Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – Part I. Dryout incipience quality

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A B S T R A C T
This two-part study concerns the development of a generalized approach to predicting both Nucleate Boiling dominated and Convective Boiling dominated heat transfer in mini/micro-channel flows. Both heat transfer regimes exhibit substantial reduction in the heat transfer coefficient at the location of partial annular liquid film dryout, hence the need to ascertain the occurrence of this important transition point. This first part of the study concerns the development of a correlation for dryout incidence quality. This goal is accomplished by first amassing a consolidated database consisting of 997 dryout data points for mini/micro-channels from 26 sources. The database includes 13 different working fluids, hydraulic diameters from 0.51 to 6.0 mm, mass velocities from 29 to 2303 kg/m² s, liquid-only Reynolds numbers from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78. The new dimensionless correlation is comprised of Weber, Capillary and Boiling numbers, from 125 to 53,770, Boiling numbers from 0.31 × 10⁻⁴ to 4.43 × 10⁻³, and reduced pressures from 0.005 to 0.78.
Crowding, Sublayer Dryout, and Interfacial Lift-off. The Boundary Layer Separation Model is based on the assumption that CHF occurs when the rate of vapor effusion normal to the heated wall reaches a threshold that causes the liquid velocity gradient near the wall to become very small, resulting in separation of the liquid from the wall [25,26]. The Bubble Crowding Model is based on the assumption that CHF occurs when turbulent fluctuations in the core liquid flow become too weak to allow liquid to penetrate the thick bubbly wall layer and supply adequate liquid to the wall [27,28]. The Sublayer Dryout Model is based on the premise that CHF commences when the heat supplied at the wall exceeds the enthalpy of liquid replenishing a thin sublayer beneath long, coalescent vapor bubbles at the wall [29]. The Interfacial Lift-off Model is built upon the observation that the vapor coalesces into a fairly continuous vapor layer before CHF [30–33]. The wavy interface between the core liquid and vapor layer is able to make contact with the heated wall in the wave troughs to provide adequate cooling, and CHF occurs when the wave troughs are lifted away from the wall due to intense vapor effusion.

Dryout is more closely associated with saturated inlet conditions and development of a clearly identifiable annular flow regime. Fig. 1(a) and (b) shows schematics of two types of heat transfer regimes that are associated with saturated inlet conditions and terminated with dryout. The first, Fig. 1(a), is Nucleate Boiling Dominant heat transfer (e.g. [34–36]), where bubbly and slug flow regimes occupy a significant portion of the channel length, and the heat transfer coefficient decreases due to gradual suppression of nucleate boiling. In contrast, Fig. 1(b) depicts Convective Boiling Dominant heat transfer (e.g. [37–39]), where annular flow spans a significant fraction of the channel length. Here, gradual evaporation and thinning of the annular liquid film causes the heat transfer coefficient to increase along the channel length. With a sufficiently high wall heat flux or sufficiently long channel, the annular film becomes vanishingly thin for both heat transfer regimes. A lack of perfect symmetry in the film flow or uneven evaporation causes initial dry patches to form at the location of Dryout Incipience (i.e., onset of dryout, or partial dryout), where the heat transfer coefficient begins to decrease appreciably. Eventually, Dryout Completion occurs at a location farther downstream, where the film is fully evaporated.

Prior authors have adopted different guidelines to identifying dryout incipience and dryout completion conditions. According to Martín-Callizo [36] and Ali and Palm [40], dryout incipience could be identified from a shift in the slope of the measured boiling curve with increasing heat flux, where wall temperature starts to increase steeply following a small heat flux increment. This slope change occurs before the large temperature excursion attributed to dryout completion and common referred to as CHF. They attributed the slope change corresponding to dryout incipience to intermittent dry patches that begin to appear in the annular film. Unfortunately, the distinction between dryout incipience and dryout completion in published studies is quite elusive and often not clearly pointed out. Differences between heat fluxes corresponding to these two conditions are greatly influenced by working fluid, as shown in Fig. 2(a) and (b). Fig. 2(a) shows a boiling curve measured by Qu and Mudawar [41] for water flow boiling in rectangular micro-channels in which CHF corresponding to the dryout region. The narrow dryout region depicted in Fig. 2(a) is typical of micro/mini-channel water data and is largely the result of the high latent heat and high CHF values for water, and corresponding fast wall temperature excursion at

### Nomenclature

- **A**: flow area
- **Bd**: Bond number
- **Bo**: Boiling number, \( q_{\text{fo}}/G_{\text{hf}} \)
- **Ca**: Capillary number
- **D**: tube diameter
- **Dh**: hydraulic diameter
- **Er**: surface roughness
- **Fr**: Froude number
- **Fr**\(_m\): modified Froude number
- **G**: mass velocity
- \( g \): gravitational acceleration
- **hfg**: latent heat of vaporization
- **h_{\text{lp}}**: two-phase heat transfer coefficient
- **MAE**: mean absolute error
- **N**: number of data points
- **P**: pressure
- **P_{\text{crit}}**: critical pressure
- **P_{\text{rt}}**: wetted perimeter of channel
- **Pr_{\text{ht}}**: heated perimeter of channel
- **Pr_0**: reduced pressure, \( P_{\text{ht}} = P/P_{\text{crit}} \)
- \( q^r \): heat flux
- **q_{\text{fo}}**: heat flux based on heated perimeter of channel
- **Re**: Reynolds number
- **Re_{\text{fo}}**: liquid-only Reynolds number, \( Re_{\text{fo}} = G_{\text{dh}}/\nu_{\text{f}} \)
- **T**: temperature
- **T_{\text{w,rad}}**: standard deviation of wall temperature
- **We**: Weber number
- **X**: thermodynamic equilibrium quality
- **X_{\text{crit}}**: dryout completion (CHF) quality
- **X_{\text{in}}**: dryout incipience quality
- **z**: stream-wise coordinate
- **\( v \)**: percentage predicted within ±30%; channel inclination angle
- **\( \mu \)**: dynamic viscosity
- **\( \rho \)**: density
- **\( \sigma \)**: surface tension
- **\( \theta \)**: percentage predicted within ±50%
- **\( \beta \)**: base area of micro-channel heat sink
- **\( \beta_{\text{ct}} \)**: critical
- **\( \exp \)**: experimental (measured)
- **\( \gamma \)**: saturated liquid
- **\( \gamma_{\text{fo}} \)**: liquid only
- **\( \gamma_{\text{vapor}} \)**: saturated vapor
- **\( \gamma_{\text{in}} \)**: inlet
- **\( \gamma_{\text{pred}} \)**: predicted
- **\( \gamma_{\text{sat}} \)**: saturation
- **\( \gamma_{\text{tp}} \)**: two-phase
- **\( \gamma_{\text{w}} \)**: wall

### Greek Symbols

- \( \theta \): percentage predicted within ±30%; channel inclination angle
- \( \mu \): dynamic viscosity
- \( \rho \): density
- \( \sigma \): surface tension

### Subscripts

- **b**: bottom of micro-channel
- **base**: base area of micro-channel heat sink
- **crit**: critical
- **exp**: experimental (measured)
- **fo**: liquid only
- **in**: inlet
- **pred**: predicted
- **sat**: saturation
- **tp**: two-phase
- **w**: wall
CHF. On the other hand, the relatively broad dryout region depicted in Fig. 2(b) is representative of data for refrigerants and dielectric fluids, which possess relatively low latent heat and low CHF values, and exhibit slow temperature excursion at CHF.

This first part of a two-part study examines dryout phenomena for saturated flow boiling in mini/micro-channels. The primary objective of the second part of this study [43] is to develop a generalized pre-dryout saturated flow boiling heat transfer correlation for mini/micro-channels. Since many published studies include data downstream of dryout incipience (i.e., partial dryout as well as post-dryout data), it is crucial to exclude those data points from the original databases when developing a predictive method for the pre-dryout heat transfer coefficient.

The primary goal of the present study is to develop a generalized correlation for dryout incipience quality for flow boiling in mini/micro-channels that is applicable to working fluids with drastically different thermophysical properties and to broad ranges of operating conditions. This goal is achieved by, first, amassing published dryout incipience quality and dryout completion quality (CHF) data for flow boiling in mini/micro-channel flows from 26 sources [34–40,44–62]. The consolidated database is then compared to predictions of previous dryout incipience quality correlations [56,61,63–69]. Finally, a new generalized correlation is proposed that is shown to predict dryout incipience quality data with superior accuracy.

2. New consolidated mini/micro-channel database

A new consolidated database consisting of 997 data points for dryout incipience quality, $x_{di}$, and dryout completion quality (CHF), $x_{crit}$, in mini/micro-channels is amassed from 26 sources [34–40,44–62]. Table 1 provides key information on the individual databases comprising the consolidated database in chronological order. The database consists of 664 data points for water from six sources, and 333 data points for other fluids from 20 sources. The water data of Becker [44], Lezzi et al. [45], Baek and Chang [46], Roach et al. [47], Kim et al. [48], and Yu et al. [50] correspond to dryout completion quality at which CHF occurs. Notice that different criteria were adopted by individual authors to determine CHF and therefore the corresponding dryout completion quality, $x_{crit}$. For example, Lezzi et al. [45] identified CHF by a 5 °C increase in average wall temperature following a small heat flux increment and long waiting period. On the other hand, Baek and Chang [46] identified CHF as occurring when the wall temperature exceeded a fairly high limit of 250 °C. Therefore, the CHF criterion of Lezzi et al. is in fact more closely related to dryout incipience, while the CHF criterion of Baek and Chang is indicative of dryout completion, or true CHF. Since, as shown in Fig. 2(a), the dryout incipience and dryout completion conditions are quite close for water, the data for dryout completion quality, $x_{crit}$, for water in Table 1 are used to represent data for dryout incipience quality, $x_{di}$, in the

![Fig. 1. Schematics of flow regimes, wall dryout and variation of heat transfer coefficient along uniformly heated channel for (a) nucleate boiling dominant heat transfer and (b) convective boiling dominant heat transfer.](image-url)
development of the present correlation for dryout incipience quality.

Among the 333 dryout incipience quality data for fluids other than water, 203 data points were reported by the original authors, and 130 data points are identified by the present authors by the falling off in measured two-phase heat transfer coefficient attributed by the original authors to dryout incipience. For fluids other than water, the large differences between $x_{di}$ and $x_{crit}$ (as shown in Fig. 2(b)) necessitate accurate determination of $x_{di}$ values.

Fig. 2. Boiling curves for (a) water [41] and (b) R134a [42] flows in rectangular micro-channels.
Table 1
Consolidated database for saturated boiling mini/micro-channel flows used to develop present dryout incipience quality correlation.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Channel geometrya</th>
<th>Channel material</th>
<th>D_th [mm]</th>
<th>Relative roughness, e/D_th</th>
<th>Fluid(s)</th>
<th>G [kg/m²s]</th>
<th>Data points</th>
<th>Remarksb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becker (1970) [44]</td>
<td>C, single, VU</td>
<td>–</td>
<td>2.4, 3.0</td>
<td>–</td>
<td>Water</td>
<td>365–2725</td>
<td>82</td>
<td>x_crit identified by fast increase of T_w, x_4 identified by fast increase of T_w of 5°C</td>
</tr>
<tr>
<td>Lezzi et al. (1994) [45]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.0</td>
<td>Smooth</td>
<td>Water</td>
<td>776–2738</td>
<td>68</td>
<td>x_crit identified by fast increase of T_w when T_w &gt; 250°C, x_4 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Baek and Chang (1997) [46]</td>
<td>C, single, VU</td>
<td>Stainless steel</td>
<td>6.0</td>
<td>–</td>
<td>Water</td>
<td>29–277</td>
<td>232</td>
<td>x_crit identified by fast increase of T_w when T_w &gt; 250°C, x_4 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Roach et al. (1999) [47]</td>
<td>C, single, H</td>
<td>Copper</td>
<td>1.168,</td>
<td>0.0017, 0.0014</td>
<td>Water</td>
<td>256–1037</td>
<td>42</td>
<td>x_crit identified by fast increase of T_w when T_w &gt; 250°C, x_4 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Kim et al. (2000) [48]</td>
<td>C, single, VU</td>
<td>Inconel-625</td>
<td>6.0</td>
<td>–</td>
<td>Water</td>
<td>99–277</td>
<td>210</td>
<td>x_crit identified by fast increase of T_w when T_w increase rate of 50°C/s x_4 identified by falling off of h_T, x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Yang and Fujita (2002) [49]</td>
<td>R, single, H</td>
<td>Copper bottom, Pyrex cover</td>
<td>0.976</td>
<td>–</td>
<td>R113</td>
<td>100–200</td>
<td>3</td>
<td>x_3 identified by fast increase of T_w, x_2 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Yu et al. (2002) [50]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>2.98</td>
<td>–</td>
<td>Water</td>
<td>50–151</td>
<td>30</td>
<td>x_3 identified by fast increase of T_w, x_2 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Saitoh et al. (2005) [51]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>0.51, 1.2, 3.1</td>
<td>Smooth</td>
<td>R134a</td>
<td>150–410</td>
<td>41</td>
<td>x_3 identified by fast increase of T_w, x_2 identified by fast increase of T_w</td>
</tr>
<tr>
<td>Yun et al. (2005) [34]</td>
<td>R, multi, H</td>
<td>Stainless steel</td>
<td>1.14</td>
<td>–</td>
<td>CO₂</td>
<td>300–400</td>
<td>2</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Hibara and Dang (2007) [52]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.0, 2.0, 4.0, 6.0</td>
<td>Smooth</td>
<td>CO₂</td>
<td>360–1440</td>
<td>16</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Greco (2008) [53]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>6.0</td>
<td>Smooth</td>
<td>R134a, R22, R407C, R410A</td>
<td>199–1079</td>
<td>7</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Shiferaw (2008) [54]</td>
<td>C, single, VU</td>
<td>Stainless steel</td>
<td>1.1, 2.88, 4.26</td>
<td>0.0012, 0.0005, 0.0004</td>
<td>R134a</td>
<td>200–400</td>
<td>13</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Ohla et al. (2009) [55]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>0.51</td>
<td>–</td>
<td>FC72</td>
<td>107–215</td>
<td>2</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Wang et al. (2009) [56]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.3</td>
<td>–</td>
<td>R134a</td>
<td>312–676</td>
<td>9</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Martin-Callizo (2010) [36]</td>
<td>C, single, VU</td>
<td>Stainless steel</td>
<td>0.64</td>
<td>0.0012</td>
<td>R134a, R22, R245a</td>
<td>185–541</td>
<td>42</td>
<td>x_3 identified by change of slope in boiling curve, and wall temperature fluctuation from T_w, x_2 identified by change of slope in boiling curve, and wall temperature fluctuation from T_w, x_1 identified by change of slope in boiling curve, and wall temperature fluctuation from T_w, x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Ali and Palm (2011) [40]</td>
<td>C, single, VU</td>
<td>Stainless steel</td>
<td>1.22, 1.70</td>
<td>0.0021, 0.0001</td>
<td>R134a</td>
<td>50–600</td>
<td>23</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Ducoulombier (2011) [56]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>0.529</td>
<td>0.0015–0.0030</td>
<td>CO₂</td>
<td>200–1410</td>
<td>48</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Oh and Son (2011a) [37]</td>
<td>C, single, H</td>
<td>Copper</td>
<td>1.77, 3.36, 5.35</td>
<td>Smooth</td>
<td>R134a, R22</td>
<td>200–400</td>
<td>6</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
<tr>
<td>Oh and Son (2011b) [57]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>4.57</td>
<td>Smooth</td>
<td>CO₂</td>
<td>600–900</td>
<td>8</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<tr>
<td>Oh et al. (2011) [58]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.5, 3.0</td>
<td>Smooth</td>
<td>R22, R410A, R290</td>
<td>100–500</td>
<td>9</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<tr>
<td>Wu et al. (2011) [38]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.42</td>
<td>–</td>
<td>CO₂</td>
<td>300–600</td>
<td>18</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<td>Del Col and Bortolin (2012) [59]</td>
<td>C, single, H</td>
<td>Copper</td>
<td>0.96</td>
<td>0.0014</td>
<td>R134a, R245a, R32</td>
<td>101–902</td>
<td>43</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<tr>
<td>Karayannis et al. (2012)</td>
<td>C, single, VU</td>
<td>Stainless steel</td>
<td>1.1</td>
<td>0.0012</td>
<td>R134a</td>
<td>300–900</td>
<td>3</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<tr>
<td>Li et al. (2012) [39]</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>2.0</td>
<td>Smooth</td>
<td>R1234yf, R32</td>
<td>100–400</td>
<td>8</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
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<td>Mastrullo et al. (2012)</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>6.0</td>
<td>0.00007</td>
<td>CO₂, R410A</td>
<td>150–501</td>
<td>28</td>
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<td>Tibirić et al. (2012)</td>
<td>C, single, H</td>
<td>Stainless steel</td>
<td>1.0</td>
<td>0.0006</td>
<td>R1234ze</td>
<td>300–600</td>
<td>4</td>
<td>x_3 identified by falling off of h_T, x_2 identified by falling off of h_T, x_1 identified by falling off of h_T</td>
</tr>
</tbody>
</table>

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b x_crit: critical quality data reported by original authors, x_4 identified by fast increase of T_w, dryout incipience quality data identified by present authors by falling off in measured two-phase heat transfer coefficient attributed by original authors to dryout incipience.

Data having a broad range of relative roughness are included in the consolidated database since the surface roughness ranges indicated in Table 1 where deemed to have minimal influence on dry-out incipience quality. For the database of Ohta et al. [55], data points exhibiting flow rate fluctuations at the test section inlet are excluded from the consolidated database. For the data of Del Col and Bortolin [59], average heat flux values are used to represent non-uniformly heated micro-channels.
Table 2
Previous correlations for dryout incipience quality.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Equation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun (2001) [63]</td>
<td>$x_{in} = 10.795(q_{in}/1000)^{0.123}G^{-0.331}(1000D_h)^{-0.07} \exp \left(0.01715 \times 10^{-5}P\right)$ for 4.9 bar $\leq P \leq 29$ bar, $x_{in} = 19.398(q_{in}/1000)^{0.123}G^{-0.331}(1000D_h)^{-0.07} \exp \left(-0.00255 \times 10^{-5}P\right)$ for 29.4 bar $\leq P \leq 98$ bar, $x_{in} = 32.302(q_{in}/1000)^{0.123}G^{-0.331}(1000D_h)^{-0.07} \exp \left(-0.00795 \times 10^{-5}P\right)$ for 98 bar $\leq P \leq 196$ bar, $P' = \frac{\sqrt{\rho L}}{\sqrt{\rho_r L_r}} = \theta = 0$ for horizontal flow, $x_a = x_{in} = \frac{\pi}{\sqrt{\rho L}} q_{in}$ in [W/m²], $G$ in [kg/m² s], $D_h$ in [m], $P$ in [Pa]</td>
<td>$D = 4.572$ mm, CO₂</td>
</tr>
<tr>
<td>Yoon et al. (2004) [64]</td>
<td>$x_a = 0.0012R^2_{Bo} (1000Bo)^{0.09}Bd^{-1.76}$, $Re_B = \frac{\rho g_{bo}}{\rho_B} Bo = \frac{g}{\rho_B} Bd$</td>
<td>$D = 7.53$ mm, CO₂</td>
</tr>
<tr>
<td>Wojtan et al. (2005) [65]</td>
<td>$x_a = 0.58 \exp \left[0.52 - 0.235 \frac{\rho_{ig}}{\rho_l} p_{ig, \infty}^{0.17} \frac{p_{ig, \infty}^{0.25} \left(\frac{q_{in}}{q_{in, \infty}}\right)}{q_{in, \infty}^{0.70}}\right]$</td>
<td>$D = 8.00$, 13.84 mm, R22, R410A</td>
</tr>
<tr>
<td>Cheng et al. (2006) [66]</td>
<td>$x_a = 0.58 \exp \left[0.52 - 0.67 \frac{c_{ig}^{h} h_l}{\rho_l} \left(\frac{\rho_{ig}}{\rho_l} - \rho_{ig, \infty}\right)^{0.25} \left(\frac{q_{in}}{q_{in, \infty}}\right)^{0.70}\right]$</td>
<td>$D_h = 0.8$–10.06 mm, CO₂</td>
</tr>
<tr>
<td>Del Col et al. (2007) [67]</td>
<td>$x_a = 0.4695 \left(\frac{4G}{C_d D_h} - \frac{RLL}{q_{in, \infty}}\right)^{-1.472} \left(\frac{G}{C_d D_h} \frac{0.3234}{0.1816} \frac{D_h}{D_h, 0.0071} \left(1 - \frac{P_g}{P_{g, \infty}}\right)^{0.123}\right)^{1.06}$</td>
<td>Mini-channels, refrigerants, CO₂</td>
</tr>
<tr>
<td>Cheng et al. (2008) [68]</td>
<td>$x_a = 0.58 \exp \left[0.52 - 0.236 \frac{c_{eg}^{h} h_l}{\rho_l} \left(\frac{\rho_{eg}}{\rho_l} - \rho_{eg, \infty}\right)^{0.25} \left(\frac{q_{in}}{q_{in, \infty}}\right)^{0.27}\right]$</td>
<td>$D_h = 0.6$–10.06 mm, CO₂</td>
</tr>
<tr>
<td>Jeong and Park (2009) [69]</td>
<td>$x_a = 6.2 R e^2_{kg} 0.5 Bo^{-0.2} B d^{-0.41}$</td>
<td>$D = 0.80$, 0.81 mm, CO₂</td>
</tr>
<tr>
<td>Ducoulobier et al. (2011) [56]</td>
<td>$x_a = 1 - 3388 R^{0.721} p_{kg}^{0.41}$</td>
<td>$D = 0.529$ mm, CO₂</td>
</tr>
<tr>
<td>Mastrullo et al. (2012) [61]</td>
<td>$x_a = 1 - 20.82 q_{in, \infty}^{0.377} \frac{C_d}{C_l} D_h^{2.152} \left(\frac{\rho_{eg}}{\rho_l}\right) \frac{H}{D_h^{0.721}} \frac{H}{D_h} \frac{0.721}{\left(\frac{\rho_{eg}}{\rho_l}\right)}$</td>
<td>$D = 6.00$ mm, R410A, CO₂</td>
</tr>
</tbody>
</table>

The consolidated database covers a broad range of reduced pressures, from 0.005 to 0.78. The high pressure data include those of Yun et al. [34], $P_g = 0.54$, Hihara and Dang [52], $P_g = 0.69$, Ducoulobier et al. [56], $P_g = 0.36$–0.47, Oh and Son [57], $P_g = 0.61$–0.78, Wu et al. [38], $P_g = 0.14$–0.47, and Mastrullo et al. [61], $P_g = 0.30$–0.64.

In all, the consolidated database includes 997 dryout incipience quality and dryout completion quality (CHF) data points with the following coverage:

– Hydraulic diameter: 0.51 < Dh < 6.0 mm.
– Mass velocity: 29 < G < 2303 kg/m² s.
– Liquid-only Reynolds number: 125 < Refo = GDh/µf < 53,770.
– Boiling number: 0.31 < B = q00/Hghf < 44.3.
– Reduced pressure: 0.005 < PR < 0.78.

3. Evaluation of previous correlations

Three different parameters are used to assess the accuracy of individual correlations. θ and ξ are defined as the percentages of predictions within ±30% and ±50%, respectively, of the data, and MAE is the mean absolute error, which is defined as

\[
\text{MAE} = \frac{1}{N} \sum \left| \frac{x_{di,\text{pred}} - x_{di,\text{exp}}}{x_{di,\text{exp}}} \right| \times 100\%
\]

When comparing the consolidated database to predictions of previous models or correlations, thermophysical properties are obtained using NIST’s REFPROP 8.0 software [70], excepting those for FC-72, which are obtained from 3M Company.

### Table 3

New dryout incipience quality correlation for saturated boiling mini/micro-channel flows.

\[
x_{di} = 1.4 \left( \frac{W_{efo}}{\mu_f} \right)^{0.15} \left( \frac{P_r}{P_f} \right)^{0.15} D_h^{0.15} \left( \frac{q_f}{P_f} \right)^{0.15} \left( \frac{P_f}{P_t} \right)^{0.06}
\]

where \( W_{efo} = \frac{q_f}{\mu_f} \), \( P_r = \frac{P}{P_f} \), \( P_t = \frac{P}{P_{cr}} \), \( q_f = \frac{q_f}{\mu_f} \), \( \mu_f \): effective heat flux averaged over heated perimeter of channel, \( P_{cr} \): heated perimeter of channel, \( P_f \): wetted perimeter of channel.

### Table 2

<table>
<thead>
<tr>
<th>Fluid</th>
<th>θ (±30%)</th>
<th>ξ (±50%)</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>74.2%</td>
<td>89.7%</td>
<td>24.2%</td>
</tr>
<tr>
<td>CO₂</td>
<td>81.6%</td>
<td>91.7%</td>
<td>31.7%</td>
</tr>
<tr>
<td>CO₂</td>
<td>73.3%</td>
<td>89.7%</td>
<td>24.1%</td>
</tr>
<tr>
<td>Water</td>
<td>73.3%</td>
<td>81.6%</td>
<td>24.1%</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of consolidated 997 point database with predictions of previous correlations: (a) Sun (2001) [63], (b) Wojtan et al. (2005) [65], (c) Cheng et al. (2006) [66], (d) Del Col et al. (2007) [67], (e) Cheng et al. (2008) [68], (f) Jeong and Park (2009) [69], (g) Ducoulombier et al. (2011) [56], and (h) Mastrullo et al. (2012) [61].

Fig. 4. Comparison of predictions of new correlation with 997 point consolidated database.
developed by Kon’kov [71] for water upward through vertical tubes. The correlation of Wojtan et al. [65] was based on a functional formulation by Mori et al. [72], and the correlations of Cheng et al. [66, 68] are modified versions of those of Wojtan et al. [65] tailored specially to CO₂ flows. The correlation of Jeong and Park [69] was based on a functional formulation by Yoon et al. [64]. The relatively simple correlation of Ducoulombier et al. [56] was developed specifically for lower saturation temperatures and lower heat fluxes.

Fig. 3 compares the entire 997-point consolidated database for mini/micro-channel flows with predictions of previous correlations for dryout incipience quality, $q_{\text{fo}}$. Given the large differences in thermophysical properties for different working fluids, the 13 fluids are segregated into three categories: refrigerants, CO₂, and water. The correlation of Yoon et al. [64] is excluded from this comparison because of its unusually high MAE and significant scatter. Fig. 3(a) shows the correlation of Sun [63] highly overpredicts most of the consolidated database except for water data. Large portions of the consolidated database are highly underpredicted by the correlations of Wojtan et al. [65], Fig. 3(b), Cheng et al. [66], Fig. 3(c), and Jeong and Park [69], Fig. 3(f). As shown in Fig. 3(d), the correlation of Del Col et al. [67] displays some scatter against the consolidated database, and significant underprediction of CO₂ data. Excluding water data, the correlation of Cheng et al. [68] provides fair predictions, Fig. 3(e), marred by some overprediction of refrigerant data and some underprediction of CO₂ data. The correlation of Ducoulombier et al. [12] shows large scatter against most of the consolidated database, especially for refrigerants and water. Interestingly, the correlation of Mastrullo et al. [61], which was developed for refrigerants and CO₂ flows in 6-mm diameter circular tubes, shows better MAE than all other seven correlations, despite some overprediction of the data.

4. New generalized correlation

Various combinations of dimensional parameters are examined in the development of a generalized correlation for dryout incipience quality. The relative influences of inertia, viscous force, and surface tension, are accounted for using the Weber and Capillary numbers, which are defined as

$$W_{\text{fo}} = \frac{G^2 D_h}{\rho_l \sigma}$$

and

$$Ca = \frac{\mu_l G}{\rho_l \sigma} \frac{W_{\text{fo}}}{Re_{\text{fo}}}$$

respectively. Both reduced pressure, $P_r = P / P_{\text{crit}}$, and density ratio, $\rho_l / \rho_v$, are also considered to cope with different working fluids, such as refrigerants, CO₂, and water, and broad variations in operating pressure. The effect of heat flux is accounted for using the Boiling number, which is defined as

$$\text{Bo} = \frac{q}{h_d}$$

where $h_d$ is the convective heat transfer coefficient.
\[ Bo = \frac{q^*_g}{G_{Hfg}} \]  

where \(q^*_g\) is the effective heat flux averaged over the heated perimeters of the channel. The ratio of the flow channel's heated to wetted perimeters, \(P_H/P_F\), is also considered to cope with one-sided wall heating by Yang and Fujita [49]. Using the entire consolidated database for flow boiling in mini/micro-channels, the following correlation for dryout incipience quality is proposed,

\[ x_{di} = 1.4 W e^{0.03} q_{g}^{0.08} - 15.0 \left( \frac{Bo}{P_{H}/P_{F}} \right)^{0.15} C_d^{0.35} \left( \frac{P_k}{P_f} \right)^{0.06} \]  

whose empirical constants are optimized to yield least MAE. Table 3 provides detailed definitions of this correlation's individual dimensionless parameters.

Fig. 4 shows the new dryout incipience quality correlation predicts the 997-point consolidated mini/micro-channel flow boiling database with good accuracy, evidenced by a MAE of 12.5%, with 93.6% and 98.0% of the data falling within ±30% and ±50% error bands, respectively.

But achieving low overall MAE is by no means the only definitive means for ascertaining the effectiveness of the new correlation. Equally crucial is the ability of the correlation to predict data evenly over relatively broad ranges of all relevant parameters [19-21,23,24].

Fig. 5 shows, for each parameter, both a lower bar chart distribution of number of data points, and corresponding upper bar chart distribution of MAE in the predictions of the new correlation. The 997-point consolidated database is segregated into different working fluids and narrow bins of hydraulic diameter, \(D_h\), mass velocity, \(G\), liquid-only Reynolds number, \(Re_{fg}\), Boiling number, \(Bo\), and reduced pressure, \(P_r\). The new correlation shows very good predictions for most parameter bins, evidenced by MAE values mostly below 20%.

Another measure of the accuracy of the new correlation is the ability to yield evenly good predictions for individual databases comprising the consolidated database. Table 4 compares individual mini/micro-channel databases from 26 sources with predictions of the present correlation as well as select previous correlations that have shown relatively superior predictive capability as discussed earlier. The present correlation provides good predictions for all individual databases with MAE values mostly around 10% and 11 databases predicted more accurately than by any of the select previous correlations. The new correlation also possesses the best overall MAE of 12.5%.

Fig. 6 shows an assessment of the accuracy and limitations of the select previous correlations against hydraulic diameter. Notice that the correlations of Wojtan et al. [65] and Cheng et al. [68]
provide inferior predictions for most diameters below 3 mm. On the other hand, the correlations of Del Col et al. [67] and Mastrullo et al. [61] provide inferior predictions for most diameters above 3 mm. In contrast, the predictive accuracy of the new correlation is not compromised for different diameter bins.

To further explore the accuracy of the present correlation, the effects of different working fluids are examined. Table 5 shows predictions of the present and previous correlations compared to three subsets of the consolidated database: refrigerants, CO2, and water. Notice that, while some of the previous correlations do provide fair predictions for one fluid subset, they generally show poor predictions for other fluid subsets. On the other hand, the new correlation shows the best predictions for all three data subsets, evidenced by MAEs of 17.1% for refrigerants, 11.2% for CO2, and 11.2% for water.

Fig. 7(a)–(d) shows a parametric assessment of the effects of working fluid, heat flux, channel diameter, and saturation pressure, respectively, on dryout incipience quality using the new correlation. Fig. 7(a) shows the predicted dryout incipience quality decreases with increasing mass velocity for FC72, R134a, and CO2, whereas, for water, it increases with increasing mass velocity. Notice in Fig. 7(b) the change in the trend of $G$ vs. $x_{di}$ with increasing heat flux for water: $x_{di}$ increases with increasing $G$ for low heat fluxes but decreases for high heat fluxes. In the same figure, the trend of $G$ vs. $x_{di}$ for R134a is monotonic regardless of heat flux. Fig. 7(c) shows the dryout incipience quality increases with

![Graph showing distribution of MAE in predictions of select previous correlations and present correlation for entire 997 point database relative to hydraulic diameter.](image)

**Table 5**

Assessment of previous correlations and present correlation against consolidated database for refrigerants, CO2, and water.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Refrigerants dryout incipience database (223 points)</th>
<th>CO2 dryout incipience database (110 points)</th>
<th>Water dryout incipience database (664 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAE (%)  $\delta$ (%)  $\zeta$ (%)</td>
<td>MAE (%)  $\theta$ (%)  $\zeta$ (%)</td>
<td>MAE (%)  $\theta$ (%)  $\zeta$ (%)</td>
</tr>
<tr>
<td>Sun (2001) [63]</td>
<td>85.2  20.6  32.7</td>
<td>128.6  0.9  10.0</td>
<td>22.7  78.5  92.9</td>
</tr>
<tr>
<td>Yoon et al. (2004) [64]</td>
<td>– 2.2  2.2</td>
<td>14.6  80.9  98.2</td>
<td>51.1  34.8  56.2</td>
</tr>
<tr>
<td>Wojtan et al. (2005) [65]</td>
<td>27.3  63.7  81.2</td>
<td>40.4  44.5  62.7</td>
<td>75.0  9.3  18.5</td>
</tr>
<tr>
<td>Cheng et al. (2006) [66]</td>
<td>44.8  39.5  62.3</td>
<td>40.8  20.0  73.6</td>
<td>26.7  68.1  94.3</td>
</tr>
<tr>
<td>Del Col et al. (2007) [67]</td>
<td>21.3  74.9  92.8</td>
<td>18.9  80.9  100</td>
<td>26.1  71.4  75.8</td>
</tr>
<tr>
<td>Cheng et al. (2008) [68]</td>
<td>21.0  79.4  93.7</td>
<td>– 0  0</td>
<td>– 0  0</td>
</tr>
<tr>
<td>Jeong and Park (2009) [69]</td>
<td>85.3  16.1  36.3</td>
<td>57.3  30.9  40.9</td>
<td>72.3  5.1  10.7</td>
</tr>
<tr>
<td>Ducoulombier et al. (2011) [56]</td>
<td>32.5  54.7  75.8</td>
<td>22.0  74.5  83.6</td>
<td>33.0  53.2  83.3</td>
</tr>
<tr>
<td>Mastrullo et al. (2012) [61]</td>
<td>36.1  50.2  66.4</td>
<td>19.0  80.0  95.5</td>
<td>20.9  80.0  96.6</td>
</tr>
<tr>
<td>New correlation</td>
<td>17.1  87.9  97.8</td>
<td>11.2  98.2  100</td>
<td>11.2  94.7  97.7</td>
</tr>
</tbody>
</table>

*Dash indicates mean absolute error $\geq$ 100%.
increasing diameter. Fig. 7(d) shows the influence of reduced pressure is not monotonic because of the strong dependence of thermophysical properties in the individual dimensionless parameters of the new correlation on saturation pressure. For both R134a and water, Fig. 7(d) shows $x_{di}$ increasing with increasing saturation pressure up to $P_R = 0.2$ and decreasing for higher pressures.

5. Conclusions

This two-part study examines the development of a generalized approach to predicting heat transfer for flow boiling in mini/micro-channel flows. Boiling heat transfer in small channels is either Nucleate Boiling dominated or Convective Boiling dominated, and the generalized approach must be able to tackle both heat transfer regimes. However, both regimes exhibit substantial reduction in the heat transfer coefficient where partial dryout commences in the annular liquid film, and this occurs upstream of the complete film dryout associated with CHF. Therefore, a systematic generalized heat transfer correlation must address both the Nucleate Boiling dominated and Convective Boiling dominated regimes only up to the location of incipient dryout because of the drastic changes in heat transfer behavior that occur downstream of this location. This points to the need for determining the occurrence of this important transition point. This first part of the study concerns the development of a correlation for dryout incidence quality. This goal is accomplished by first amassing a consolidated database consisting of 997 dryout incipience quality and dryout completion quality data points for 13 fluids from 26 sources. Key findings from the study are as follows:

1. Comparing the consolidated database with predictions of previous dryout incipience correlations shows poor results for certain fluids. By segregating data into three fluid subsets of water, CO$_2$ and refrigerants, it is shown that some of the prior correlations provide fair predictions for one or two fluid subsets, and poor predictions for the other(s).

2. A generalized correlation is proposed for dryout incipience quality in mini/micro-channel flows. This correlation shows excellent predictive capability against the entire consolidated database, with an overall MAE of 12.5%, and 93.6% and 98.0% of the predictions falling within ±30% and ±50% of the data, respectively. The predictive accuracy of the new correlation is also fairly even for the 13 different working fluids, and over broad ranges of all relevant parameters.

Acknowledgment

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