attempted to improve the accuracy of an earlier correlation[21] by increasing the number of adjustable constants from 11 to 132. The forms of the correlations were identical except that a different set of 11 constants was utilized within different regions of mass velocity and pressure. The correct constants for the Caira et al. correlation[24] were obtained from Caruso[57] since the constants tabulated in Caira et al.[24] yielded CHF predictions many orders of magnitude above the actual CHF. The new correlation resulted in a mean absolute error 1% lower than the earlier correlation for the subcooled data within the parametric range specified by the correlation, but it resulted in an rms error 4% higher. In both of the mass velocity regions, the more simplistic correlation[21] outperformed the new correlation.[24] The larger errors of the new correlation resulted from a combination of a large number of adjustable constants (132) and a limited number of data points within some regions (e.g., only eight data points in the region $G > 20 \times 10^3$ kg/m$^2$·s and $3 < P < 5$ bars was available to obtain 11 constants, which is statistically impossible to accomplish).

Figure 5 displays a bar chart of the six correlations having the lowest mean absolute error (<35%) in the (a) low mass velocity region and (b) high mass velocity–small diameter region. As shown in Table II, only 3 of 24 correlations in the low mass velocity region and 4 of 15 in the high mass velocity region exhibited errors lower than those obtained using data only within the parametric range specified by the correlation. This emphasizes the principle of not extrapolating a correlation beyond its specified parametric range. The Glushchenko[16] and Caira et al.[21] correlations were the only ones to appear in the top six in both mass velocity regions.

The ten correlations having the lowest mean absolute error when tested with all subcooled CHF data in the PU-BTPFL CHF database are presented in Fig. 6. The correlation developed by Caira et al.[21] (see Appendix) had the lowest mean absolute error (18.0%) and

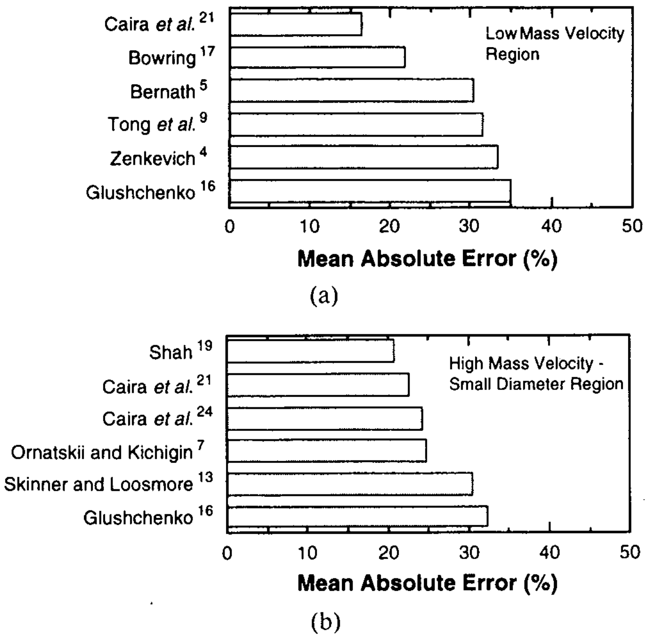

Fig. 5. Correlations having the lowest mean absolute error in the (a) low mass velocity region and (b) high mass velocity-small diameter region.

lowest rms error (25.5%). This correlation is an upstream condition correlation, which is peculiar since CHF is typically regarded as a local phenomenon in subcooled flow boiling. The success of the Caira et al. correlation does not immediately illuminate the effect of system parameters or local conditions on CHF since the correlation is dimensional, having 11 adjustable constants, and independent of pressure and outlet quality. Interestingly, the Caira et al. correlation has an equation form similar to the Bowring correlation,[17] which had the second lowest mean absolute error (29.4%), the main difference being the absence of a pressure effect in the Caira et al. correlation. In sharp contrast to the complex Caira et al. and Bowring correlations, the nondimensional correlation of Glushchenko,[16] which contained dimensionless groups relevant to subcooled boiling and only four adjustable constants, had a mean absolute error of only 34.5%. Further study of these correlations is required to determine if the correlations behave strangely at high pressure and/or ultra-high mass velocity where the concentration of experimental data is relatively low.

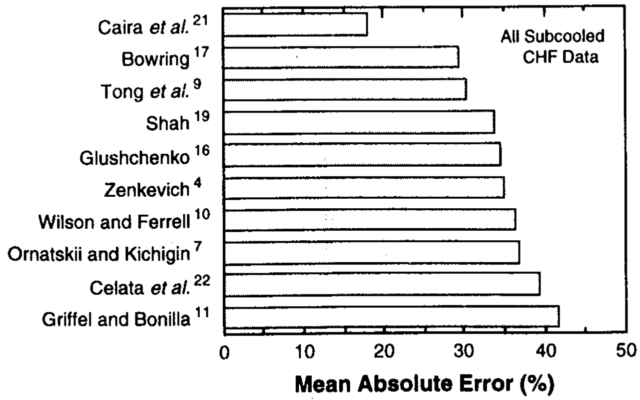

Fig. 6. Correlations having the lowest mean absolute error for the subcooled CHF data.

## V. CONCLUSIONS

The PU-BTPFL CHF database was compiled from the world literature dating back to 1949 and represents the largest CHF database (vertical upflow of water in a uniformly heated tube) ever cited in an archival publication. The database was filtered for premature CHF data and other unreliable data. The collection of all CHF correlations applicable to flow boiling of water in a uniformly heated round tube was initiated. This study presents the results of a statistical analysis performed on 25 subcooled CHF correlations with the PU-BTPFL CHF database. Key conclusions from this study are as follows:

1. Regions of low mass velocity and high mass velocity-small diameter were defined by inspection of the subcooled CHF data and correlations in the mass velocity-pressure plane. This process allowed correlations having different parametric ranges to be compared with fairness and without adding to the complexity of the analysis.

2. Extrapolation of empirical correlations beyond the range of parameters utilized to develop the correlation often leads to significant errors.

3. The most accurate correlation tested[21] was dimensional and rather complex, proving that there are enough "adjustable" constants in any predictive equation to permit an acceptable correlation of the data.

4. Correlations must be closely examined in regions where experimental data are sparse since accuracy of the correlation may be biased toward regions of dense data. Also, additional CHF data must be obtained in these regions of low data concentration (e.g., ultra-high mass velocity region associated with fusion reactor thermal hydraulics where existing data are questionable) to verify or improve accuracy of existing correlations.

## APPENDIX

The Caira et al.[21] correlation was developed using the ENEA CHF database,[36] which contains 1865 subcooled CHF data points obtained with various flow configurations. The parametric range of the correlation is as follows: $0.3 \times 10^{-3} \leq D \leq 25.4 \times 10^{-3}$ m, $2.5 \times 10^{-3} \leq L \leq 610 \times 10^{-3}$ m, $0.9 \times 10^3 \leq G \leq 90 \times 10^3$ kg/m$^2\cdot$s, $1 \times 10^5 \leq P \leq 84 \times 10^5$ N/m$^2$, and $90 \leq \Delta T_{sub,i} \leq 230$°C. The correlation is

TABLE A.I

Constants in the Caira et al.[21] Correlation

| | |
|---|---|
| $C_1$ | 10 829.54 |
| $C_2$ | −0.0547 |
| $C_3$ | 0.7133 |
| $C_4$ | 0.9780 |
| $C_5$ | 0.1882 |
| $C_6$ | −0.4856 |
| $C_7$ | 0.4615 |
| $C_8$ | 0.1882 |
| $C_9$ | −1.1996 |
| $C_{10}$ | −0.3600 |
| $C_{11}$ | 0.9109 |

$$q_m = \frac{F_1 + F_2(0.25\Delta h_{sub,i})^{C_4}}{1 + F_3 L^{C_{11}}} ,$$

where

$$F_1 = C_1 D^{C_2} G^{C_3} ,$$

$$F_2 = C_5 D^{C_6} G^{C_7} ,$$

and

$$F_3 = C_8 D^{C_9} G^{C_{10}} .$$

The units of $D$, $L$, $G$, $\Delta h_{sub,i}$, and $q_m$ are m, m, kg/m$^2$·s, J/kg, and W/m$^2$, respectively. The values of the constants are given in Table A.I.

## NOMENCLATURE

$c_p$ = specific heat at constant pressure

$D$ = inside diameter of tube

$G$ = mass velocity

$h$ = enthalpy of fluid

$h_f$ = enthalpy of saturated liquid

$h_{fg}$ = latent heat of vaporization

$L$ = length of tube

$N$ = number of CHF data points

$P$ = pressure

$q_m$ = critical heat flux

$T$ = temperature

$T_i$ = bulk liquid temperature at inlet

$T_o$ = bulk liquid temperature at outlet (defined only if $x_o < 0$)

$x$ = thermodynamic equilibrium quality, $(h - h_f)/h_{fg}$

*Greek*

$\Delta h_{sub}$ = liquid subcooling, $h_f - h$

$\Delta T_{sub}$ = liquid subcooling, $T_{sat} - T$

$\mu$ = viscosity

$\rho$ = density

$\sigma$ = surface tension

*Subscripts*

$f$ = liquid

$g$ = vapor

$i$ = tube inlet condition

*meas* = measured value

$o$ = tube outlet condition

*pred* = predicted value

*sat* = saturated condition

*sub* = subcooled condition

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