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Subcooled boiling regime map for water at low saturation temperature and subatmospheric pressure

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Abstract

Subatmospheric pool boiling heat transfer was investigated experimentally. At low vapor pressure, the static head of the liquid column induces a non-negligible pressure gradient. This results in a local pressure-induced subcooling that makes the case of boiling at low vapor pressure with a high level of liquid a particular case of subcooled boiling. The experiments were conducted for variety of working parameters: three vapor pressures (2.4 kPa, 3.1 kPa, 4.1 kPa), four levels of liquid (15 cm, 28 cm, 35 cm, 60 cm) and five applied heat fluxes ($3.6 \text{ W}\cdot\text{cm}^{-2}$, $4.4 \text{ W}\cdot\text{cm}^{-2}$, $5.2 \text{ W}\cdot\text{cm}^{-2}$, $6.1 \text{ W}\cdot\text{cm}^{-2}$ and $7.1 \text{ W}\cdot\text{cm}^{-2}$). Owing to a statistical analysis of the signal of a heat flux sensor coupled with high-speed video recording, four different boiling regimes were identified: the regime of convection or small popping bubbles, the regime of isolated bubbles, the regime of intermittent boiling and the regime of fully developed boiling. The small popping bubbles and the intermittent boiling regimes are specific to the low pressure boiling: they are governed by the phenomenon of condensation driven by the aforementioned static pressure induced subcooling. Finally, to provide a visual representation of the influence of the working parameters on the boiling behavior, a dimensionless boiling regime map was proposed. This type of representation is a tool to predict the boiling regimes from a set of operating conditions but it is also useful to interpret the physical phenomena involved and how they differ from those occurring at higher pressure.

Keywords: Pool boiling, Low pressure, Experiments, Boiling regimes, Statistical analysis, Boiling regime map

Nomenclature

A	Area	m^2
c_p	Specific heat	$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
g	Gravitational constant	$\text{m} \cdot \text{s}^{-2}$
H	Height	m
Ja	Jakob number	-
Ja^*	Modified Jakob number	-
L_c	Capillary length	m
p	Pressure	Pa
q	Heat flux	$\text{W} \cdot \text{m}^{-2}$
s	Sensitivity of the sensor	$\text{V} \cdot (\text{W} \cdot \text{m}^{-2})^{-1}$ or $\text{V} \cdot \text{K}^{-1}$
t	Time	s
T	Temperature	$^{\circ}\text{C}$
u	Voltage output	V
Greek letters		
Δh	Enthalpy difference	$\text{J} \cdot \text{kg}^{-1}$
Δq	Heat flux span	$\text{W} \cdot \text{m}^{-2}$
ΔT	Temperature difference	K
λ	Thermal conductivity	$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
ρ	Density	$\text{kg} \cdot \text{m}^{-3}$
Subscripts		
app	Applied value	
co	Connection cable	
l	Liquid	
n	Number of sensor's zone	
sat	Saturation conditions	
$stat$	Static head of liquid	
sub	Subcooling	
v	Vapor	
$wall$	Heated surface	
Abbreviations		
CDF	Cumulative distribution function	
CHF	Critical heat flux	
PDF	Probability density function	

2 1. Introduction

3 Over the last decades, knowledge on subatmospheric boiling has been suc-
4 cessfully growing. The research efforts were driven by ecological concerns that
5 make it necessary to study phase transitions of refrigerants evaporating at
6 low pressures, e.g. water which is the most natural, safe and environmentally-
7 friendly refrigerant. Models commonly used to describe the process of boiling
8 occurring at higher pressures cannot be extrapolated to predict the dynamics
9 of subatmospheric phase transitions [1, 2]. This is due to specific changes
10 of thermophysical properties of the fluid at such conditions. For example,
11 for water at low pressure, the specific volume of vapor significantly increases
12 in comparison to atmospheric pressure, what results in increased size of the
13 bubbles. The critical radius of nucleation sites is enlarged due to the change
14 in vapor density and surface tension [3]. This leads to a lower number of
15 the active nucleation sites. The wall superheat required for the nucleation
16 process must be higher than typically 10 K [2, 4]. These features of subatmo-
17 spheric boiling and others were addressed by various authors: e.g. lowered
18 heat transfer coefficient, low bubble departure frequency, surface tempera-
19 ture fluctuations, large bubble size at detachment, long waiting time between
20 two successive bubbles *etc.* [1, 2, 4, 5, 6]. However, only very recent stud-
21 ies noted the importance of the liquid level at low pressures - most of the
22 previous works ignored this parameter. The authors who were aware of its
23 impact usually conducted the experiments for liquid column smaller than 20
24 cm [1, 6, 7, 8, 9]. Wojtasik et al. [10] performed their experiments on a
25 polished, horizontal surface with a single artificial nucleation site and three
26 different levels of liquid (2 cm, 15 cm, 28 cm). They emphasized that the
27 bubble dynamics is extremely dependent on the liquid level. They noted that
28 the size of the bubbles is reduced due to an intense vapor condensation in
29 the subcooled environment caused by the static pressure *gradient* imposed
30 by the column of liquid.

31 1.1. Temperature-induced subcooled boiling

32 Subcooled boiling was primarily studied in the case of temperature-induced
33 subcooling (liquid bulk temperature being lower than the saturation temper-
34 ature corresponding to the vapor pressure: $T_l < T_{sat}(p_v)$). The studies of Ku-
35 tateladze [11] showed that subcooling increases the critical heat flux. Many
36 researchers confirmed this dependency (e.g. Ivey and Morris [12], Inoue et
37 al. [13], Rainey et al. [14]). They created multiple correlations predicting

38 the occurrence of critical heat flux depending on the level of subcooling. It is
39 crucial for the application where large quantities of heat needs to be removed
40 (e.g. nuclear or fusion reactors [15]), as the CHF is the most important lim-
41 iting factor of maintaining high heat transfer rate at feasible temperatures
42 during the boiling process.

43 Besides, subcooling is described as having a little effect on the nucle-
44 ate boiling regime [16, 17] and slightly enhance the natural convection heat
45 transfer [16]. Nevertheless, Petrovic et al. [18] and Marek and Straub [19]
46 noted the influence of the Marangoni effect on the convective heat transfer
47 as a result of surface tension variation along liquid-gas interface when the
48 subcooling is sufficient. Its effect gets more intense if more noncondensable
49 gases are dissolved inside the working medium. Finally, as the subcooling has
50 often negligible influence on heat transfer coefficient [14], most of the nucle-
51 ate boiling correlations for saturation conditions can be used for subcooled
52 boiling [20].

53 Concerning bubble dynamics, for a given operating pressure the subcool-
54 ing reduces the size of bubbles, making this type of boiling beneficial for small
55 thermal devices [21]. Inada et al. [22] and Wang and Chen [23] showed the
56 existence of microbubble emission boiling. This phenomenon occurs for high
57 subcooling (more than 30 K) and high heat fluxes. After their contact with
58 cold surrounding liquid, the bubbles break into a cluster of microbubbles.
59 Judd [24] described subcooled boiling as being submitted to two opposing
60 phenomena. One the one hand, the larger wall to fluid temperature difference
61 (with respect to saturated boiling) fosters convection, but on the other hand,
62 the reduction of the bubble size limits the heat transfer. Because of these
63 opposing phenomena, the bubbles frequency first decreases when increasing
64 the subcooling, until it reaches a minimum and the starts increasing. Other
65 researchers note different relations concerning this parameters. According to
66 Shen at al. [25], the bubble frequency is lower in a subcooled environment
67 than at saturation conditions. Goel et al. [15] stated that the subcooling
68 generally results in the increase in the bubble frequency, but for subcooling
69 smaller than 5 K, opposite trend can be observed.

70 1.2. Pressure-induced subcooling

71 The liquid level plays an important role during low pressure boiling. At
72 atmospheric conditions, the pressure in the whole liquid bulk usually can
73 be considered homogeneous in typical operational conditions (few tenths of
74 centimeters of liquid). Those statements are not valid if the pressure is

75 significantly reduced. At low pressure the liquid column induces a hydrostatic
 76 pressure which is of similar order of magnitude as the vapor pressure. The
 77 value of local pressure inside the liquid pool increases from the vapor pressure
 78 (at free surface level) to the wall pressure (at heated surface level) which is
 79 written as:

$$p_{wall} = p_v + \rho(T_l) \cdot g \cdot H \quad (1)$$

80 During pool boiling experiments, when the liquid temperature is uni-
 81 form in the whole volume of liquid and equal to the saturation temperature
 82 corresponding to the vapor pressure (which can be checked in practical or
 83 experimental configurations [26]) the saturation temperature rises due to the
 84 increase of local pressure. This increase of saturation temperature induces a
 85 pressure-induced subcooling which can be defined as the difference between
 86 local saturation temperature and liquid temperature. At the wall level, this
 87 subcooling can be expressed as:

$$\Delta T_{sub_{wall}} = T_{sat}(p_{wall}) - T_l \quad (2)$$

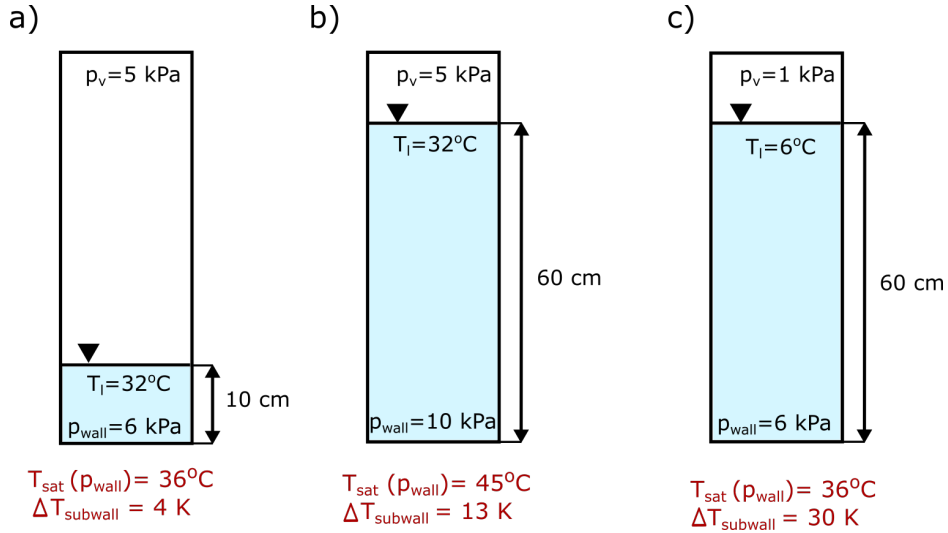


Figure 1: Configuration of three different situations of low pressure pool boiling highlighting the pressure-induced subcooling.

88 The importance of the pressure-induced subcooling at low pressure is
 89 schematically presented in Fig. 1. Two first cases (1a, 1b) show the boiling

90 environment for the same vapor pressure $p_v = 5$ kPa and two liquid levels
 91 ($H_l = 10$ cm and 60 cm). The difference in the liquid height influences the
 92 value of the pressure at the wall, which is almost twice as high for $H_l = 60$
 93 cm. This affects the local saturation temperature at the wall level, as well
 94 as the value of subcooling which increases from 4 K up to 13 K. To obtain
 95 the same pressure at the wall level and for the heighest liquid height ($H_l =$
 96 60 cm), the vapor pressure has to be reduced (see Fig. 1c). In this case, the
 97 liquid bulk temperature changes, also resulting in a variation of subcooling
 98 inside the pool.

99 The influence of subcooling is stronger for higher liquid levels. Calculated
 100 values of pressure, saturation temperature, liquid temperatures and subcool-
 101 ing at the wall level for four various liquid heights (15 cm, 28 cm, 35 cm,
 102 60 cm) are presented in Tab. 1. All the values of fluid thermophysical prop-
 103 erties or liquid-vapor equilibrium data are taken from the open-source library
 104 of fluid properties CoolProp [27].

Table 1: Boiling parameters of water ($p_v = 3.1$ kPa, i.e. $T_{sat} = T_l = 24.6^\circ\text{C}$)

H_l	15 cm	28 cm	35 cm	60 cm
p_{wall}	4.6 kPa	5.8 kPa	6.5 kPa	9.0 kPa
$T_{sat}(p_{wall})$	31.3°C	35.7°C	37.7°C	43.7 °C
T_l	24.6°C	24.6°C	24.6°C	24.6 °C
$\Delta T_{sub_{wall}}$	6.6 K	11.0 K	17.5 K	19.1 K

105 Pressure-induced subcooled boiling has not been studied in the literature.
 106 It is intended in this paper to investigate the dependence of various oper-
 107 ational parameters on the boiling behavior, with special attention paid to
 108 subcooling caused by the level of liquid. The study is focused on the boiling
 109 regimes and their thermal effects.

110 Beyond the descriptions of the specific features of the regimes existing
 111 in the presence of a pressure-induced subcooling, a boiling regime map is
 112 proposed. This kind of representation will be especially helpful for designing
 113 heat exchangers, as it provides knowledge of which parameters should be
 114 applied to obtain any boiling regime and take benefit of its thermal features.

115 **2. Experimental setup and procedures**

116 The experimental setup (see Fig. 2) consists of a stainless steel cylindrical
117 vessel with inner diameter of 200 mm and height of 420 mm made according
118 to ISO-K vacuum technology. Four circular viewports with inner diameter
119 of 100 mm allow to visualize and record the boiling process. One viewport
120 is used to illuminate the boiling area. A high-speed camera is installed on the
121 opposite side.

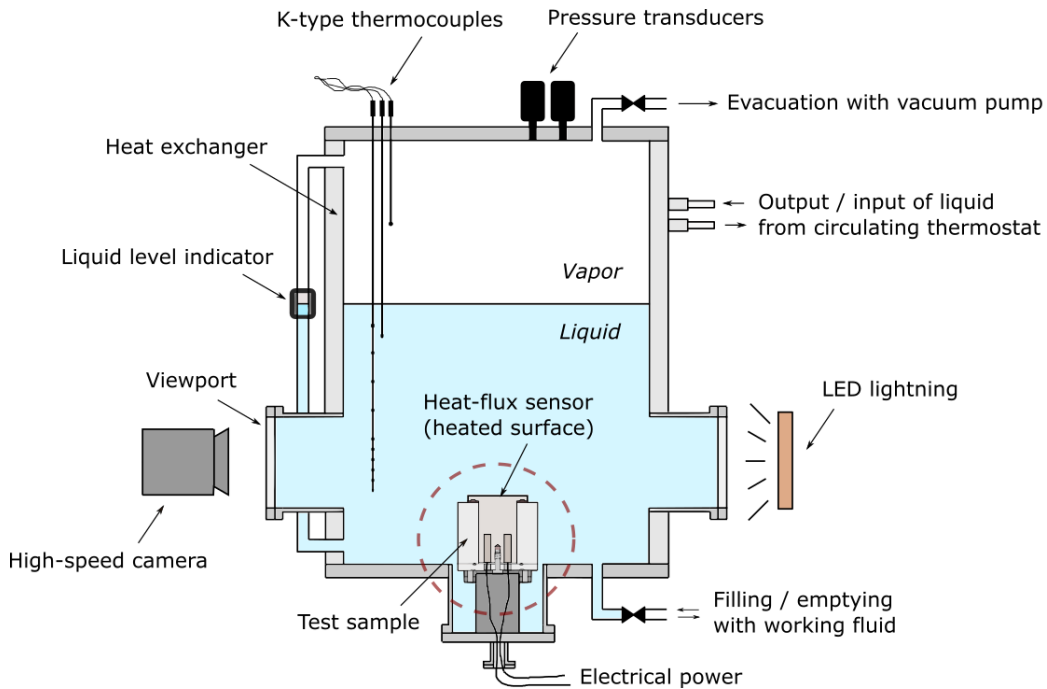


Figure 2: Experimental apparatus used in the experiments.

122 A copper cylinder with two cartridge heaters (maximum power 450 W
123 each) is installed at the base of the vessel. A customized heat flux sensor,
124 with dimensions equal to the size of the copper surface (diameter 78 mm),
125 is embedded on its top. A schematic of the sensor is presented in Fig. 3: it
126 is divided into seven annular zones allowing for independent measurements
127 of heat flux at each section. This feature was used in a previous study [26]
128 but not for the present series of experiment. The top surface was treated
129 with emery paper to obtain a rough surface and create multiple nucleation
130 sites. The surface roughness was determined with confocal microscope as

131 $R_a = 3.5 \mu\text{m}$. The sensitivity of the heat flux measurement for each zone
 132 is presented in Table 2. These values were estimated during the calibration
 133 process by the manufacturer of the sensor.

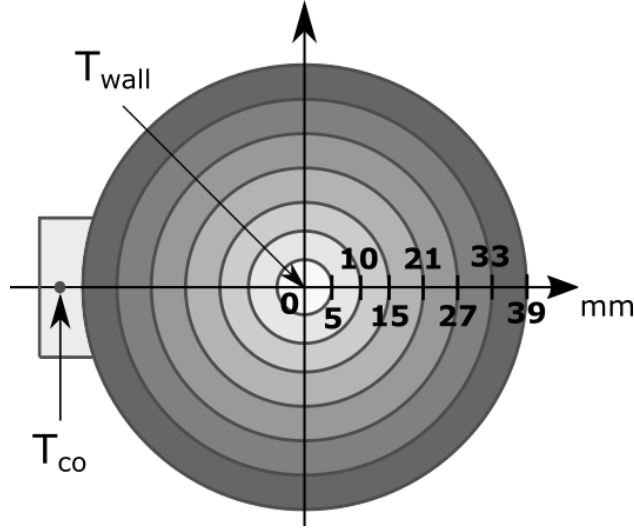


Figure 3: Schematic of the heat flux sensor divided into seven concentric zones

134 The heat flux for each zone can be calculated as the voltage output divided
 135 by the sensitivity of given measurement zone:

$$q_n = \frac{u_n}{s_n} \quad (3)$$

136 The total heat flux over all seven zones of the sensor can be calculated as
 137 follows:

$$q_{1-7} = \frac{\sum_{n=1}^7 q_n A_n}{\sum_{n=j}^k A_n} \quad (4)$$

138 The sensitivity of the temperature difference between the connection zone
 139 and the center of the heater ΔT is estimated as $s_{\Delta T} = 32 \mu\text{V} \cdot \text{K}^{-1}$. The
 140 temperature difference is then calculated by dividing the signal output by
 141 this value of sensitivity:

$$\Delta T = \frac{u_{\Delta T}}{s_{\Delta T}} \quad (5)$$

142 The sensor allows to measure the temperature at the connection ribbon
 143 (T_{co}) and to determine the temperature difference between the connection
 144 ribbon cable and the center of the sensor ($\Delta T = T_{wall} - T_{co}$). The uncertainty
 145 for the heat flux measurement is equal to $\pm 3\%$, while for thermocouples, it
 146 is ± 0.5 °C.

Table 2: Sensitivities of the measurement zones of the heat flux sensor

Zone number	$s, \mu V \cdot (W \cdot m^{-2})^{-1}$
Zone 1	0.667
Zone 2	2.50
Zone 3	4.14
Zone 4	8.02
Zone 5	11.7
Zone 6	14.1
Zone 7	13.8

147 The vessel presented in Fig. 2 is equipped with two valves. The top
 148 valve serves as a connection to a vacuum pump in order to reduce pressure
 149 and remove any non-condensable gases from the vessel. The bottom valve is
 150 used to fill and remove the working fluid from the vessel. The level of liquid
 151 is determined using liquid level indicator (a transparent hose). The liquid
 152 height is calculated as the difference between positions of the free surface
 153 and the heated surface. Measurements are made with a cathetometer with
 154 an uncertainty of ± 0.1 cm.

155 The temperature and the pressure in the tank are controlled with a heat
 156 exchanger wrapped around the tank and connected to a flow of water with
 157 adjustable temperature. The saturation pressure is monitored with two pres-
 158 sure transducers (operating pressures ranges 0 - 100 kPa and 0 - 16 kPa) with
 159 an accuracy of 0.25% of their full scale range (i.e. ± 250 Pa and ± 40 Pa re-
 160 spectively).

161 The fluid temperature is monitored with twelve K-type thermocouples.
 162 They measure liquid or vapor temperatures, depending on the applied level
 163 of liquid. Ten of those thermocouples form a multi-point probe with a
 164 diameter of 6 mm and are spread across the distance of 15 cm. Their location
 165 was set in such a way that thermocouple T_1 is located at the same level as
 166 the heated wall (see Fig. 4a).

167 The temperature measurements inside the liquid pool confirmed that the
 168 liquid temperature field in the vessel is uniform (see Fig. 4b). The difference

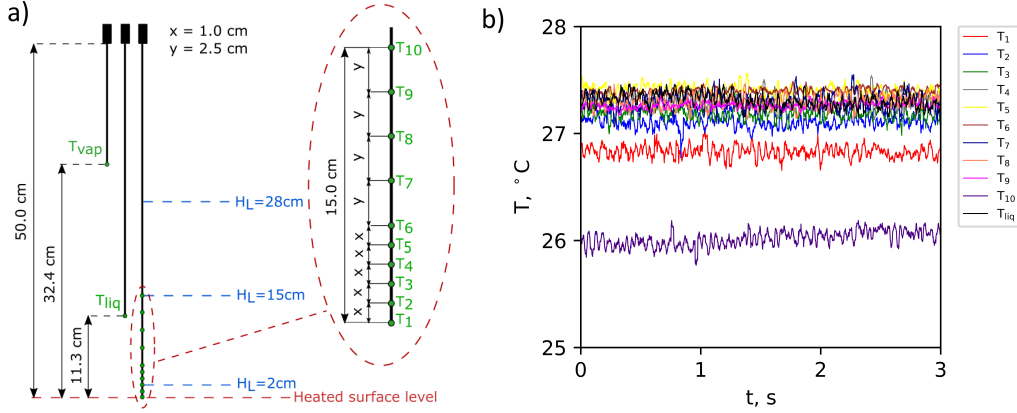


Figure 4: (a) Positioning of thermocouples, (b) Example measurement for $H_l=15$ cm.

169 between thermocouples measurements $T_1 - T_9$ and bulk liquid temperature
 170 T_{liq} never exceeds 0.5 K. Only the temperature measured by the thermocou-
 171 ple at the free surface level T_{10} is noticeably lower, because it was placed
 172 for that experiment on the liquid-vapor interface where vaporization occurs
 173 which leads to to an extraction of heat.

174 2.1. Experimental operating conditions

175 Experiments were performed for three different water vapor pressures (p_v
 176 = 2.4 kPa, 3.1 kPa, 4.1 kPa) and four distinct liquid levels ($H_l = 15$ cm,
 177 28 cm, 35 cm, 60 cm). Various applied heat fluxes q_{app} were applied: 3.6
 178 $W \cdot cm^{-2}$, 4.4 $W \cdot cm^{-2}$, 5.2 $W \cdot cm^{-2}$, 6.1 $W \cdot cm^{-2}$ and 7.1 $W \cdot cm^{-2}$.

179 When the surface temperature exceeded $80^\circ C$, the measurements were
 180 stopped, as excessive wall temperature could damage the sensor. Each mea-
 181 surement was recorded over 60 s. The acquisition frequency was equal to
 182 500 Hz (every 2 ms). The thermal measurements were complemented with
 183 high-speed video recordings with framerate 500 Hz (recorded during 3.072 s
 184 due to camera memory limitations).

185 3. Data reduction and results analysis

186 3.1. Statistical analysis of heat flux distribution

187 Even when the overall boiling behavior appears in steady state, the time
 188 evolution of the heat flux transmitted to the water through all seven zones

189 of the sensor is irregular (see Fig. 5a). It is not possible to draw any general
 190 conclusion about the frequency, the size or the number of bubbles. The
 191 nucleation does not occur at the same value of heat flux and bubbles possess
 192 different sizes resulting in the observed temporal variation of the heat flux.
 193 When the applied heat flux increases, the peaks of heat flux become more
 194 densely packed making the analysis even more difficult.

195 Physical phenomena showing highly fluctuating features can be analyzed
 196 statistically, using tools like the probability density function. The graph
 197 showing instantaneous value of heat flux over all seven zones of the sensor
 198 (calculated according to Eq. 4) vs. time can be divided into intervals (exam-
 199 ple interval is marked red in Fig. 5a). The set of intervals for the whole range
 200 of heat flux allows the creation of the density histogram. Fig. 5b presents
 201 the histogram created for the heat flux intervals with the exact thickness as
 202 shown in Fig. 5a. This kind of graph represents the occurrence frequency of
 203 each heat flux interval. If the interval's thickness approaches zero, the his-
 204 togram will turn into a continuous probability density function - PDF (see
 205 Fig. 5c).

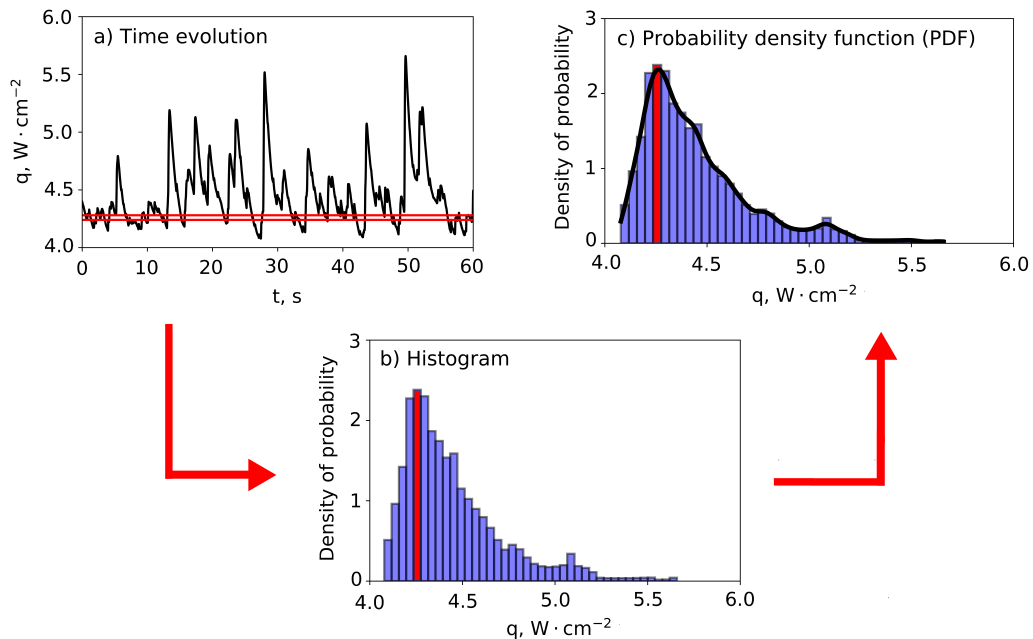


Figure 5: Formation of the PDF from the function of time evolution (for all seven zones of the sensor).

206 The PDF is always associated with continuous variables (e.g. heat flux
 207 distribution for high acquisition frequency). The PDF represents a distribu-
 208 tion of probability, not the probability itself. The exact value of probability
 209 of a certain interval can be calculated by taking the integral over this inter-
 210 val. This feature is shown in Fig. 6a. The area under the PDF graph over
 211 the interval $[0; x_p]$ represents the probability of occurrence of any value from
 212 this interval. The values on the ordinate axis are expressed in an arbitrary
 213 unit: they do not represent probability of occurrence of certain value 'x'.
 214 The values on the ordinate axis depend on the range of 'x' for which the
 215 calculations were performed and a change of the measurement time would
 216 change the values on the ordinate axis.

217 Fig. 6b shows the cumulative distribution function (CDF) which is based
 218 on the PDF shown in Fig. 6 a). The ordinate of the CDF for a certain point
 219 x_p gives the actual value of probability that any value from the interval $[0; x_p]$
 220 can occur. This value is equal to the area under the PDF graph. Since the
 221 vertical axis of the CDF is probability, it must fall between zero and unity.

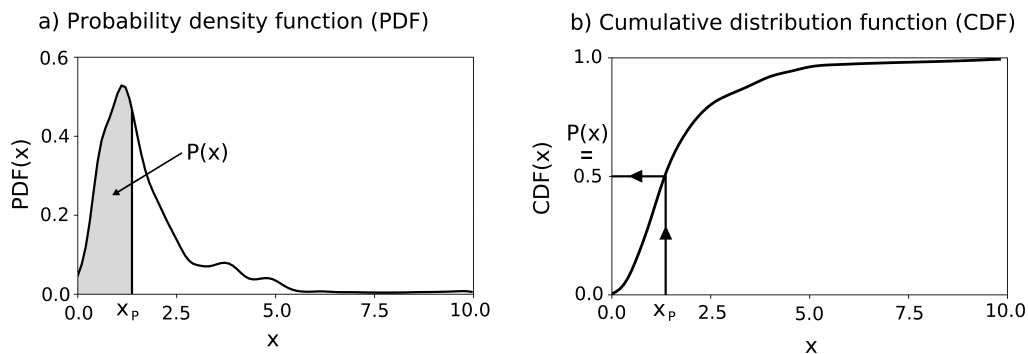


Figure 6: Probability density function (PDF) and cumulative distribution function (CDF).

222 4. Boiling regimes at low pressure

223 For various operating conditions (different vapor pressures p_v , liquid lev-
 224 els H_l , applied heat fluxes q_{app}), individual PDF graphs were created. Four
 225 distinct boiling regimes could be identified from the PDF graphs, visual ob-
 226 servations (performed with high-speed camera) and from the thermal signals
 227 recorded by the heat flux sensor: the convection or small popping bubbles
 228 regime, the isolated bubbles regime, the intermittent boiling regime and the

229 fully developed boiling regime. The characteristic features of each regime
 230 will be described in this section. The typical video sequences of each type of
 231 low-pressure boiling is presented in Fig. 7.

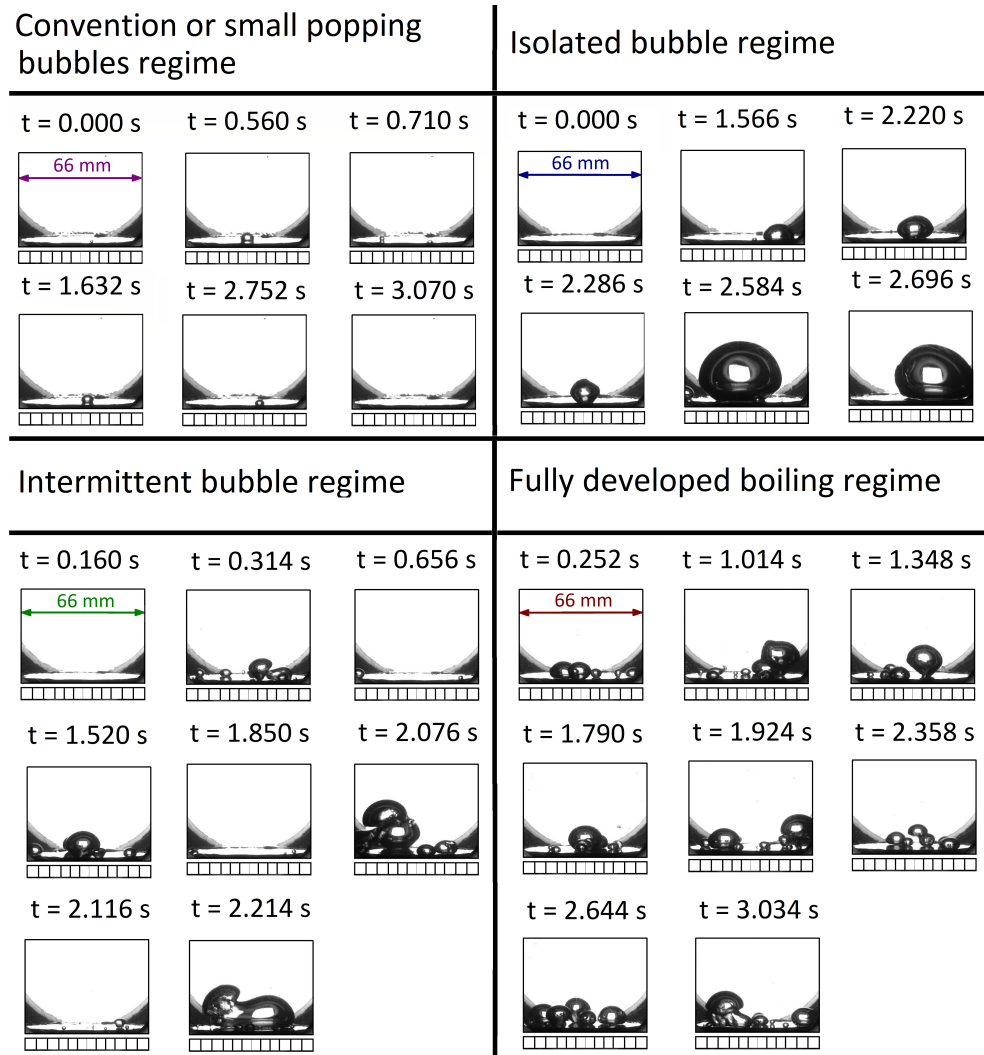


Figure 7: Video sequences of various boiling regimes occurring at low pressure

232 4.1. Convection or small popping bubbles regime

233 This regime primarily occurs when the heat flux is too small to initiate
 234 any substantial nucleation. For highly subcooled liquid (when the liquid level

235 is high enough), small popping bubbles (few millimeters in size) can never-
 236 theless grow on the heated wall, but because of their size, they are almost
 237 undetectable by the heat flux sensor. The bubbles actually pop (they col-
 238 lapse) because of the subcooling that induces intense condensation of vapor
 239 and rapid bubble collapse. The lack of large or frequently detaching bubbles
 240 significantly limits the effectiveness of heat extraction from the surface, which
 241 results in an almost constant heat flux: no major fluctuation is detected (Fig.
 242 8, top). The PDF, due to low heat flux fluctuation ($\Delta q < 0.5 \text{ W}\cdot\text{cm}^{-2}$), is
 243 characterized by very narrow peak - few times narrower in comparison to
 244 other regimes (see Fig. 8, bottom).

1) Convection / Small popping bubbles

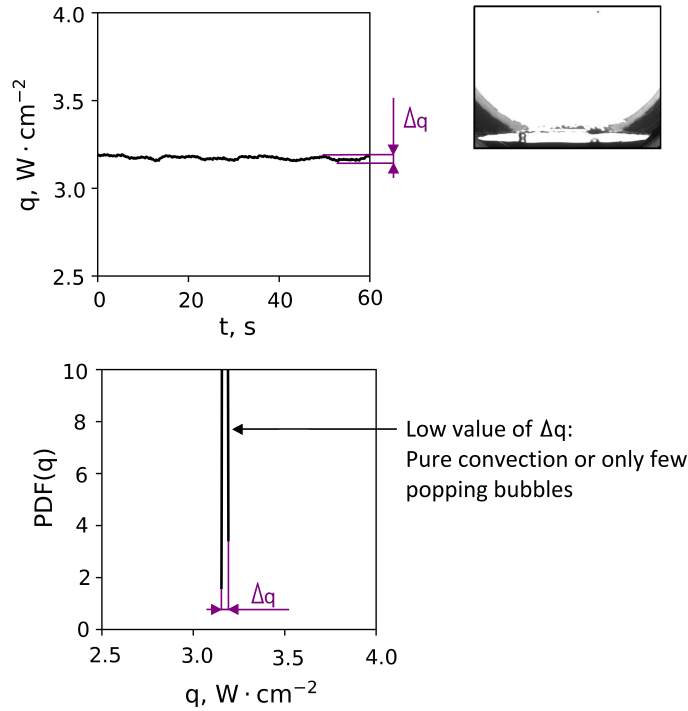


Figure 8: Example of thermal signature (heat flux vs. time) and PDF for convection or small popping bubbles regime ($p_v = 2.4 \text{ kPa}$, $H_l = 60 \text{ cm}$, $q_{app} = 4.4 \text{ Wcm}^2$).

245 4.2. Isolated bubble regime

246 This regime consists of the succession of large bubbles separated by long
 247 waiting time. The forming bubbles are large and they do not interact with

2) Isolated bubble regime

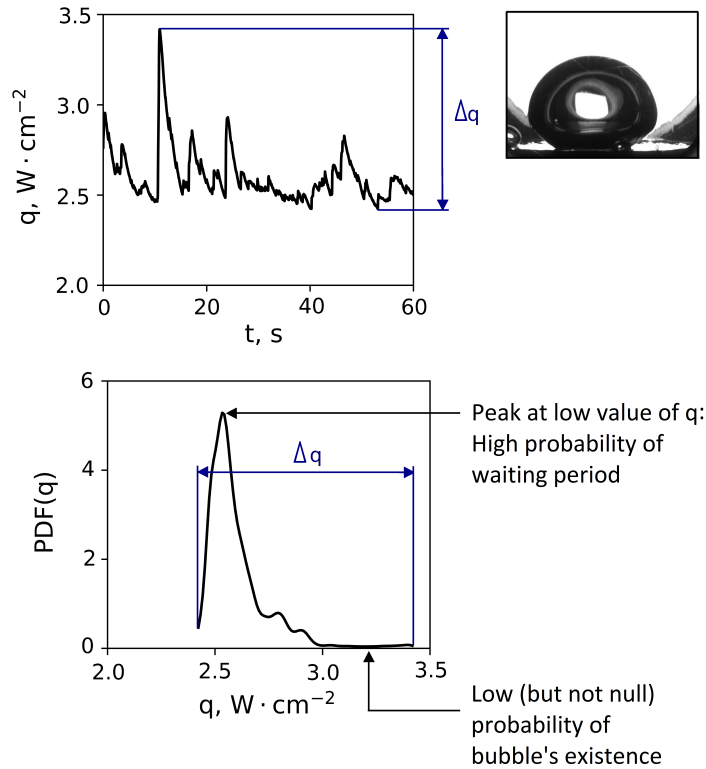


Figure 9: Example of thermal signature (heat flux vs. time) and PDF for isolated bubbles regime ($p_v = 2.4$ kPa, $H_l = 15$ cm, $q_{app} = 3.6$ Wcm^2).

248 each other (in most of the cases there is just one bubble at a time due to
 249 large bubble diameters (order of few centimeters), comparable to size of the
 250 heated surface). This type of boiling is the most commonly described in the
 251 literature [1, 6, 10], as this regime exists for the most often applied working
 252 conditions (level of liquid between 10 cm and 20 cm, moderate value of heat
 253 flux). Analyzing the heat flux evolution (Fig. 9, top), one can notice the
 254 clearly visible peaks occurring at low frequency. Single phase convection is
 255 present for most of the time, except when, from time to time, a bubble is
 256 emitted. These characteristics locate the peak of the PDF on the left side
 257 of the graph (towards the low values of q), which represents high probability
 258 of the waiting period occurrence during this regime (Fig. 9, bottom). The
 259 bubbles appear on the surface rarely, so the values of $PDF(q)$ at high heat

260 fluxes are close (but not equal) to zero.

261 4.3. Intermittent boiling regime

262 This regime is characterized by many bubbles present on the surface. The
263 size of individual bubble is reduced in comparison to the ones at isolated
264 bubble regime. However, they interact with each other and form bigger
265 bubble columns. Their size is reduced in comparison to the isolated bubble
266 regime, Also present are intervals of single phase convection (resembling the
267 long waiting period at the isolated bubble regime). During these periods, the
268 heat flux has almost a constant value over time (Fig. 10, top). The PDF in
269 such case is represented by a flat peak and symmetrical shape, meaning that
270 high and low values of heat flux have similar probabilities (Fig. 10, bottom).

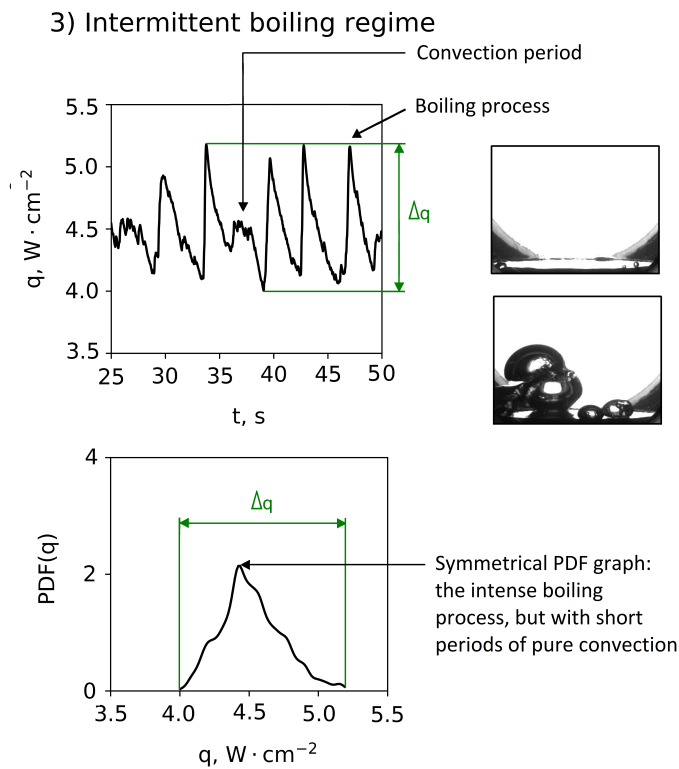


Figure 10: Example of thermal signature (heat flux vs. time) and PDF for intermittent boiling regime ($p_v = 4.1$ kPa, $H_l = 28$ cm, $q_{app} = 6.1$ Wcm²).

271 4.4. Fully developed boiling regime

272 Fully developed boiling is characterized by an intense boiling process.
273 Large number of bubbles nucleate at the same time and they can interact
274 with each other and form larger bubble clusters. The heat flux evolution
275 is densely packed (see Fig. 11, top) as the applied heat flux is sufficient
276 enough to avoid periods of single phase convection without bubbles on the
277 surface. For this type of boiling, the PDF graph (Fig. 11, bottom) can be
278 symmetrical or skewed right towards high values of heat flux (which indicates
279 a high probability of bubble occurrence).

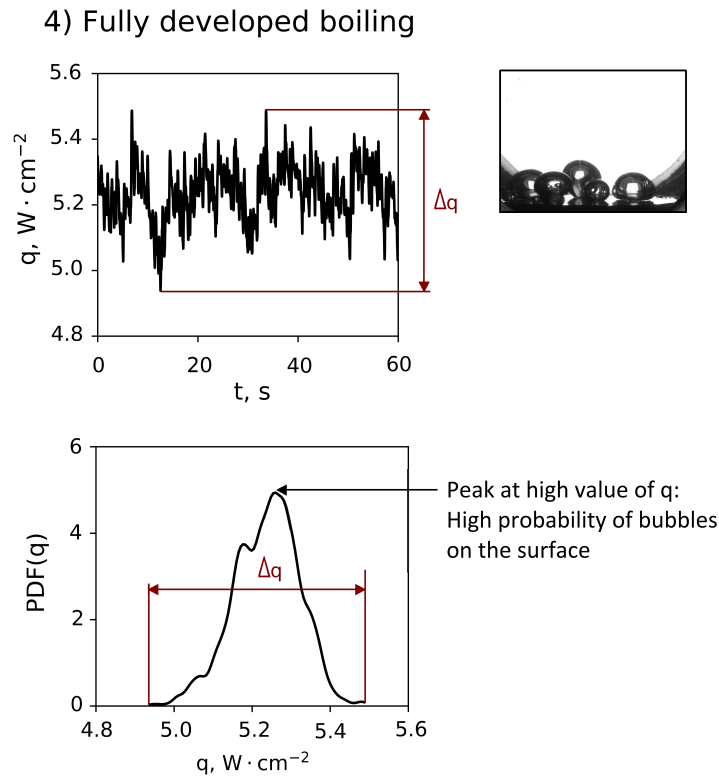


Figure 11: Example of thermal signature (heat flux vs. time) and PDF for fully developed boiling regime ($p_v = 2.4$ kPa, $H_l = 15$ cm, $q_{app} = 7.1$ Wcm^2).

280 4.5. Influence of the liquid level and of the heat flux on the boiling regimes

281 The set of PDF graphs created for a vapor pressure of $p_v = 2.4$ kPa and
282 four distinct liquid levels ($H_l = 15$ cm, 28 cm, 35 cm, 60 cm) is presented in

283 Fig. 12. Each graph represents the PDF obtained for a specific level of liquid
 284 and five different heat fluxes ($q_{app} = 3.6 \text{ W}\cdot\text{cm}^{-2}$, $4.4 \text{ W}\cdot\text{cm}^{-2}$, $5.2 \text{ W}\cdot\text{cm}^{-2}$,
 285 $6.1 \text{ W}\cdot\text{cm}^{-2}$ and $7.1 \text{ W}\cdot\text{cm}^{-2}$). Increasing applied heat flux tends to shift the
 286 values of instantaneous heat flux q detected by sensor towards higher values.
 287 Boiling regimes were marked by different colors: convection or popping bub-
 288 bles regime in purple, isolated bubbles regime in blue, intermittent boiling
 289 regime in green and fully developed boiling regime in red. When the PDF
 290 graphs were not sufficient to definitely distinguish the intermitted boiling
 291 regime from the fully developed boiling regime (e.g. cases for $H_l = 15 \text{ cm}$
 292 and $q_{app} = 5.2 \text{ W}\cdot\text{cm}^{-2}$ and $q_{app} = 6.1 \text{ W}\cdot\text{cm}^{-2}$), the video recording was used
 293 to make the final decision. If periods of pure convection were observed, the
 294 experiment was decided to belong to the intermitted boiling regime. In the
 295 opposite case - the measurement was assigned to the fully developed boiling
 296 regime.

297 It is more difficult to initiate the boiling process for a high level of liquid
 298 due to increased degree of liquid subcooling. More energy is required to
 299 heat up the liquid, i.e. higher wall superheat is necessary to initiate boiling.
 300 Larger subcooling of the liquid reduces the size of bubbles because of the
 301 condensation mechanism described previously. That is why, for the highest
 302 level of liquid $H_l = 60 \text{ cm}$ and almost all applied heat fluxes, convection or
 303 small popping bubbles regime is observed.

304 The span of heat flux Δq on the PDF graphs is the highest for liquid level
 305 $H_l = 15 \text{ cm}$ and low or moderate heat flux. At such conditions bubbles have
 306 large diameters, provoking strong fluctuations of heat flux. The waiting time
 307 is long, thus the probability of high heat flux occurrence is close to zero. For
 308 the fully developed boiling regime, increasing applied heat flux leads to higher
 309 values of instantaneous heat flux (corresponding to more intense boiling pro-
 310 cess). The bubbles are nucleating, growing and detaching continuously. The
 311 waiting time remains low and there are always some bubbles on the surface.
 312 Although multiple bubbles are present on the surface at the same time, the
 313 heat flux span Δq tends to be reduced due to their small diameters. One
 314 can also notice that the intermittent boiling regime for this vapor pressure
 315 is observed only for $H_l = 15 \text{ cm}$ and $q_{app} = 5.2 \text{ Wcm}^{-2}$. This indicates that
 316 this boiling mode exists only for a narrow set of operating parameters.

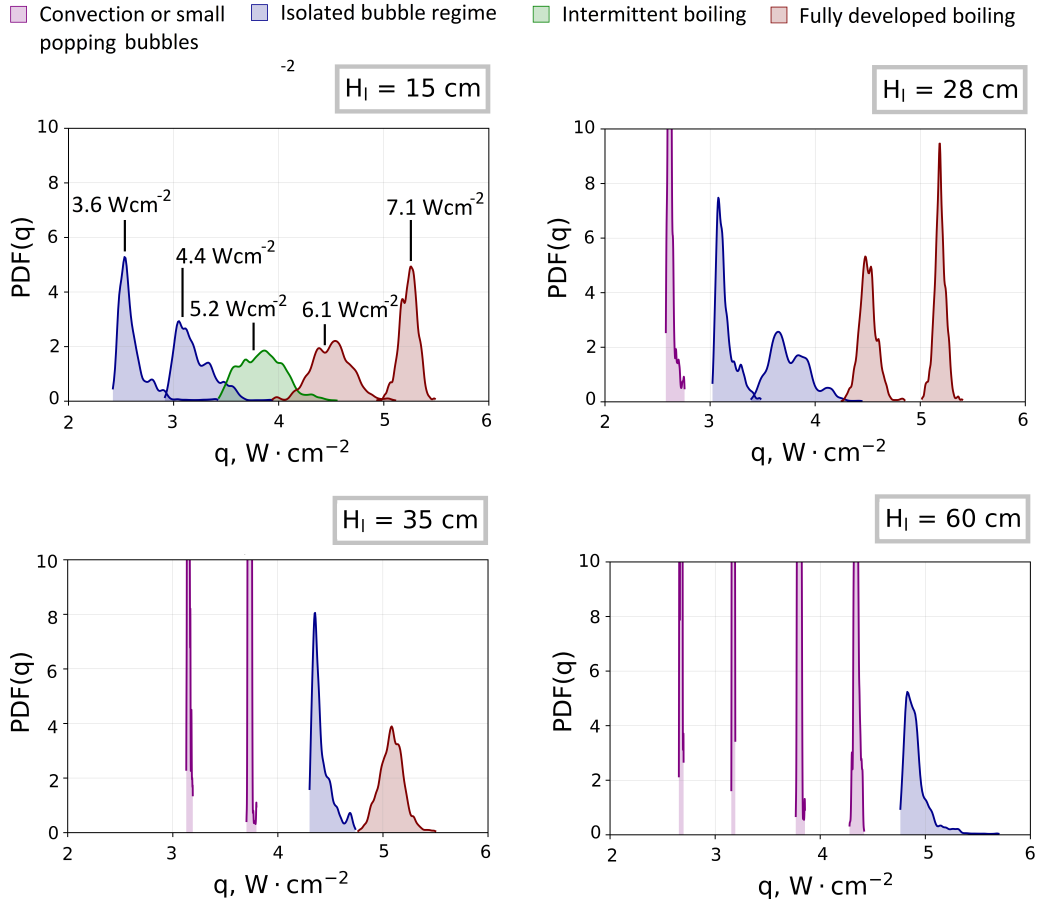


Figure 12: PDF graphs for vapor pressure $p_v = 2.4$ kPa (applied heat fluxes for the graphs from left to right: $3.6 \text{ W}\cdot\text{cm}^{-2}$, $4.4 \text{ W}\cdot\text{cm}^{-2}$, $5.2 \text{ W}\cdot\text{cm}^{-2}$, $6.1 \text{ W}\cdot\text{cm}^{-2}$ and $7.1 \text{ W}\cdot\text{cm}^{-2}$).

317 5. Boiling regime map

318 The analysis of the PDFs was performed for all operating conditions
 319 (three vapor pressures, four levels of liquid, five applied heat fluxes). To
 320 illustrate how changes of the operating parameters affect the type of the
 321 boiling regime, boiling regime maps are proposed. These maps identify the
 322 regime as a function of applied heat flux (abscissa) and liquid level (ordinate)
 323 for a given vapor pressure (Fig. 13).

324 For the studied values of vapor pressures, all boiling maps look different,
 325 although they possess some common features - at least, for all cases, the same
 326 boiling regimes can be observed. When increasing the applied heat flux, first

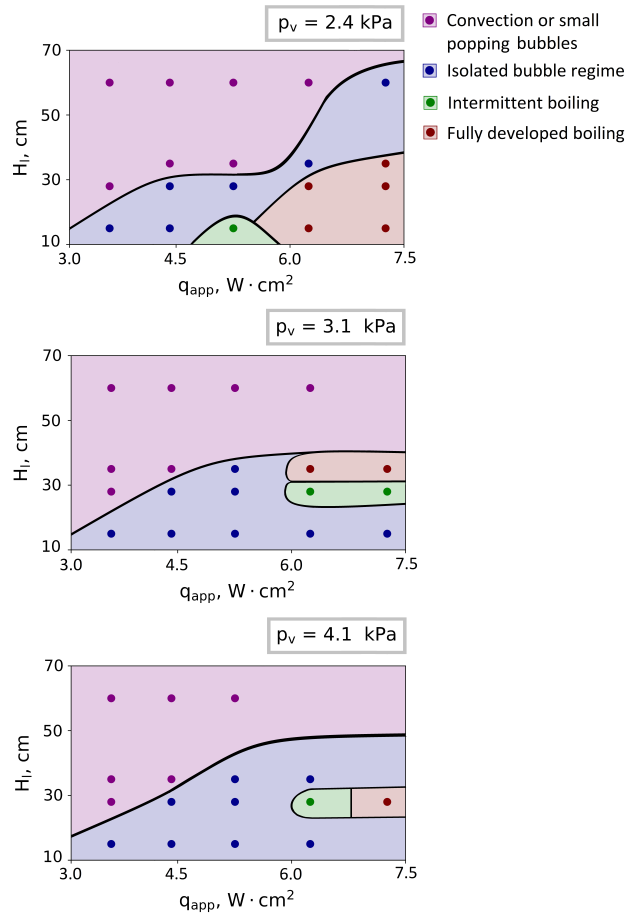


Figure 13: Boiling regime maps created for various pressures, liquid levels and applied heat fluxes.

327 there is a region of convection or eventually small popping bubbles (purple
 328 region). Then, isolated bubbles not interacting with each other start to be
 329 formed (blue region). At low pressure, due to low vapor density, the bubbles
 330 usually exhibit a large size, comparable to the size of the heated surface, so
 331 only one bubble is present on the surface at a time. When the applied heat
 332 flux is increased further, the fully developed boiling regime occurs, which is
 333 characterized by existence of multiple bubbles, often interacting with each
 334 other (red region). For certain conditions also the intermittent boiling regime
 335 is detected (green region).

336 For given level of liquid and value of applied heat flux, the regime depends

337 on the vapor pressure. For instance, for $p_v = 2.4$ kPa and $H_l = 15$ cm, with
 338 increasing applied heat flux, one can observe successively isolated bubble
 339 regime, intermittent boiling regime and fully developed boiling regime. For
 340 the other vapor pressures ($p_v = 3.1$ kPa and $p_v = 4.1$ kPa), only the isolated
 341 bubble regime is observed. These differences are caused by the increase
 342 of saturation temperature for higher vapor pressures, as it requires higher
 343 applied heat flux to initiate boiling or reach specific type of regime.

344 To develop a dimensionless boiling map for low pressure boiling, it was
 345 first chosen the abscissa to be the rate of the vapor pressure to the static
 346 pressure (p_v/p_{stat}). This ratio is believed to be good representative of both
 347 low pressure conditions (p_v) and intensity of the subcooling degree (p_{stat}).
 348 For the ordinate, physical considerations led to the definition of a modified
 349 Jakob number. The Jakob number is dimensionless number often used in the
 350 analysis of phase change heat transfer to represent the ratio of the sensible
 351 and the latent heat. Therefore, one of its most common form is [29, 30]:

$$Ja = \frac{c_{p(l)} \Delta T_{wall}}{\Delta h_{lv}} \quad (6)$$

352 This form of the Jakob number is particularly suitable to constant tem-
 353 perature conditions. It cannot be used directly to include the heat flux in
 354 the analysis, while it was demonstrated that the heat flux strongly affects
 355 the boiling regimes. To include the effect of the heat flux, it was decided
 356 to replace the temperature difference of the Jakob number by one scaling
 357 of it. This is a common practice for instance in the case of single phase
 358 convection, when the classical Grashof number is changed to the so-called
 359 "modified Grashof number" [31].

360 The proposed scaling for the wall superheat is based on the process of heat
 361 diffusion in the thermal boundary layer, in the fluid above the heated wall.
 362 This was the physical basis of the nucleation model of Mikic and Rohsenow
 363 [32]: in this model, the thickness of the boundary layer was supposed to be
 364 of the order of magnitude of the bubble size, that can besides be approached
 365 by the capillary length. Therefore, assuming that

$$\Delta T \sim \frac{q_{app} L_c}{\lambda_l} \quad (7)$$

366 the modified Jakob number can be defined as:

$$Ja^* = \frac{c_{p(l)} L_c q_{app}}{\Delta h_{lv} \lambda_l} \quad (8)$$

367 The boiling map created based on the modified Jakob number defined
 368 by Eq. 8 is presented in Fig. 14. various boiling regions are marked in the
 369 same manner as on previous boiling maps (purple color - convection or small
 370 popping bubbles region, blue color - isolated bubble region, green color -
 371 intermittent boiling region, red color - fully developed boiling region).

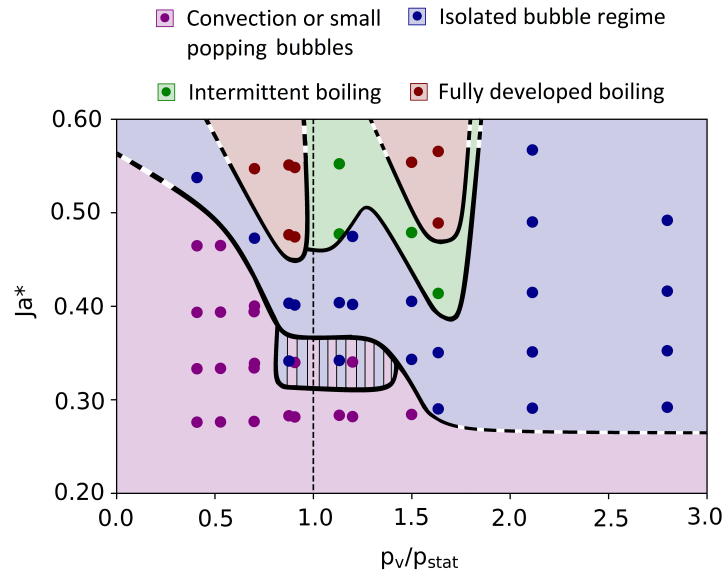


Figure 14: Dimensionless boiling map for subatmospheric pressure.

372 The map is divided into two parts. For $p_v/p_{stat} < 1.0$, the boiling process
 373 is mainly driven by high value of subcooling. This explain the existence of
 374 large regions of convection or small popping bubbles. In the case of $p_v/p_{stat} >$
 375 1.0 , the low pressure effects are induced mainly by low value of vapor pressure.
 376 The hydrostatic pressure influences the boiling behavior to a smaller extent
 377 because it has lower value than the vapor pressure. At such conditions, low
 378 values of heating power (low Jakob number) cause immediately the existence
 379 of isolated bubble regime

380 High values of heat flux lead to fully developed boiling regime. This
 381 type of boiling was obtained for lower Jakob number in the close proximity
 382 of $p_v/p_{stat} = 1$. For the highest applied heat flux reached in the present

383 experiments ($q_{app} = 7.1 \text{ Wcm}^2$), if p_{stat} or p_v are too large, the isolated
 384 bubble regime is observed. For high heat fluxes and p_v/p_{stat} value in the
 385 range $[1; 1.6]$, the intermittent boiling regime was also observed.

386 The region close to $p_v/p_{stat} = 1$ and $Ja^* = 0.35$ occurred to be the
 387 transition between the convection or small popping bubbles region (purple
 388 area) and isolated bubble regime (blue area).

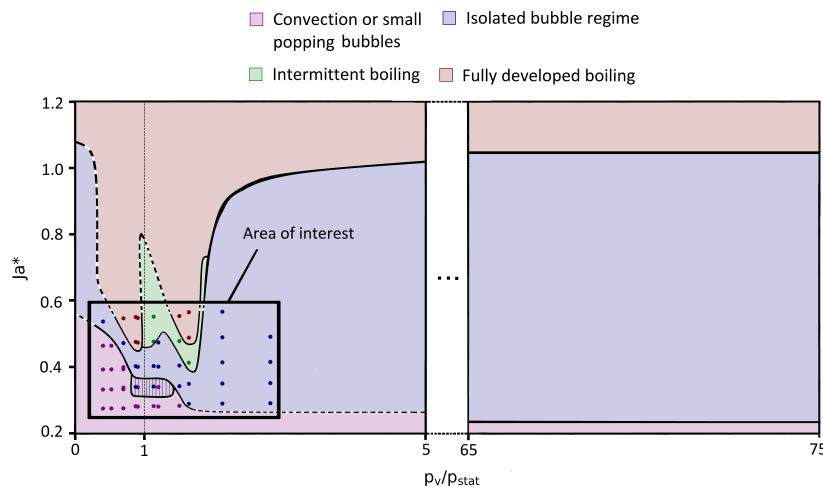


Figure 15: Dimensionless boiling map for a broad range of input parameters (up to atmospheric pressure).

389 The experiments were performed for low vapor pressure, which corre-
 390 sponds to $p_v/p_{stat} < 5$. However, most of the experiments for water reported
 391 in the literature were conducted close to the atmospheric pressure. For $p_v =$
 392 100 kPa and $H_l = 15 \text{ cm}$, the pressure ratio p_v/p_{stat} is equal to 70. At such
 393 conditions, three different regimes are usually distinguished. For instance,
 394 Gaertner [33] observed the convection regime up to $q_{app} = 3.3 \cdot 10^4 \text{ W}\cdot\text{m}^{-2}$
 395 ($Ja^* = 0.25$), the isolated bubbles regime ($3.3 \cdot 10^4 \text{ W}\cdot\text{m}^{-2} < q_{app} < 1.5 \cdot 10^5$
 396 $\text{W}\cdot\text{m}^{-2}$ what corresponds to $0.25 < Ja^* < 1.08$) and the fully developed boil-
 397 ing regime ($q_{app} > 1.5 \cdot 10^5 \text{ W}\cdot\text{m}^{-2}$ what corresponds to $Ja^* > 1.08$). The
 398 region which was the scope of the present experiments, is thus quite narrow
 399 in respect to all possible operating conditions: Fig. 15 shows how the present
 400 boiling map could be extended to the range of high p_v/p_{stat} corresponding
 401 to Gaertner’s observations and where the boiling regimes this author distin-
 402 guished would be located on such a map. This graph reveals the huge gap
 403 between the conditions studied in the present work and the published data

404 on pool boiling close to the fluid normal point. It also highlights that the
405 regime of intermittent boiling is specific to low pressure boiling. The com-
406 plexity of the distribution of the regimes on the map justifies the importance
407 of further investigation of the pool boiling close to the triple point. The
408 high pressure is much less sensitive to the changes of the liquid level, thus
409 the borders between specific regimes are very clear and form straight, almost
410 horizontal lines.

411 6. Conclusions

412 Subatmospheric pool boiling experiments were conducted for various work-
413 ing parameters: vapor pressures ranging from 2.4 kPa up to 4.1 kPa, liquid
414 levels of 15 cm, 28 cm, 35 cm, 60 cm and several applied heat fluxes (3.6
415 $\text{W}\cdot\text{cm}^{-2}$, 4.4 $\text{W}\cdot\text{cm}^{-2}$, 5.2 $\text{W}\cdot\text{cm}^{-2}$, 6.1 $\text{W}\cdot\text{cm}^{-2}$ and 7.1 $\text{W}\cdot\text{cm}^{-2}$). The liq-
416 uid level is of specific importance for subatmospheric boiling: it was indeed
417 shown that it controls through the static pressure it imposes, a subcooling of
418 liquid that affects the heat transfer. Thermal measurements including mea-
419 surements of temperatures and of instantaneous heat flux transmitted to the
420 fluid were synchronized with high-speed camera recordings.

421 To discover how the different operating parameters influence the boil-
422 ing behavior, the analysis of the time evolution of heat flux was performed
423 statistically based on probability density functions (PDFs). It was then ex-
424 emplified how this type of analysis constitutes a good tool for studies of
425 the boiling behavior. Owing to this type of statistical analysis, supported
426 by visual observations, four distinct boiling regimes were distinguished and
427 characterized: the convection or small popping bubbles regime, the isolated
428 bubble regime, the intermittent boiling regime, the fully developed boiling
429 regime.

430 For liquid levels $H_l = 15$ cm and $H_l = 28$ cm, the most common regime
431 is the one of isolated bubbles. It is characterized by bubbles with large
432 diameters detaching with low frequency. For the high level of liquid mostly
433 the convection or small popping bubbles were observed.

434 The variety of the regimes observed at low pressures at different liquid
435 levels proves the importance of the subcooling caused by the static head.
436 In the future, it would be of interest to study the difference between the
437 temperature-induced subcooling and pressure-induced subcooling. For this
438 purpose, the boiling process should be studied firstly for high level of liquid
439 (e.g. $H_l=60$ cm, $T_l = T_{sat}$) and then lower liquid level with liquid bulk

440 temperature lower than saturation temperature (e.g. $H_l=15$ cm $T_l < T_{sat}$)
441 in such a way that at wall level both subcoolings are equivalent.

442 To provide a more general description of boiling regimes over the range
443 of operating conditions tested, a dimensionless boiling regime map was pro-
444 posed. The abscissa was chosen to be the ratio of vapor pressure to the static
445 pressure. It is a good representative of both, low pressure conditions (p_v),
446 and subcooling of liquid (strongly dependent by p_{stat}). As an ordinate, a mod-
447 ified Jakob number was proposed adapted to conditions of constant heat flux
448 encountered in the present experiments. When $p_v/p_{stat} < 1.0$, the boiling
449 mode is mostly driven by intense liquid subcooling (thus, mostly convection
450 or small popping bubbles regime is observed as the subcooling induced by
451 the high static pressure results in a strong condensation of any generated
452 vapor). When $p_v/p_{stat} > 1.0$, even for low values of applied heat fluxes,
453 other regimes are often already noted. This boiling regime map is useful
454 to determine the thermo-hydrodynamic feature of subatmospheric boiling.
455 Its consistency with the knowledge developed for higher pressures (typically
456 close to atmospheric pressure) remains to be investigated in detail, both for
457 saturated and subcooled conditions. Finally, to truly validate the correctness
458 of dimensionless boiling map, more experiments with various working fluids
459 should be conducted.

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