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Flow boiling of R-245fa at high saturation temperature (high reduced temperature: Tred = Tsat / Tcrit): a tool for an improved understanding of the thermohydraulics of boiling refrigerants in micro-, mini- and macrochannels

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- **Conclusions**

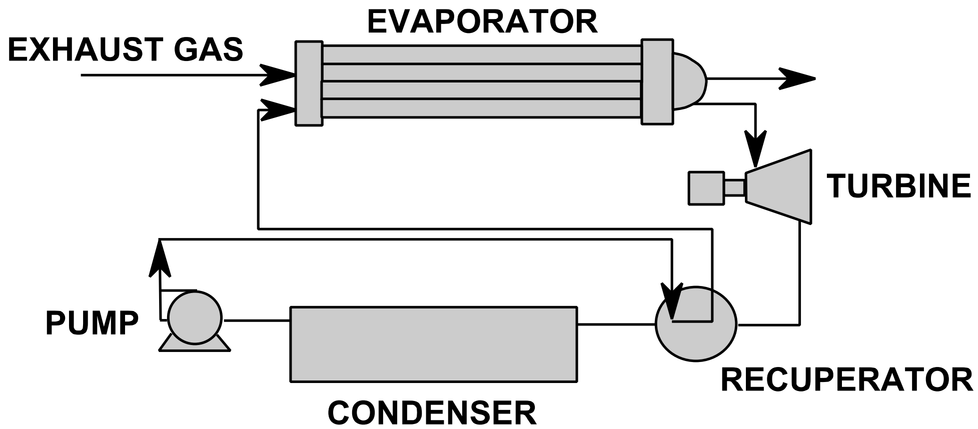
Introduction

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**
- Exhauxt gas temperatures**: 400 – 900°C**
- Refrigerant evaporation temperature **> 100°C**

(critical temperature ~ 155°C : T/Tcrit ~0.7 – 0.9)

Introduction

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

Prediction models or correlations **cannot be accurately extrapolated** to…

Different fluids (change of properties : μ, ρ, σ)	**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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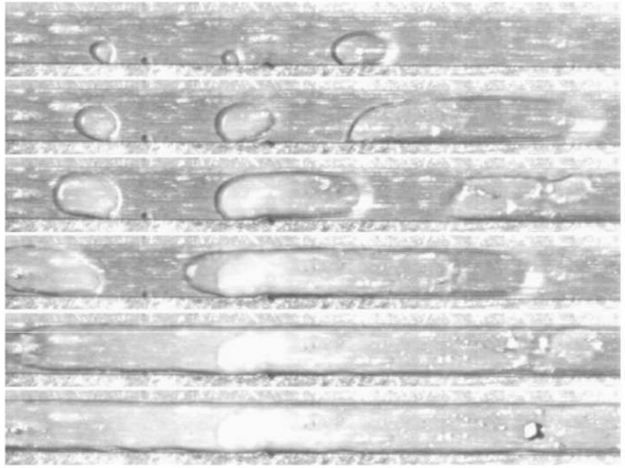
State of the art review

A current issue in flow boiling : "macrochannels vs. microchannels"

- Confinement effect (Kandlikar (2005))



- Stratification of the flow (Revellin et al. (2006))

2.0 mm 0.8 mm 0.5 mm

State of the art review

Transition from macrochannels to microchannels

- **Geometrical (practical) approach** : Kandlikar (2002)
  - **Conventional channels : d_h > 3 mm**
  - **Minichannels : d_h = 200 µm - 3 mm**
  - **Microchannels : d_h = 10 µm - 200 µm**

- **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), …

$$l_{cap} = \sqrt{\frac{\sigma}{g \cdot (\rho_L - \rho_V)}} \qquad Co = \frac{1}{d_h} \cdot \sqrt{\frac{\sigma}{g \cdot (\rho_L - \rho_V)}} \qquad E\ddot{o} = \frac{g \cdot (\rho_L - \rho_V) \cdot l_c^2}{8 \cdot \sigma} \qquad Bd = \frac{g \cdot (\rho_L - \rho_V) \cdot d_h^2}{\sigma}$$

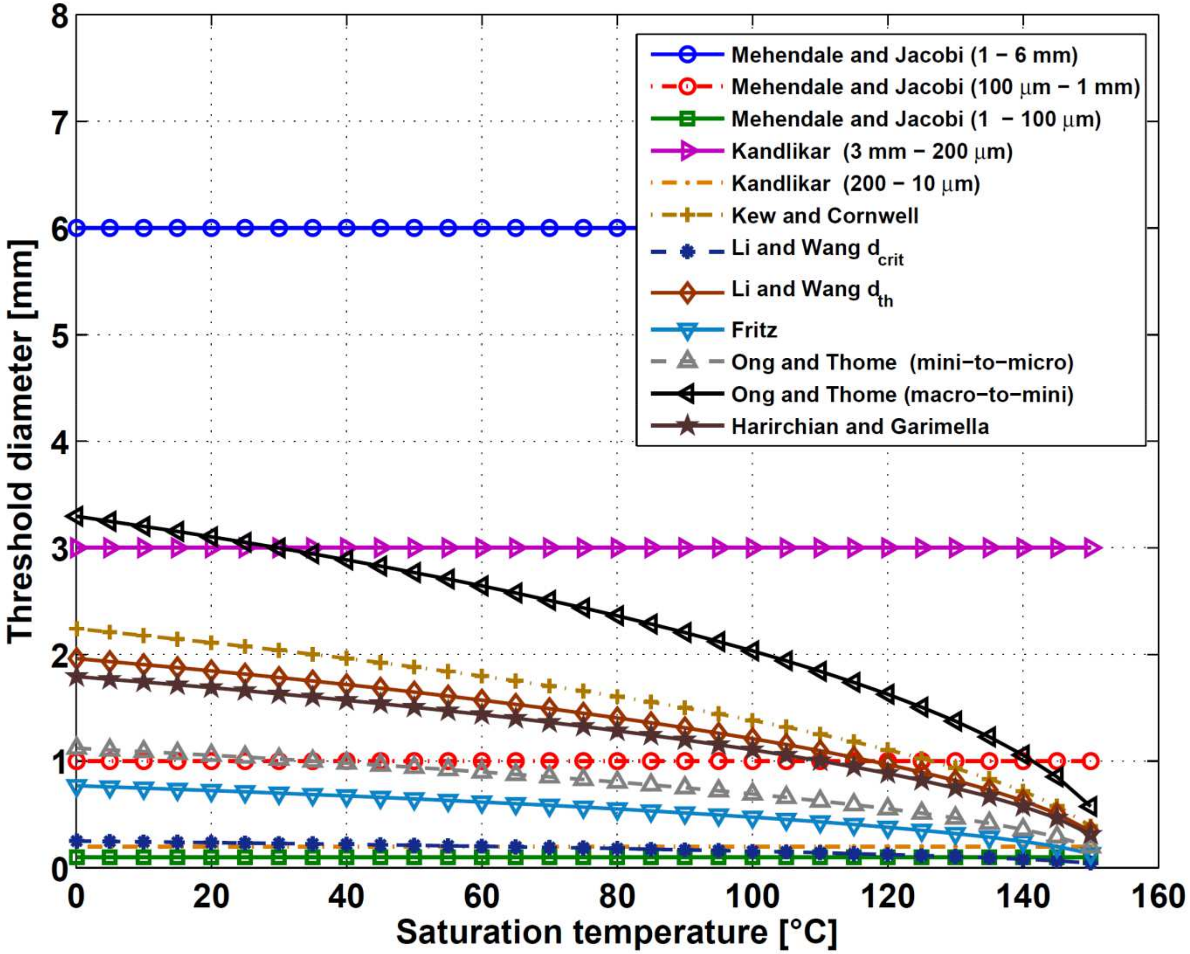
State of the art review

Transition from macrochannels to microchannels

Authors	Diameters	Eötvos number
Kew and Cornwell (1997)	$d_{th} = 2 \, . \, l_{cap}$	$Eö = 4$
Ong and Thome (2011)	$d_{th} = 2.94 \, . \, l_{cap}$ $d_{crit} = 1 \, . \, L_{cap}$	$Eö = 8.65$ $Eö = 1$
Cheng and Wu (2006)	$d_{th} = 1.73 \, . \, l_{cap}$ $d_{crit} = 0.224 \, . \, L_{cap}$	$Eö = 3$ $Eö = 0.05$
Ullman and Brauner (2007)	$d_{th} = 0.4 \, . \, l_{cap}$	$Eö = 0.16$
Harirchian and Garimella (2010)	$d_{th} = (160/Re_{LO}) \, . \, l_{cap}$	$Eö = (160/Re_{LO})^2$
Li and Wang (2003)	$d_{th} = 1.75 \, . \, l_{cap}$ $d_{crit} = 0.224 \, . \, L_{cap}$	$Eö = 3.06$ $Eö = 0.05$

State of the art review

Macro-to-microscale transition with R-245fa



State of the art review

What is the influence of the saturation temperature ?

R-245fa ; d_h = 3.0 mm ; G = 200 kg/m².s ; x = 0.5

T_{sat} [°C]	σ [mN/m]	$\frac{\rho_V}{\rho_L}$	$Bd = \frac{g \cdot (\rho_L - \rho_V) \cdot d_h^2}{\sigma}$	$Fr = \frac{G^2}{g \cdot d_h \cdot \rho_{TP}^2}$	$We_L = \frac{\rho_L \cdot u_L^2 \cdot d_h}{\sigma}$
60	9.59	0.02	11.1	548.9	2.52
120	2.64	0.12	29.3 ↗	30.8 ↘	11.3 ↗

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

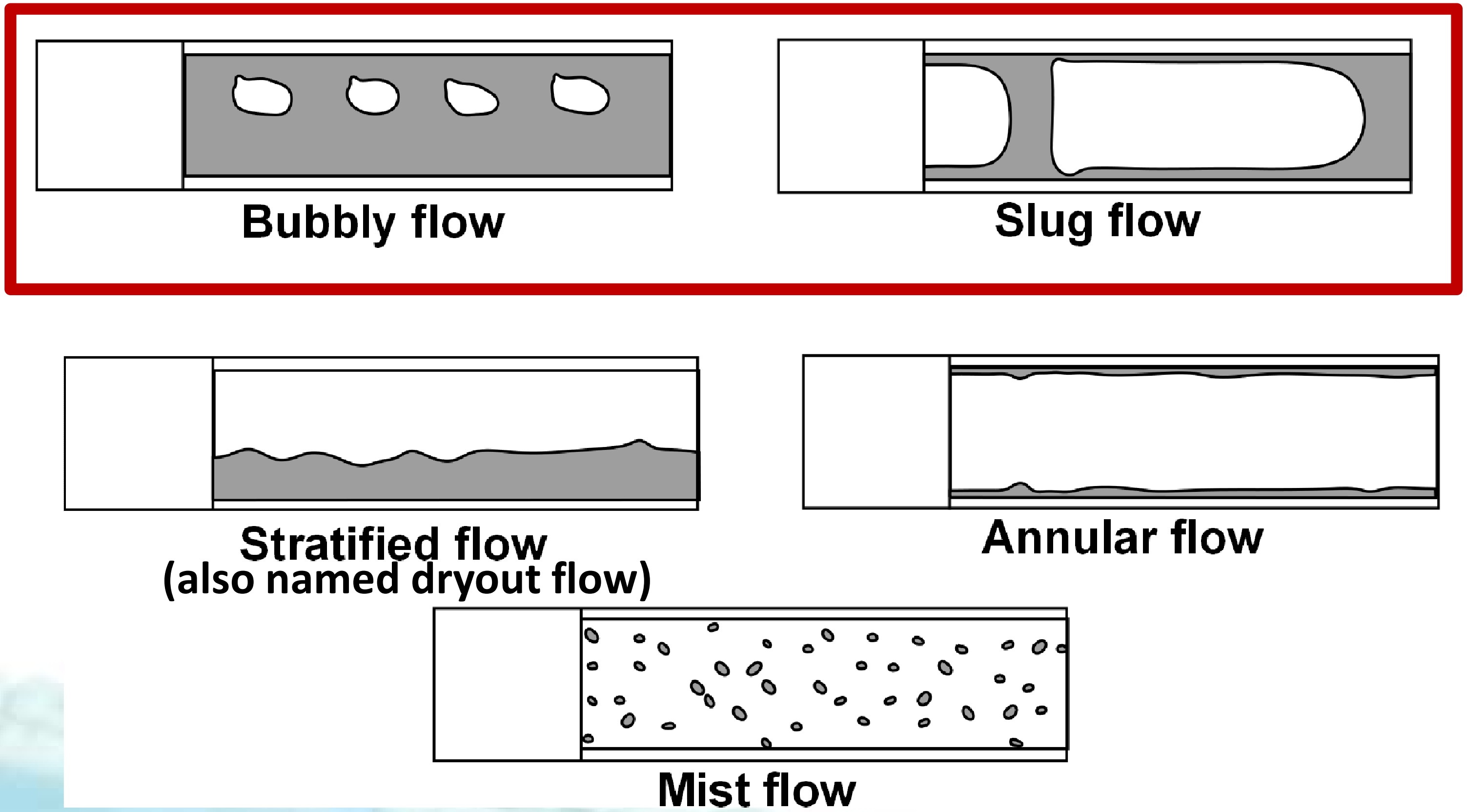
➢ **Studying flow boiling at high temperature appears as a promising tool for an improved understanding of the macro-to-microscale transition**

State of the art review

Flow patterns

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

Intermittent flows



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)*

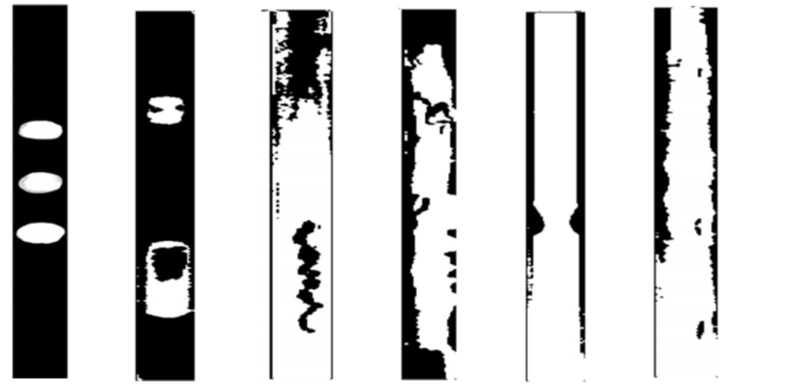
Contact measurement techniques

- **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)*

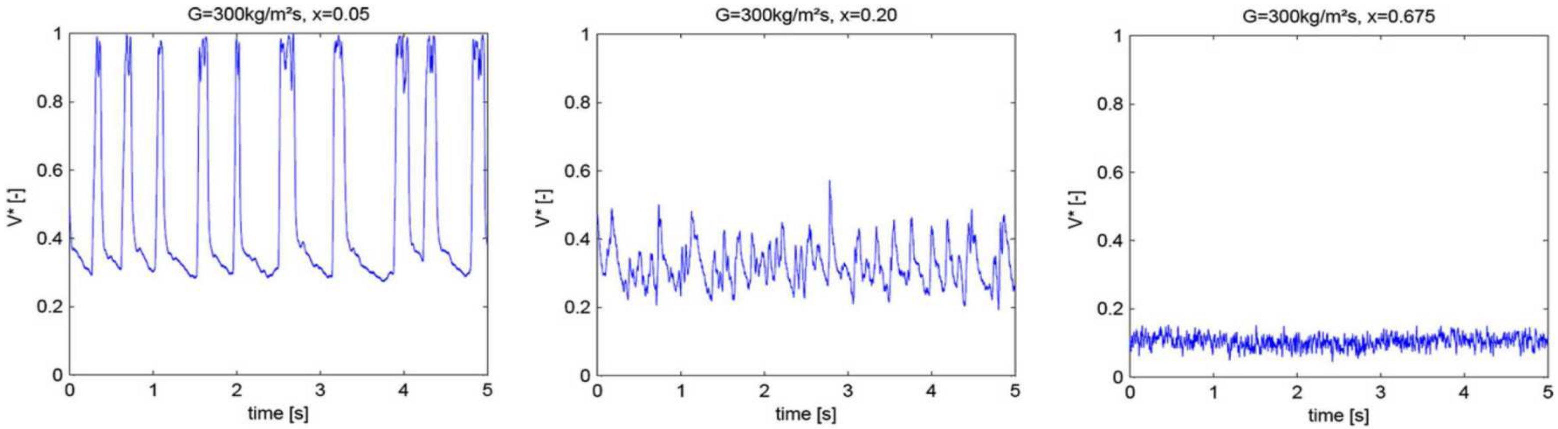
State of the art review

Flow patterns

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



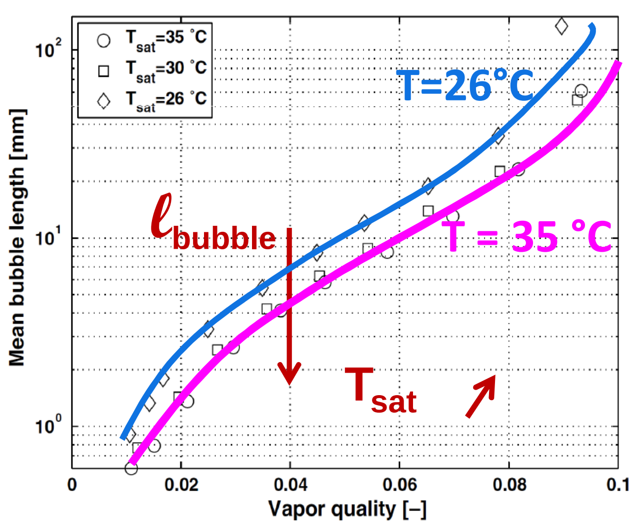
Detecting bubble passages using capacitive sensors (R-410A, 15℃ , Canière et al. 2010)



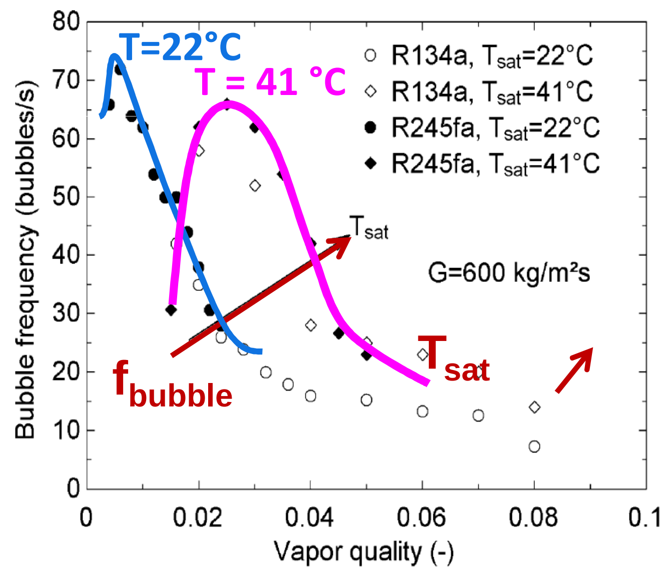
Slug flow Bubbly flow Annular flow

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**:



Revellin et al. (2008)



Arcanjo et al. (2010)

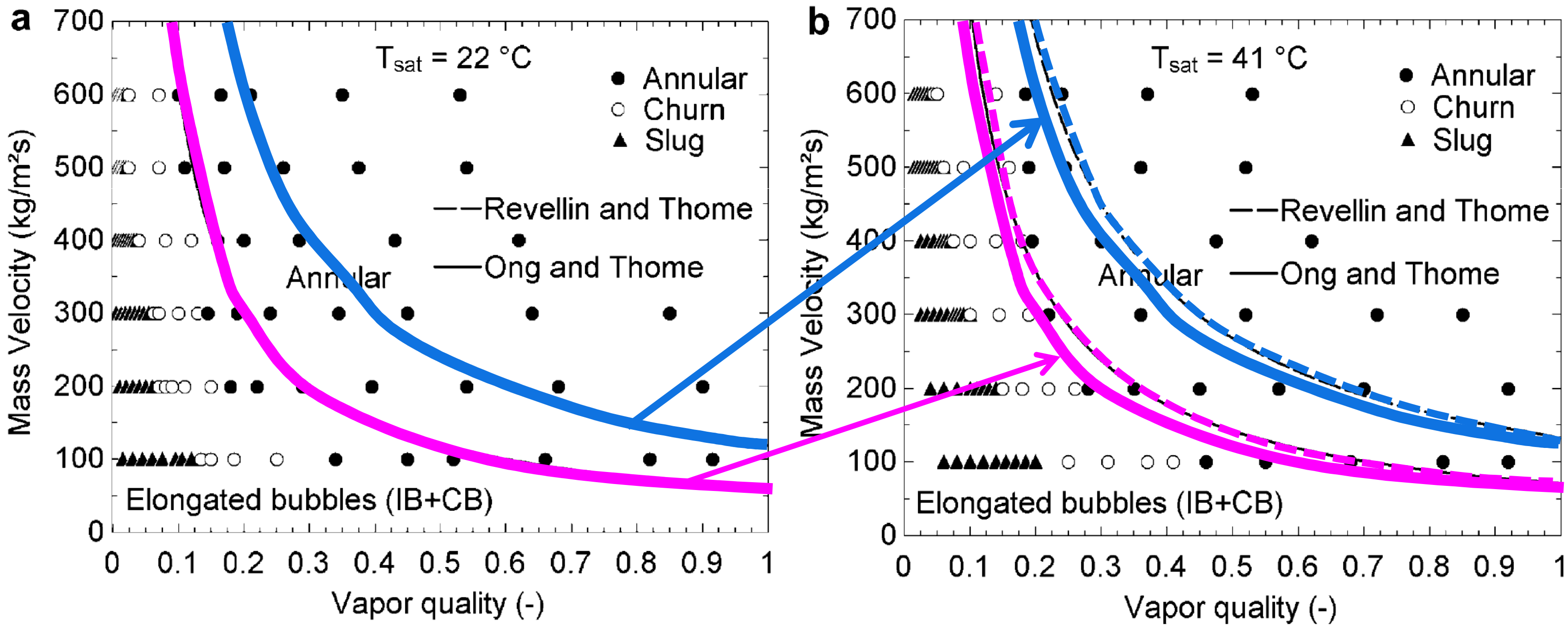
State of the art review

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 mm

T_{sat} = 22°C T_{sat} = 41°C



The current models for flow regime transition are almost not sensitive to the effect of saturation temperature, contrary to the experimental results

State of the art review

Heat transfer

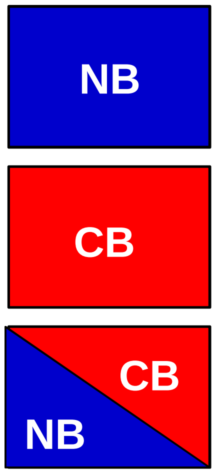
Two mechanisms are usually assumed to govern flow boiling heat transfer:

- 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 (**α**):

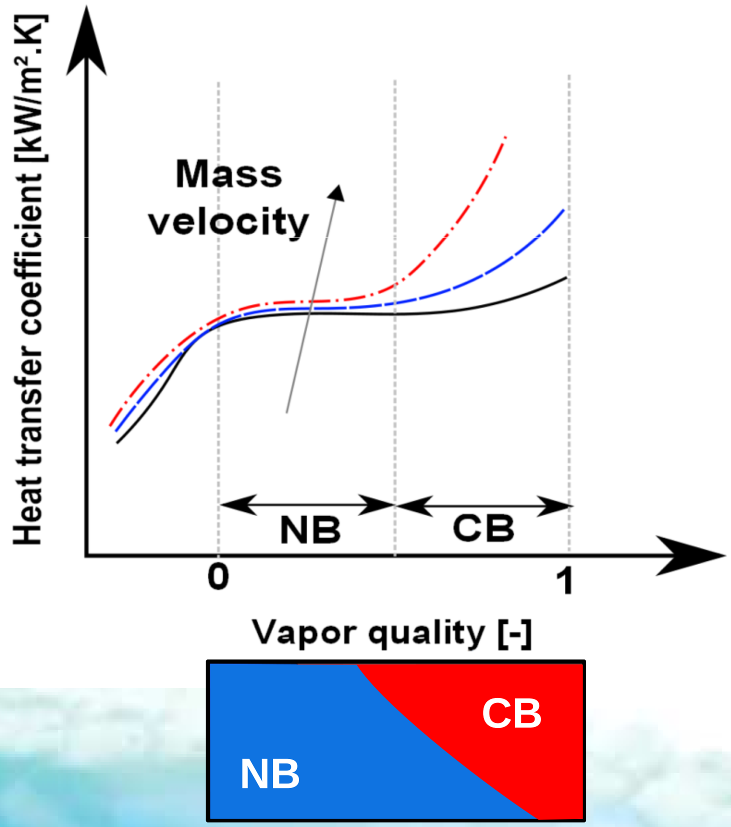
- When **NB** is **dominant**, **$\alpha = f(q, T_{sat})$ & $\alpha \neq f(G, x)$**
- When **CB** is **dominant**, **$\alpha = f(G,x)$ & $\alpha \neq f(q)$**
- When **NB** and **CB** are **equally important**, **$\alpha = f(G,q,x)$**

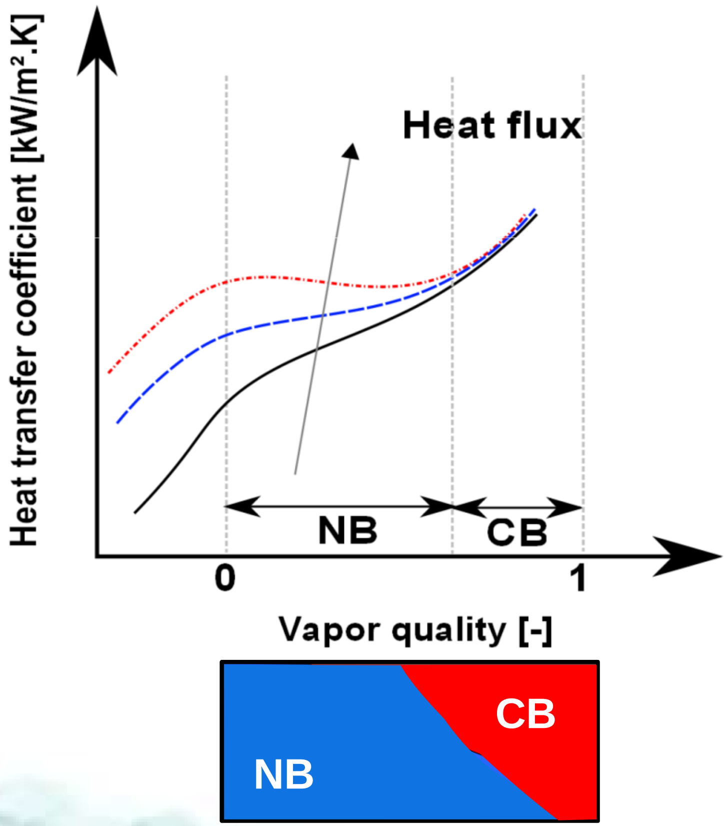


State of the art review

Heat transfer

Typical trends of heat transfer coefficient observed with **nucleate** and **convective boiling** dominant regions

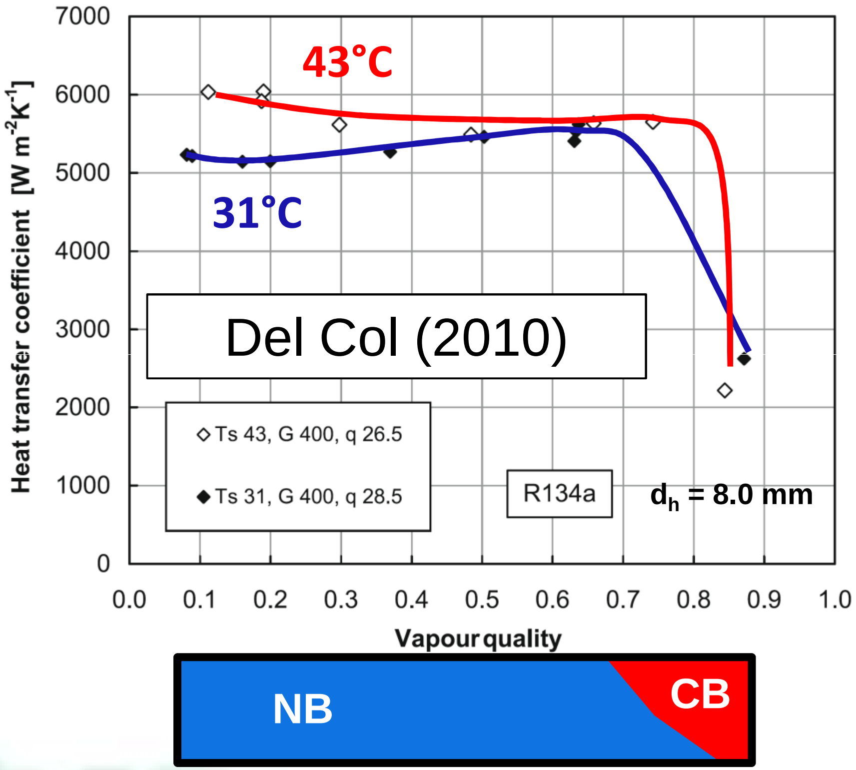


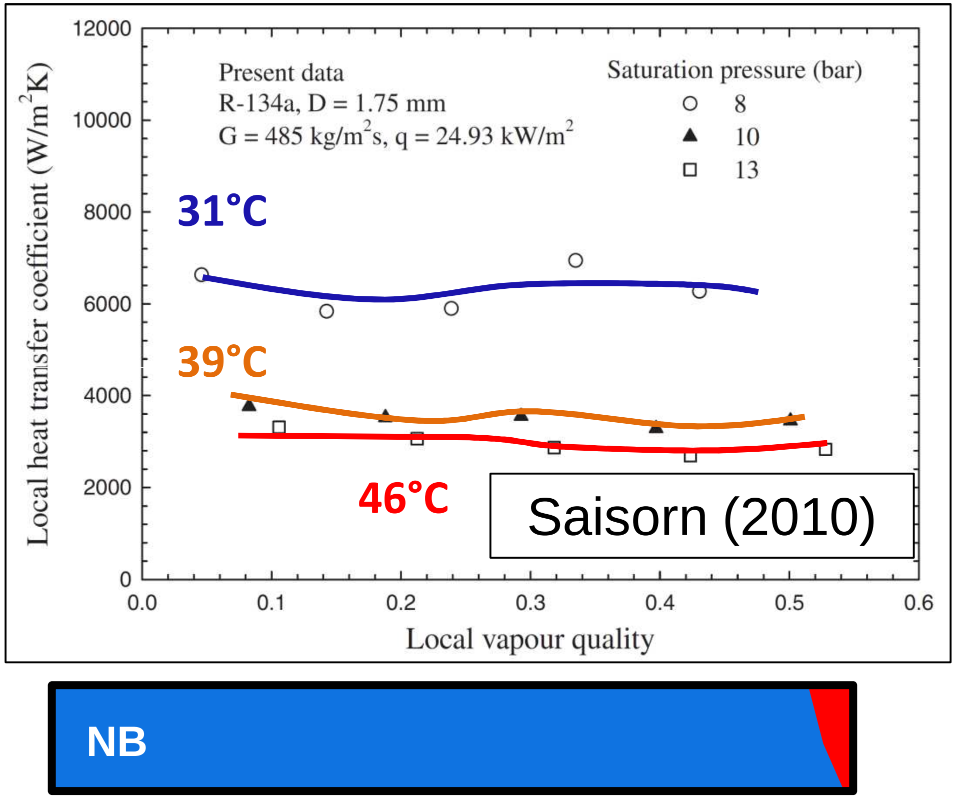


State of the art review

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

State of the art review

Heat transfer

Influence of saturation temperature

Author	Fluid	Geometry	d_h [mm]	$\dot{q}$ [kW/m^2]	G [kg/m^2·s]	T_{sat} [°C]	x [-]
[Greco and Vanoli (2005)]	R-410A/R-404A	circular	6.0	11-39	290-1100	-15-23.5	0-1.0
[Da Silva Lima et al. (2009)]	R-134a	circular	13.84	7.5-17.5	300-500	5-20	0.01-0.99
[Del Col (2010)]	(*)	circular	8.0	9-53	200-600	25-45	0-1.0
[Tibiricá and Ribatski (2010)]	R-134a/R-245fa	circular	2.3	5-55	50-700	31-68	0.05-0.99
[Agostini et al. (2008)]	R-245fa	rectangular	0.336	36-1900	281-1501	24-44	0.15-1.0
[Vakili-Farahani et al. (2013)]	R-245fa/R-1234ze	rectangular	1.3-1.45	3-107	50-400	30-70	0-1.0
[Ong and Thome (2011b)]	(**)	channel	1.03-3.04	4.8-221.5	200-1290	31-35	0-1.0
[Ali et al. (2011)]	R-134a	circular	1.70	2-156	50-600	27-32	0-1.0
[Basu et al. (2011)]	R-134a	circular	0.5-1.6	0-350	300-1500	15-45	0-1.0
[Grauso et al. (2013)]	CO_2/R-410A	circular	6.0	5-20	150-500	5-42	0-1.0
[Saisorn et al. (2010b)]	R-134a	circular	1.75	1-83	200-1000	31-50	0-0.95
[Choi et al. (2007b)]	CO_2	circular	1.5-3	20-40	200-600	-10-10	0-1.0
[Kaew-On and Wongwises (2009)]	R-410A	rectangular	3.48	5-14.25	200-400	10-30	0-1.0

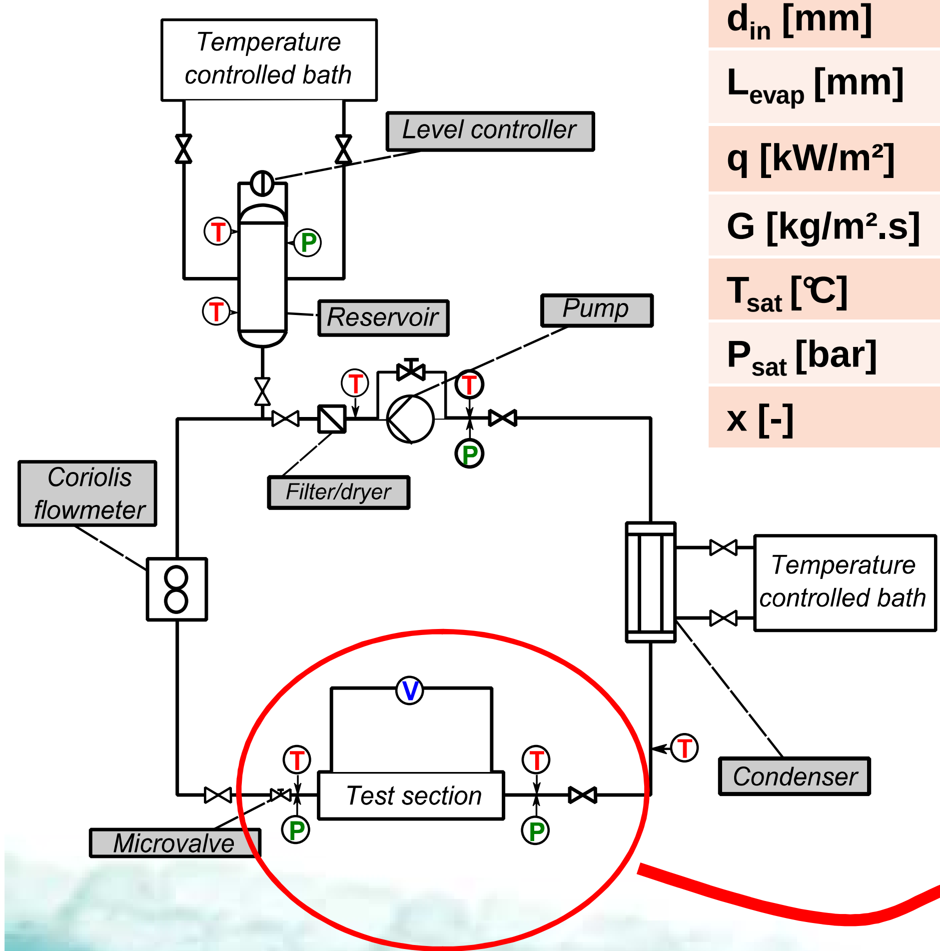
(*) R-22/R-134a/R-125/R-410A - (**) R-134a/R-236fa/R-245fa

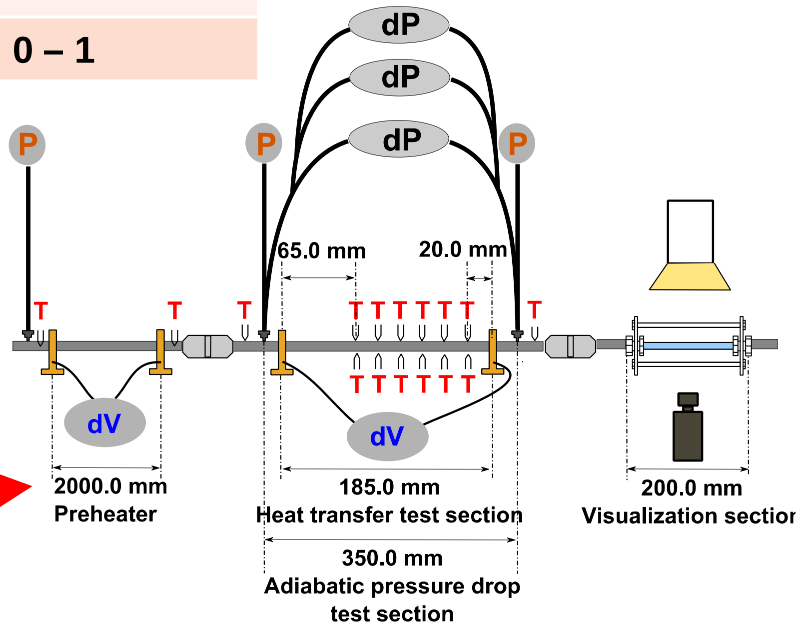
Need to investigate a different range of temperatures

Contents

Experimental setup and test section

Parameter	Range
d_{in} [mm]	3.00
L_{evap} [mm]	185.0
q [kW/m²]	10 – 90 ± 2-5 %
G [kg/m².s]	100 – 1500 ± 2 %
T_{sat} [℃]	60 – 120 ± 0.2 – 0.8
P_{sat} [bar]	4.4 – 19.2
x [-]	0 – 1





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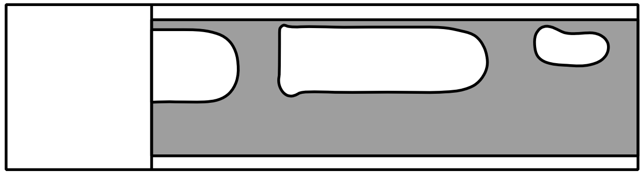
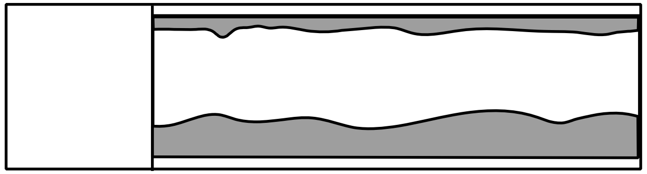
Results on flow patterns

Flow pattern characterization

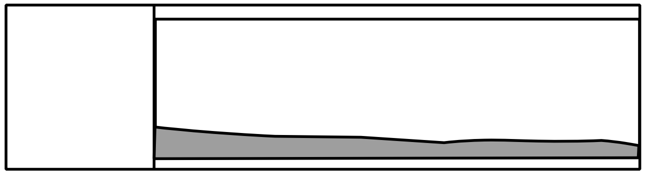
Four observed flow patterns



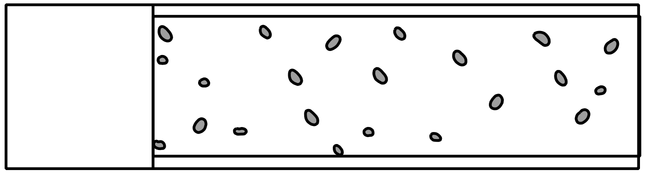
Intermittent flow



Annular flow



Dryout flow

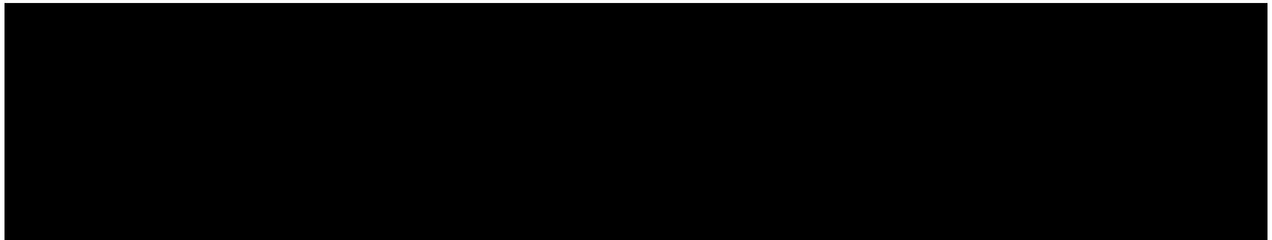


Mist flow

Influence of T_{sat} on the flow pattern

G = 300 kg/m².s, q = 50 kW/m², x = 0.15

T_{sat} = 60°C
Annular flow – f = 0 Hz



T_{sat} = 120°C
Intermittent flow– f = 78 Hz

Results on flow patterns

Influence of T_{sat} on the flow pattern

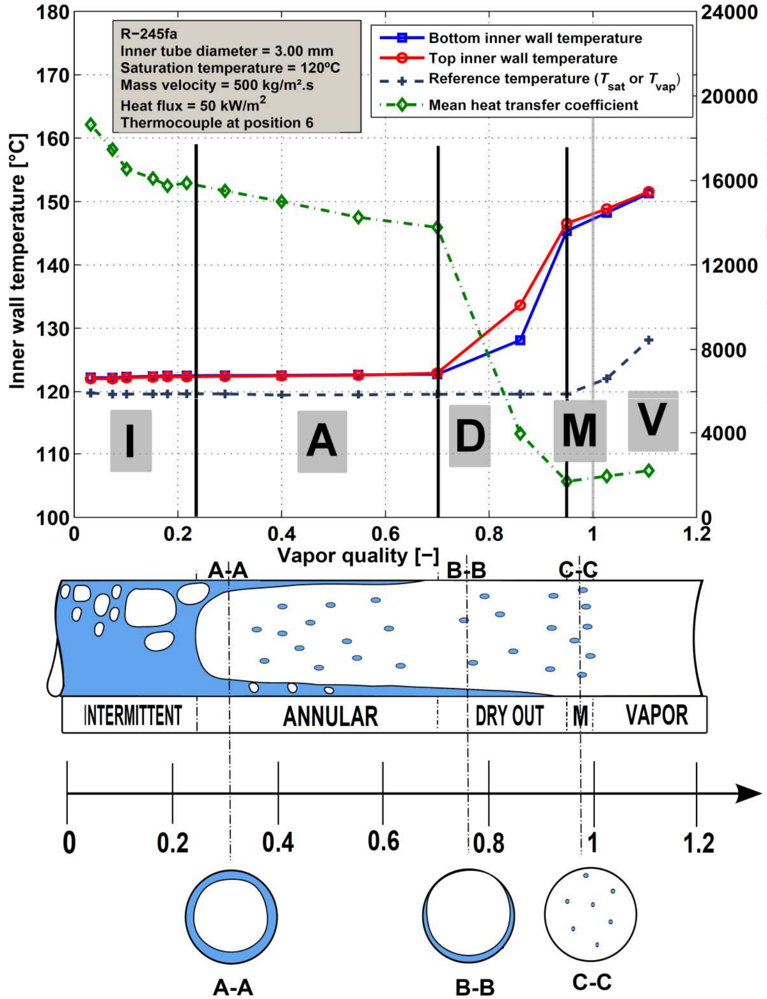
G = 300 kg/m².s, q = 50 kW/m², x = 0.30

T_{sat} = 60°C
Annular flow – f = 0 Hz

T_{sat} = 120°C
Intermittent flow– f = 41 Hz

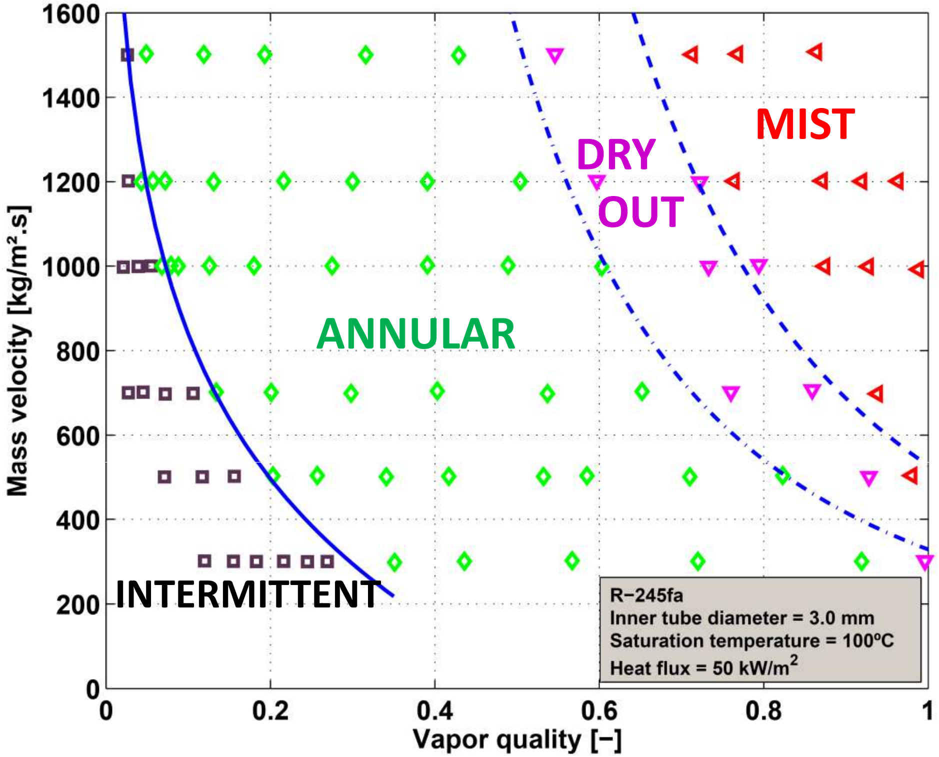
Results on flow patterns

Flow pattern characterization from heat transfer coefficient behavior

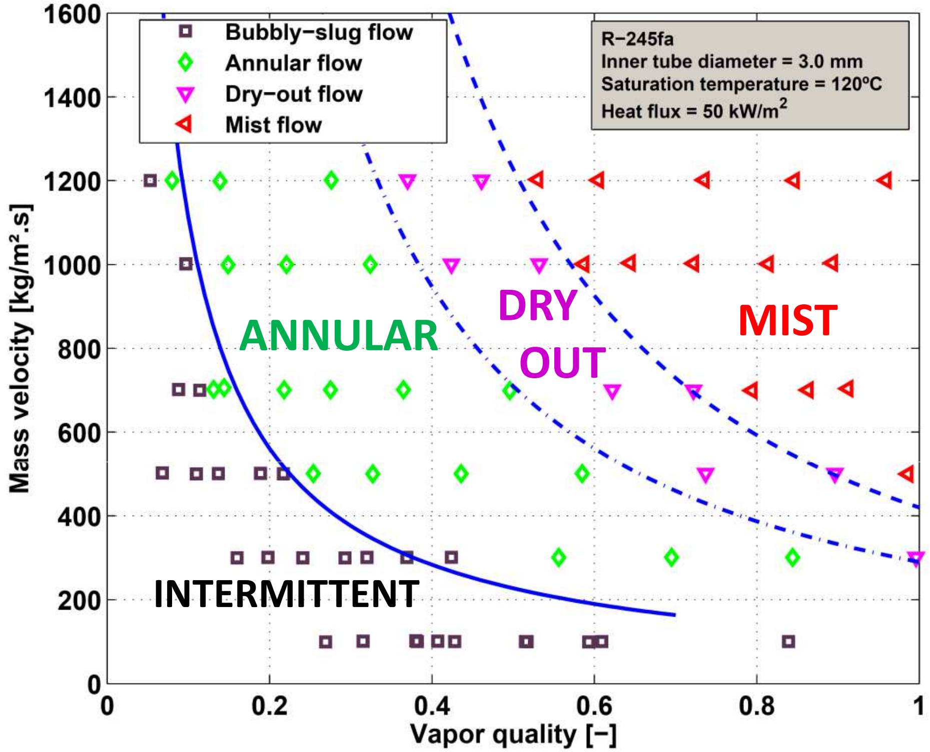


Results on flow patterns

T_{sat} = 100°C, q = 50 kW/m²



T_{sat} = 120°C, q = 50 kW/m²



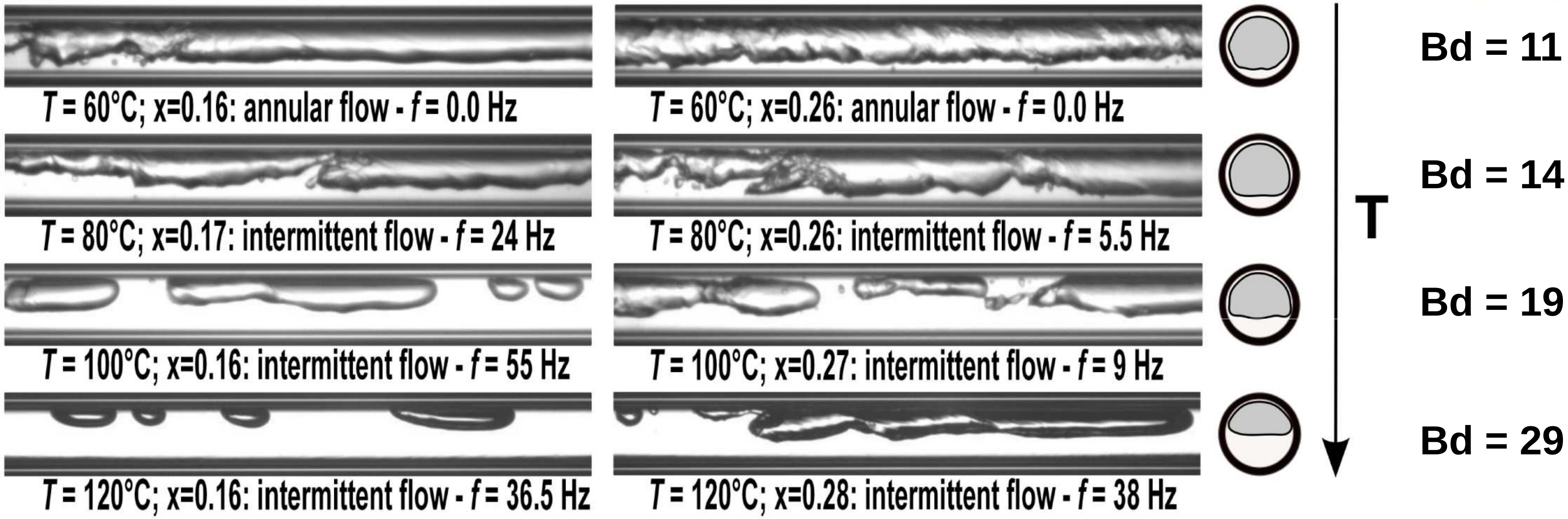
The higher the T_{sat}, the lower the vapor quality corresponding to mist flow regime inception

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_{sat} on the flow pattern

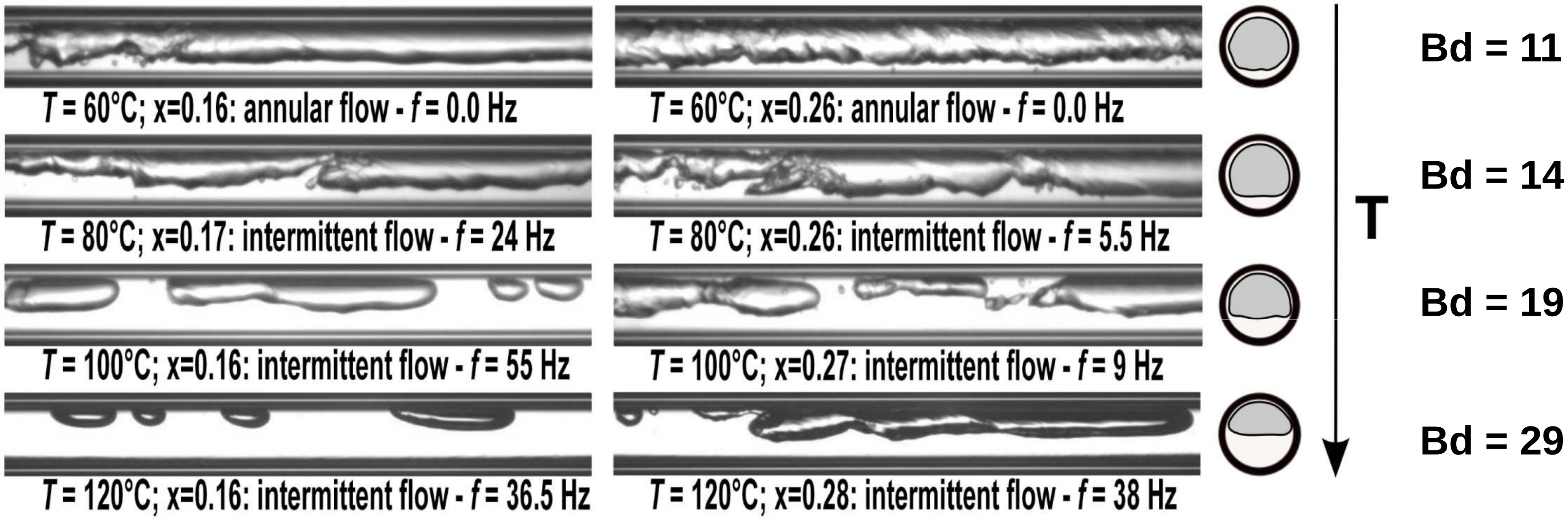


T_{sat} ↗ → σ ↘ → d_{bub} ↘ → **bubble length** ↘

T_{sat} ↗ → ρ_{vap} ↗ → **bubble length** ↘

Results on flow patterns

Influence of T_{sat} on the flow pattern

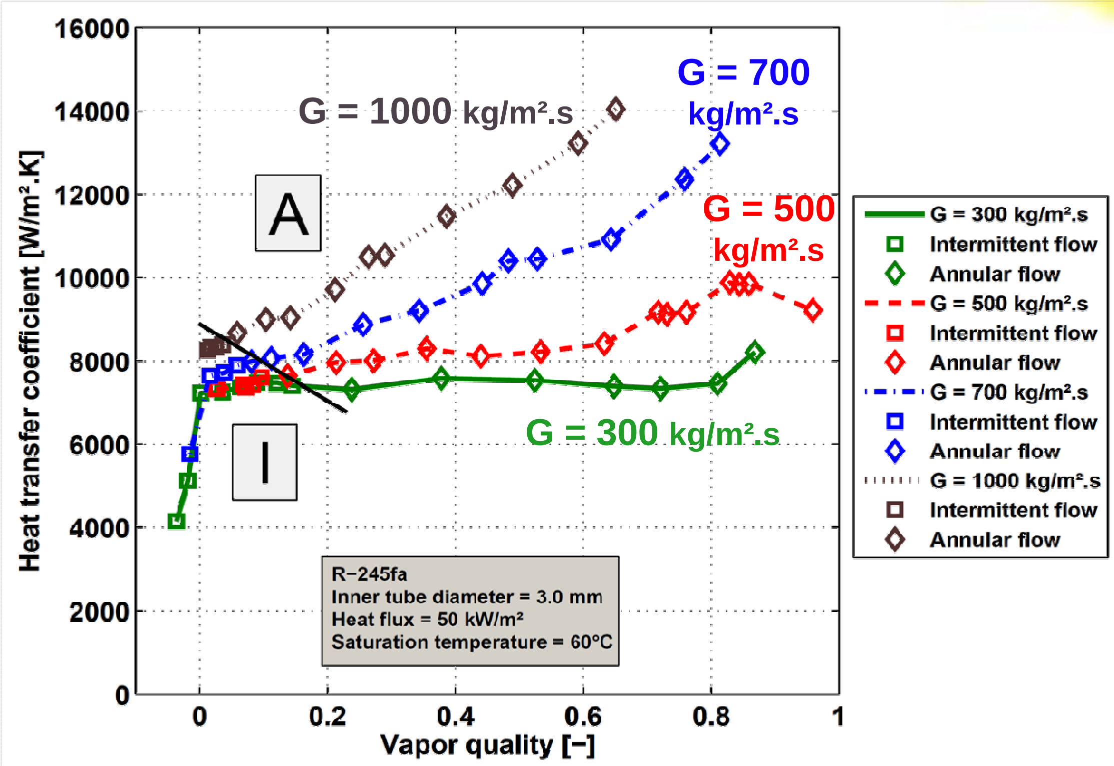


T_{sat} ↗ ⟹ σ ↘ ⟹ $$Bd = \frac{g(\rho_L - \rho_V)d^2}{\sigma}$$ ↗ ⟹ stratification ↗

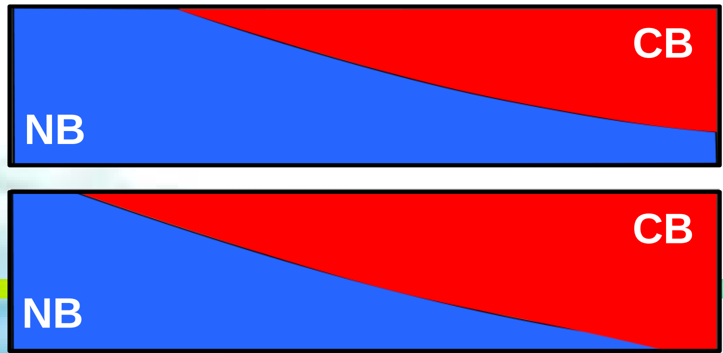
Results on heat transfer

Influence of mass velocity

T_{sat} = 60°C



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



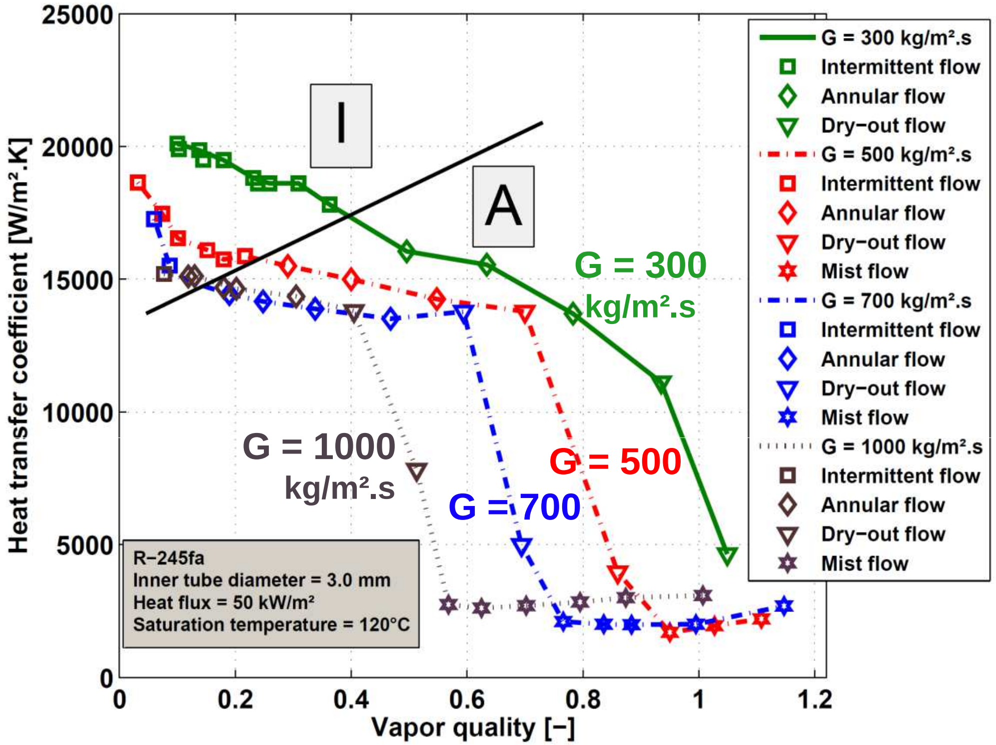
Low G

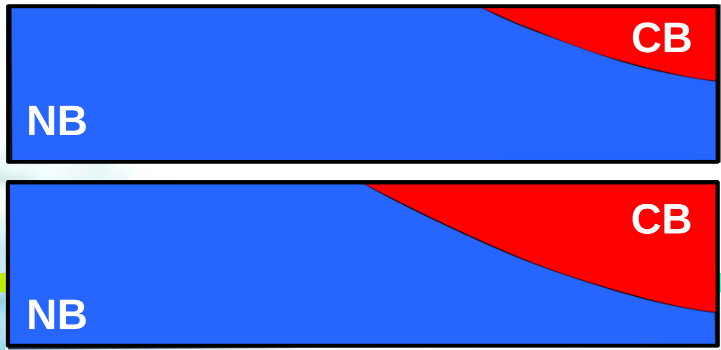
High G

Results on heat transfer

Influence of mass velocity

T_{sat} = 120℃





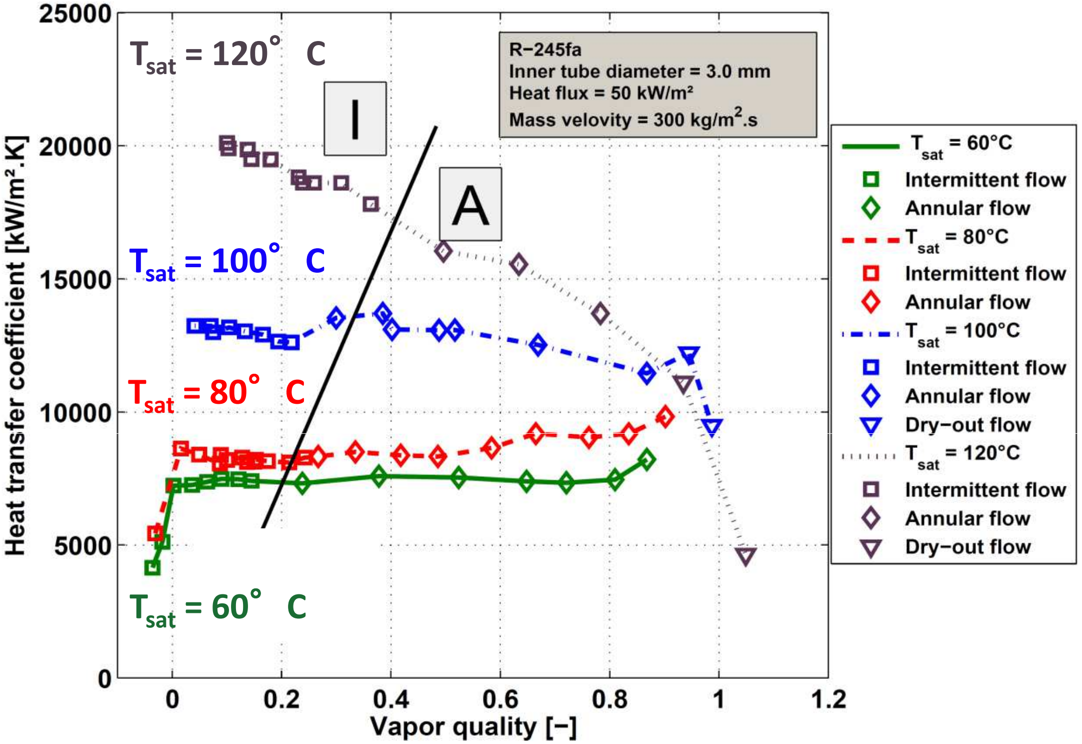
Low G

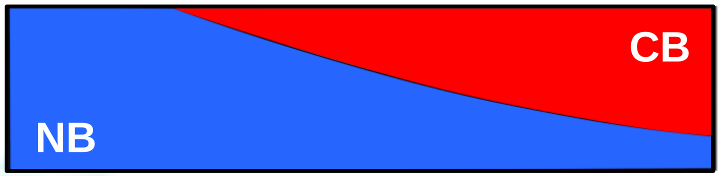
High G

Results on heat transfer

Influence of saturation temperature

G = 300 kg/m².s





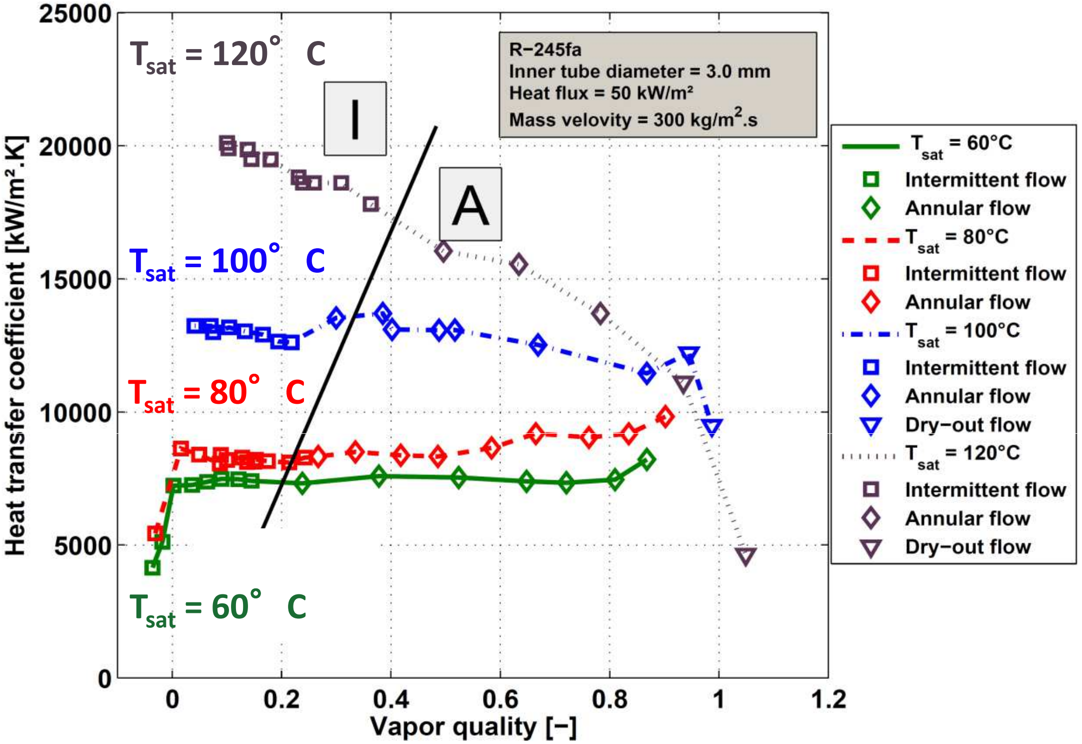
Low T_{sat}

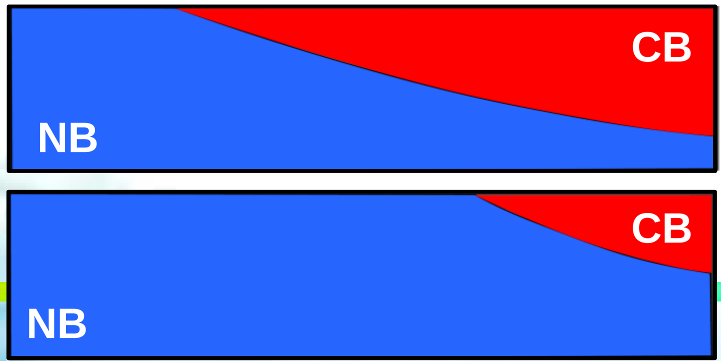
High T_{sat}

Results on heat transfer

Influence of saturation temperature

G = 300 kg/m².s





Low T_{sat}

High T_{sat}

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- **Conclusions**

Conclusions

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

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