Flow boiling of R-245fa at high saturation temperature (high reduced temperature: $T_{\text{red}} = \frac{T_{\text{sat}}}{T_{\text{crit}}}$): a tool for an improved understanding of the thermohydraulics of boiling refrigerants in micro-, mini- and macrochannels

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Why should we study flow boiling at high (reduced) temperature?

Improved energy efficiency of vehicles equipped with internal combustion engine:

- Conversion of exhaust gas heat to electricity

Organic Rankine Cycles (ORC) are an option

- A promising working fluid: R-245fa
- Exhaust gas temperatures: $400 – 900^\circ\text{C}$
- Refrigerant evaporation temperature > $100^\circ\text{C}$

(critical temperature ~ $155^\circ\text{C}$ : $T/T_{\text{crit}}$ ~0.7 – 0.9)
**Why should we study flow boiling at high (reduced) temperature?**

Prediction models or correlations cannot be accurately extrapolated to...

- **Different fluids** (change of properties: $\mu$, $\rho$, $\sigma$)
- **Different geometries**
- **Different thermodynamic conditions** ($P$, $T$)

In addition, studying boiling at high temperature may bring new insights into the physics of flow boiling (unconventional variation of fluid properties when getting closer to the critical point).
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A current issue in flow boiling: “macrochannels vs. microchannels”

- Confinement effect (Kandlikar (2005))

- Stratification of the flow (Revellin et al. (2006))
**State of the art review**

**Transition from macrochannels to microchannels**

- **Geometrical (practical) approach** : Kandlikar (2002)
  - Conventional channels : $d_h > 3 \text{ mm}$
  - Minichannels : $d_h = 200 \mu\text{m} - 3 \text{ mm}$
  - Microchannels : $d_h = 10 \mu\text{m} - 200 \mu\text{m}$

- **Mechanical forces** : buoyancy vs. surface tension

Capillary length, Confinement number, Eötvos number or Bond number: Kew and Cornwell (1997), Li and Wang (2003), Cheng and Wu (2006), Ullman and Brauner (2007), Ong and Thome (2011), ...

\[
l_{cap} = \sqrt{\frac{\sigma}{g \cdot (\rho_L - \rho_V)}} \quad C_o = \frac{1}{d_h} \cdot \sqrt{\frac{\sigma}{g \cdot (\rho_L - \rho_V)}} \quad E_\text{o} = \frac{g \cdot (\rho_L - \rho_V) \cdot l_c^2}{8 \cdot \sigma} \quad B_d = \frac{g \cdot (\rho_L - \rho_V) \cdot d_h^2}{\sigma}
\]
## Transition from macrochannels to microchannels

<table>
<thead>
<tr>
<th>Authors</th>
<th>Diameters</th>
<th>Eötvos number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kew and Cornwell (1997)</td>
<td>$d_{th} = 2 \cdot l_{cap}$</td>
<td>$Eö = 4$</td>
</tr>
<tr>
<td>Ong and Thome (2011)</td>
<td>$d_{th} = 2.94 \cdot l_{cap}$</td>
<td>$Eö = 8.65$</td>
</tr>
<tr>
<td></td>
<td>$d_{crit} = 1 \cdot L_{cap}$</td>
<td>$Eö = 1$</td>
</tr>
<tr>
<td>Cheng and Wu (2006)</td>
<td>$d_{th} = 1.73 \cdot l_{cap}$</td>
<td>$Eö = 3$</td>
</tr>
<tr>
<td></td>
<td>$d_{crit} = 0.224 \cdot L_{cap}$</td>
<td>$Eö = 0.05$</td>
</tr>
<tr>
<td>Ullman and Brauner (2007)</td>
<td>$d_{th} = 0.4 \cdot l_{cap}$</td>
<td>$Eö = 0.16$</td>
</tr>
<tr>
<td>Harirchian and Garimella (2010)</td>
<td>$d_{th} = (160/Re_{LO}) \cdot l_{cap}$</td>
<td>$Eö = (160/Re_{LO})^2$</td>
</tr>
<tr>
<td>Li and Wang (2003)</td>
<td>$d_{th} = 1.75 \cdot l_{cap}$</td>
<td>$Eö = 3.06$</td>
</tr>
<tr>
<td></td>
<td>$d_{crit} = 0.224 \cdot L_{cap}$</td>
<td>$Eö = 0.05$</td>
</tr>
</tbody>
</table>
Macro-to-microscale transition with R-245fa

State of the art review

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What is the influence of the saturation temperature?

R-245fa; \( d_h = 3.0 \text{ mm} \); \( G = 200 \text{ kg/m}^2\cdot\text{s} \); \( x = 0.5 \)

<table>
<thead>
<tr>
<th>( T_{\text{sat}} ) [°C]</th>
<th>( \sigma ) [mN/m]</th>
<th>( \frac{\rho_v}{\rho_L} )</th>
<th>( Bd = \frac{g \cdot (\rho_L - \rho_v) \cdot d_h^2}{\sigma} )</th>
<th>( Fr = \frac{G^2}{g \cdot d_h \cdot \rho_{TP}^2} )</th>
<th>( We_L = \frac{\rho_L \cdot u_L^2 \cdot d_h}{\sigma} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>9.59</td>
<td>0.02</td>
<td>11.1</td>
<td>548.9</td>
<td>2.52</td>
</tr>
<tr>
<td>120</td>
<td>2.64</td>
<td>0.12</td>
<td>29.3</td>
<td>30.8</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- The saturation temperature widely influences the liquid-vapor interactions and thus the flow patterns and the heat transfer mechanisms.

- Studying flow boiling at high temperature appears as a promising tool for an improved understanding of the macro-to-microscale transition.
Flow patterns

- No consensus on two-phase flow regime definitions
- Thome et al. (2013) defined five primary flow regimes

**Intermittent flows**

- Bubbly flow
- Slug flow
- Stratified flow (also named dryout flow)
- Annular flow
- Mist flow
State of the art review

**Flow patterns characterization**

Flow pattern characterization techniques based on **quantitative criteria**:

- **Non-contact measurement techniques**
  - **Opaque tubes**:
    - X-rays: *Jones and Zuber (1975)*
  - **Transparent tubes**:
    - Optical measurement: *Ursenbacher et al. (2004)*, *Revellin et al. (2006)*
    - Image processing: *Zhang et al. (2010)*, *Hanafizadeh et al. (2011)*

- **Contact measurement techniques**
  - **Direct methods**:
    - Hot-film anemometer: *Serizawa et al. (1975)*
    - Conductance probe: *Barnea et al. (1980)*
  - **Indirect methods**:
    - Pressure sensor: *Matsui (1984, 1986)*
    - Capacitance sensor: *Canière et al. (2010)*, *Narcy et al. (2014)*
State of the art review

**Flow patterns**

Final processed images in a 2.0 mm ID for air-water, Hanafizadeh et al., 2011

Detecting bubble passages using capacitive sensors (R-410A, 15°C, Canière et al. 2010)
State of the art review

Influence of the saturation temperature on the flow patterns

- Few studies on the effect of saturation temperature on the two-phase flow structure
- Some evidences suggest that the saturation temperature may be an important factor:

State of the art review

Flow pattern map

Comparison between the experimental data of Arcanjo et al. (2010) and the predictive methods by Ong and Thome (2009) and Revellin et al. (2006)

$R_{-245fa} - d_h = 2.32 \text{ mm}$

$T_{sat} = 22^\circ C$

$T_{sat} = 41^\circ C$

The current models for flow regime transition are almost not sensitive to the effect of saturation temperature, contrary to the experimental results.
Two mechanisms are usually assumed to govern flow boiling heat transfer:

- The nucleate boiling (NB) ↔ formation of bubbles at the wall
- The convective boiling (CB) ↔ conduction and convection (liquid film) evaporation at the liquid-vapor interface

These mechanisms were related to heat transfer coefficient (\(\alpha\)):

- When NB is dominant, \(\alpha = f(q, T_{\text{sat}})\) & \(\alpha \neq f(G, x)\)
- When CB is dominant, \(\alpha = f(G,x)\) & \(\alpha \neq f(q)\)
- When NB and CB are equally important, \(\alpha = f(G,q,x)\)
Heat transfer

Typical trends of heat transfer coefficient observed with **nucleate** and **convective boiling** dominant regions.
State of the art review

Heat transfer

Influence of saturation temperature on the heat transfer coefficient

Two cases of NB dominated heat transfer, but opposite trends of variation of heat transfer with saturation temperature
### Heat transfer

#### Influence of saturation temperature

<table>
<thead>
<tr>
<th>Author</th>
<th>Fluid</th>
<th>Geometry</th>
<th>$d_h$ [mm]</th>
<th>$\dot{q}$ [kW/m$^2$]</th>
<th>$G$ [kg/m$^2$.s]</th>
<th>$T_{sat}$ [°C]</th>
<th>$x$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Greco and Vanoli (2005)]</td>
<td>R-410A/R-404A</td>
<td>circular</td>
<td>6.0</td>
<td>11-39</td>
<td>290-1100</td>
<td>-15-23.5</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>[Da Silva Lima et al. (2009)]</td>
<td>R-134a</td>
<td>circular</td>
<td>13.84</td>
<td>7.5-17.5</td>
<td>300-500</td>
<td>5-20</td>
<td>0.01-0.99</td>
</tr>
<tr>
<td>[Del Col (2010)]</td>
<td>(*)</td>
<td>circular</td>
<td>8.0</td>
<td>9-53</td>
<td>200-600</td>
<td>25-45</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>[Tibiricá and Ribatski (2010)]</td>
<td>R-134a/R-245fa</td>
<td>circular</td>
<td>2.3</td>
<td>5-55</td>
<td>50-700</td>
<td>31-68</td>
<td>0.05-0.99</td>
</tr>
<tr>
<td>[Agostini et al. (2008)]</td>
<td>R-245fa</td>
<td>rectangular</td>
<td>0.336</td>
<td>36-1900</td>
<td>281-1501</td>
<td>24-44</td>
<td>0.15-1.0</td>
</tr>
<tr>
<td>[Vakili-Farahani et al. (2013)]</td>
<td>R-245fa/R-1234ze</td>
<td>rectangular</td>
<td>1.3-1.45</td>
<td>3-107</td>
<td>50-400</td>
<td>30-70</td>
<td>0.1-1.0</td>
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<tr>
<td>[Ong and Thome (2011b)]</td>
<td>(**)</td>
<td>channel</td>
<td>1.03-3.04</td>
<td>4.8-221.5</td>
<td>200-1290</td>
<td>31-35</td>
<td>0-1.0</td>
</tr>
<tr>
<td>[Ali et al. (2011)]</td>
<td>R-134a</td>
<td>circular</td>
<td>1.70</td>
<td>2-156</td>
<td>50-600</td>
<td>27-32</td>
<td>0-1.0</td>
</tr>
<tr>
<td>[Basu et al. (2011)]</td>
<td>R-134a</td>
<td>circular</td>
<td>0.5-1.6</td>
<td>0-350</td>
<td>300-1500</td>
<td>15-45</td>
<td>0-1.0</td>
</tr>
<tr>
<td>[Grauso et al. (2013)]</td>
<td>CO$_2$/R-410A</td>
<td>circular</td>
<td>6.0</td>
<td>5-20</td>
<td>150-500</td>
<td>5-42</td>
<td>0-1.0</td>
</tr>
<tr>
<td>[Saisorn et al. (2010b)]</td>
<td>R-134a</td>
<td>circular</td>
<td>1.75</td>
<td>1-83</td>
<td>200-1000</td>
<td>31-50</td>
<td>0-0.95</td>
</tr>
<tr>
<td>[Choi et al. (2007b)]</td>
<td>CO$_2$</td>
<td>circular</td>
<td>1.5-3</td>
<td>20-40</td>
<td>200-600</td>
<td>-10-10</td>
<td>0-1.0</td>
</tr>
<tr>
<td>[Kaew-On and Wongwis (2009)]</td>
<td>R-410A</td>
<td>rectangular</td>
<td>3.48</td>
<td>5-14.25</td>
<td>200-400</td>
<td>10-30</td>
<td>0-1.0</td>
</tr>
</tbody>
</table>

(*) R-22/R-134a/R-125/R-410A  
(**) R-134a/R-236fa/R-245fa

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Need to investigate a different range of temperatures
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Experimental setup and test section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{in}$ [mm]</td>
<td>3.00</td>
</tr>
<tr>
<td>$L_{evap}$ [mm]</td>
<td>185.0</td>
</tr>
<tr>
<td>q [kW/m$^2$]</td>
<td>10 – 90 ± 2-5 %</td>
</tr>
<tr>
<td>G [kg/m$^2$.s]</td>
<td>100 – 1500 ± 2 %</td>
</tr>
<tr>
<td>$T_{sat}$ [°C]</td>
<td>60 – 120 ± 0.2 – 0.8</td>
</tr>
<tr>
<td>$P_{sat}$ [bar]</td>
<td>4.4 – 19.2</td>
</tr>
<tr>
<td>x [-]</td>
<td>0 – 1</td>
</tr>
</tbody>
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Results on flow patterns

Flow pattern characterization

Four observed flow patterns

- Intermittent flow
- Annular flow
- Dryout flow
- Mist flow
Influence of $T_{\text{sat}}$ on the flow pattern

$G = 300 \text{ kg/m}^2\text{s}, \ q = 50 \text{ kW/m}^2, \ x = 0.15$

- $T_{\text{sat}} = 60^\circ \text{C}$
  Annular flow – $f = 0 \text{ Hz}$

- $T_{\text{sat}} = 120^\circ \text{C}$
  Intermittent flow – $f = 78 \text{ Hz}$
Results on flow patterns

Influence of $T_{\text{sat}}$ on the flow pattern

$G = 300 \, \text{kg/m}^2\text{s}, \quad q = 50 \, \text{kW/m}^2, \quad x = 0.30$

$T_{\text{sat}} = 60^\circ\text{C}$
Annular flow – $f = 0 \, \text{Hz}$

$T_{\text{sat}} = 120^\circ\text{C}$
Intermittent flow – $f = 41 \, \text{Hz}$
Results on flow patterns

Flow pattern characterization from heat transfer coefficient behavior

![Diagram showing flow patterns and temperature variations](image-url)
The higher the $T_{sat}$, the lower the vapor quality corresponding to mist flow regime inception.

The higher the $T_{sat}$, the lower the vapor quality corresponding to dryout flow regime inception.

The higher the $T_{sat}$, the narrower the range of vapor quality corresponding to annular flow whereas the larger the range of vapor quality for intermittent flow.
Results on flow patterns

Influence of $T_{\text{sat}}$ on the flow pattern

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$x$ Value</th>
<th>Flow Pattern</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 60°C$</td>
<td>0.16</td>
<td>Annular flow</td>
<td>$f = 0.0$ Hz</td>
</tr>
<tr>
<td>$T = 80°C$</td>
<td>0.17</td>
<td>Intermittent flow</td>
<td>$f = 24$ Hz</td>
</tr>
<tr>
<td>$T = 100°C$</td>
<td>0.16</td>
<td>Intermittent flow</td>
<td>$f = 55$ Hz</td>
</tr>
<tr>
<td>$T = 120°C$</td>
<td>0.16</td>
<td>Intermittent flow</td>
<td>$f = 36.5$ Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$x$ Value</th>
<th>Flow Pattern</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 60°C$</td>
<td>0.26</td>
<td>Annular flow</td>
<td>$f = 0.0$ Hz</td>
</tr>
<tr>
<td>$T = 80°C$</td>
<td>0.26</td>
<td>Intermittent flow</td>
<td>$f = 5.5$ Hz</td>
</tr>
<tr>
<td>$T = 100°C$</td>
<td>0.27</td>
<td>Intermittent flow</td>
<td>$f = 9$ Hz</td>
</tr>
<tr>
<td>$T = 120°C$</td>
<td>0.28</td>
<td>Intermittent flow</td>
<td>$f = 38$ Hz</td>
</tr>
</tbody>
</table>

Symbols:
- $T_{\text{sat}}$: Saturation Temperature
- $\sigma$: Surface Tension
- $d_{\text{bub}}$: Bubble Diameter
- $\rho_{\text{vap}}$: Vapour Density
- Bubble Length

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Results on flow patterns

Influence of $T_{\text{sat}}$ on the flow pattern

$T = 60^\circ C; \ x=0.16$: annular flow - $f = 0.0$ Hz

$T = 80^\circ C; \ x=0.17$: intermittent flow - $f = 24$ Hz

$T = 100^\circ C; \ x=0.16$: intermittent flow - $f = 55$ Hz

$T = 120^\circ C; \ x=0.16$: intermittent flow - $f = 36.5$ Hz

$T = 60^\circ C; \ x=0.26$: annular flow - $f = 0.0$ Hz

$T = 80^\circ C; \ x=0.26$: intermittent flow - $f = 5.5$ Hz

$T = 100^\circ C; \ x=0.27$: intermittent flow - $f = 9$ Hz

$T = 120^\circ C; \ x=0.28$: intermittent flow - $f = 38$ Hz

$T_{\text{sat}} \uparrow \quad \sigma \downarrow \quad \text{Bd} = \frac{g(\rho_L - \rho_v)d^2}{\sigma} \uparrow \quad \text{stratification} \uparrow$

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Results on heat transfer

**Influence of mass velocity**

$T_{\text{sat}} = 60^\circ\text{C}$

<table>
<thead>
<tr>
<th>$G$ (kg/m².s)</th>
<th>Heat transfer coefficient [W/m².K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

Typical of flow boiling at « low » temperature e.g. refrigerants in A/C or refrigeration evaporators

Low G

High G
Results on heat transfer

Influence of mass velocity

$T_{sat} = 120^\circ C$

**Low G**
- $G = 500$ kg/m².s
- $G = 700$ kg/m².s

**High G**
- $G = 1000$ kg/m².s

![Diagram showing heat transfer coefficient vs. vapor quality for different mass velocities and flow patterns. The diagram includes symbols for different flow conditions and saturation temperature of 120°C.](image-url)
Influence of saturation temperature

\[ T_{\text{sat}} = 120^\circ C \]

\[ T_{\text{sat}} = 100^\circ C \]

\[ T_{\text{sat}} = 80^\circ C \]

\[ T_{\text{sat}} = 60^\circ C \]

Results on heat transfer

\[ G = 300 \text{ kg/m}^2\text{s} \]
Influence of saturation temperature

Results on heat transfer

\[ G = 300 \text{ kg/m}^2\cdot\text{s} \]

\[ T_{\text{sat}} = 120^\circ \text{C} \]

\[ T_{\text{sat}} = 100^\circ \text{C} \]

\[ T_{\text{sat}} = 80^\circ \text{C} \]

\[ T_{\text{sat}} = 60^\circ \text{C} \]

R-245fa
Inner tube diameter = 3.0 mm
Heat flux = 50 kW/m²
Mass velocity = 300 kg/m²·s

High \( T_{\text{sat}} \)

Low \( T_{\text{sat}} \)
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Conclusions

The main conclusions on the influence of the saturation temperature on the flow patterns and the heat transfer are:

- The higher $T_{\text{sat}}$, the smaller and shorter the bubbles
- The higher $T_{\text{sat}}$, the greater the tendency to flow stratification
- The higher $T_{\text{sat}}$, the lower the value of vapor quality for dry-out inception
- The higher $T_{\text{sat}}$, the greater the flow boiling heat transfer coefficient
- The higher $T_{\text{sat}}$, the greater the contribution of nucleate boiling to the overall heat transfer coefficient
- The higher $T_{\text{sat}}$, the lower the contribution of convective boiling to the overall heat transfer coefficient

Such information must be taken into account when designing evaporators for Organic Rankine Cycles and other cycles with evaporation at high reduced temperature.
Conclusions

Such a work on influence of the saturation temperature led us to **re-investigate the concept of micro-, mini- and macrochannels.**

**Channels** for flow boiling are not « micro- », « mini- » or « macrochannels ».

The **variety of flow boiling regimes and flow boiling heat transfer mechanisms** depend on a complex combination of **inertia, buoyancy and surface tensions forces**, that are also linked to the channel diameter.

When **Fr decreases** and/or **Bd increases** intermitent flow becomes more and more likely than annular flow stratification (asymetry) is promoted.