



**HAL**  
open science

## A new experimental method for characterizing boiling regimes of water in vertical milli-channels

Guillaume Henry, Alexandra Pere-Gigante, Jacopo Seiwert, Solène Valentin, Marc Wagner, Émilien Girot, François Mendy, Jean-Marc Jean-Marc.Commenge@univ-Lorraine.Fr Commenge

### ► To cite this version:

Guillaume Henry, Alexandra Pere-Gigante, Jacopo Seiwert, Solène Valentin, Marc Wagner, et al.. A new experimental method for characterizing boiling regimes of water in vertical milli-channels. Chemical Engineering and Processing - Process Intensification, 2021, 159, pp.107889. 10.1016/j.cep.2020.107889 . hal-03198406

**HAL Id: hal-03198406**

**<https://hal.univ-lorraine.fr/hal-03198406>**

Submitted on 3 Feb 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# 1 A new experimental method for characterizing boiling regimes of 2 water in vertical milli-channels

3 Guillaume HENRY<sup>a,\*</sup>, Alexandra PERE-GIGANTE<sup>a</sup>, Jacopo SEIWERT<sup>b</sup>, Solène  
4 VALENTIN<sup>b</sup>, Marc WAGNER<sup>b</sup>, Émilien GIROT<sup>a</sup>, François MENDY<sup>a</sup>, Jean-Marc  
5 COMMENGE<sup>a</sup>

6 <sup>a</sup> Université de Lorraine, CNRS, Laboratoire Réactions et Génie des Procédés, UMR 7274, Nancy, F-54000

7 <sup>b</sup> Air Liquide, Centre de Recherche Paris-Saclay, 1 chemin de la Porte des Loges, Les Loges-en-Josas, BP 126, 78354 Jouy-  
8 en-Josas, France

9 \*Corresponding author: [guillaume.henry@univ-lorraine.fr](mailto:guillaume.henry@univ-lorraine.fr)

10 Address: 1 rue Grandville, BP 20451, F-54001 NANCY Cedex

11

## 12 **Abstract**

13 Over the past few decades, high-performance heat-transfer devices have been studied for  
14 numerous applications. Boiling flow in such confined spaces induces high-frequency flow  
15 instabilities that directly influence the heat-transfer performances. A small-scale water  
16 vaporizer with 10 millimeter-sized channels is experimentally studied over a wide range of  
17 vapor quality (0.05 – 1). The peculiarity of the setup is a transparent window that allows for  
18 high speed imaging of the boiling flow up to 5 bars. This work focuses on a post-processing  
19 method based on spatio-temporal diagrams. Hydrodynamics of the boiling flow can be  
20 observed on the diagrams enabling to understand the boiling mechanisms and the flow  
21 regimes inside the channels. Four regimes are observed, namely bubbly, slug, churn and  
22 annular flow. Diagrams are also used to estimate the local mean void fraction over time in  
23 channels, the local vapor quality, the slip ratio and a flow-regime map. For qualities under  
24 10%, the bubbly flow is predominant in channel. For higher qualities, if the specific mass  
25 flow rate of water is below 37 kg/s/m<sup>2</sup>, only the slug flow and the annular flow are observed,  
26 whereas the churn flow is also observed for larger flow rates.

27

28 **Keywords:** boiling flow, flow map, milli-channels, high-speed visualization, quality, heat  
29 transfer.

30

## 31 **1. Introduction**

32 Heat exchangers with millimeter-sized channels have raised a significant interest in the field  
33 of chemical engineering over the last few decades and for numerous industrial applications.  
34 Reference books, Stankiewicz and Moulijn [1], Dietrich [2] and Hessel et al. [3], develop the  
35 concept of process intensification by presenting the existing equipment and methods used. In  
36 particular, the main benefits of using microstructures is their high compactness and their high  
37 volume/surface ratio, which enables a better control of operating parameters such as fluid  
38 temperature or flow mixing. Meanwhile, the ever-growing interest for hydrogen as an  
39 alternative for cleaner mobility requires new process designs for its production (Surla [4]).  
40 Indeed, the main part of the hydrogen is currently produced by Steam Methane Reforming  
41 (SMR) processes and close to refinery plants (Giroudière et Le Gall [5]). Since hydrogen  
42 transport suffers from numerous hazards (explosiveness, leakages, etc.), a decentralized  
43 production is required for the deployment of this new vector of energy.

44 Some studies have been performed on the intensification of the reformer; Frauhammer et al.  
45 [6] studied the applicability of counter-current reformer with capillarity tubes. More recently,  
46 Bhat and Sadhukhan [7] presented in their review various ways to intensify the reforming  
47 process, e.g. by improving catalyst efficiency or using membranes. Although there exist  
48 technical solutions to intensify the reforming reactor, all the other pieces of equipment (heat-  
49 exchanger, separator, etc.) operating in the process have also to be considered for  
50 intensification.

51 This study focuses on the vaporizer of the SMR process called the Waste Heat Boiler (WHB),  
52 which valorizes the remaining heat of hot gases outgoing the heat-exchanger reactor as steam  
53 (required for the reforming reaction). Intensification of industrial WHB, usually designed as  
54 shell-and-tubes heat exchangers, can be performed using milli-channels.

55 Boiling flow in milli- or micro-structures has led to numerous publications during the past  
56 fifty years. Numerous modern applications, such as microchips cooling, require an efficient  
57 heat transfer to operate properly. In most studies, the fluid is a typical refrigerant such as  
58 HFE7100 for Solotych et al. [8] or R134a for Sempertegui-Tapia et al. [9] because of its low  
59 boiling temperature and its compatibility with electronic devices. However, recently water  
60 raised a new interest since it is a non-pollutant fluid with a high latent heat of vaporization  
61 (often ten times larger than freons) enabling a better heat recovery at a later stage.

62 One key parameter of boiling flow heat transfer is the two-phase heat-transfer coefficient,  
63 which indicates the performance of a micro/milli-heat exchanger. Some authors, for instance  
64 Lazarek and Black [10], Kew and Cornwell [11] or Pamitran et al.[12], worked on a  
65 predictive general correlation of this coefficient for various operating conditions and fluids.  
66 The recent review of Cheng and Xia [13] highlights the fact that these correlations are still not  
67 accurate for all experimental data available in the literature. Furthermore, the same operating  
68 conditions can lead to different values of heat-transfer coefficient, which confirms that boiling  
69 phenomena are complex to predict correctly. In addition, conclusions of a specific review by  
70 Fang et al. [14] highlight that there is no accurate correlation to predict subcooled flow  
71 boiling heat transfer applied to water.

72 The identification of the different two-phase flow regimes in a milli-channel is crucial for the  
73 understanding of heat transfer between the fluid and the walls of the channel. Focusing on the  
74 case of boiling water in channels, Yin et al. [15] studied the effect of the Boiling number,  $Bo$ ,  
75 for large aspect ratio microchannel on boiling flow regimes. They observed the flow regime

76 transitions through the following patterns with increasing Bo: discrete bubble flow, confined  
77 bubble flow, sweeping flow, churn flow and wispy flow when Critical Heat Flux is reached.  
78 Lu et al. [16] also described for water the isolated bubbly flow, the slug flow, the churn flow  
79 and the annular flow in conventional vertical channels. However, for vertical mini-channels,  
80 they reported that the effect of surface tension and the confinement force the bubbles to  
81 quickly coalesce leading to a predominant slug flow regime.

82 It is commonly admitted that boiling flow heat transfer can be related to two main heat-  
83 transfer mechanisms: nucleate boiling and convective boiling heat transfer. Both of these  
84 mechanisms encompass several flow regimes. According to Kim and Mudawar [17], nucleate  
85 boiling mechanism gathers dominant bubbly and slug flow regime whereas the convective  
86 boiling mechanism presents a dominant annular flow regime. Furthermore, Kim and  
87 Mudawar [17] present three scenarios where the value of the heat-transfer coefficient is  
88 directly related to flow regimes inside the micro/milli-structure. In numerous predictive heat-  
89 transfer models, e.g. Chen's correlation [18] or most recently the Chen derived correlation  
90 published by Yan et al. [19], the two mechanisms are taken into account and are weighted as a  
91 function of the vapor quality.

92 According to Kandlikar [20] and Thome [21], the effects of capillarity on flow regimes inside  
93 the channel only occur at a micro-scale. The Kumar et al. [22] review highlights an unclear  
94 threshold to classify geometries in the micro/milli/macro-scale. Some thresholds are based on  
95 geometry parameters such as the hydraulic diameter whereas others rely on dimensionless  
96 numbers such as the Boiling number. Kumar et al. [22] suggest a threshold between micro-  
97 and macro-scale at a hydraulic diameter of 1 mm. According to this limit, the 2 mm semi-  
98 circular channels studied ( $D_h = 1.22$  mm) in this paper are considered macro-channels.  
99 Therefore, flow regimes similar to those presented in details by Chen [23] are expected,  
100 namely bubbly, slug, churn and annular flow. Nevertheless, in order to avoid any confusion

101 about this unclear threshold, it has been decided to qualify the studied channels according to  
102 their dimension and not their type, e.g. milli-channels.

103 High-frequency films are a common practice for the identification of boiling flow regime in  
104 milli- or microstructures since observed phenomena last less than one second. Flow regime  
105 observations on a single channel, in various references in the literature, are presented through  
106 a sequence of channel pictures with a specific time step. Steinke and Kandlikar [24] used this  
107 method to present flow reversal and micro-channel dry-out flow of a water boiling flow in a  
108 single vertical channel. More recently, Yin et al. [15] also used it to present the effect of the  
109 Boiling number on the flow regime observed. The sweeping, the churn and wispy flow are  
110 also described. If this common method enables to highlight a specific phenomenon in the  
111 channels, it is not well adapted to describe all the boiling events over time and the related  
112 instabilities. The description of all the phenomena can become a tedious task if a consequent  
113 number of pictures has to be temporally spotted, extracted and presented.

114 In this work, an original post-treatment method of high-speed movies of a water boiling flow  
115 in vertical semi-circular channels is developed. The result of this method is called spatio-  
116 temporal diagrams. It enables the spotting and the understanding of localized hydrodynamics  
117 that occur in the channels and flow boiling patterns and regimes can be identified. A  
118 quantitative approach of the spatio-temporal diagram is applied to assess the local quality in  
119 channels in order to draw a flow-regime map. The thermal performance of a small-scale water  
120 vaporizer measured experimentally under various operating conditions is used to validate this  
121 approach. In addition, the global vapor quality produced by the vaporizer is also discussed.

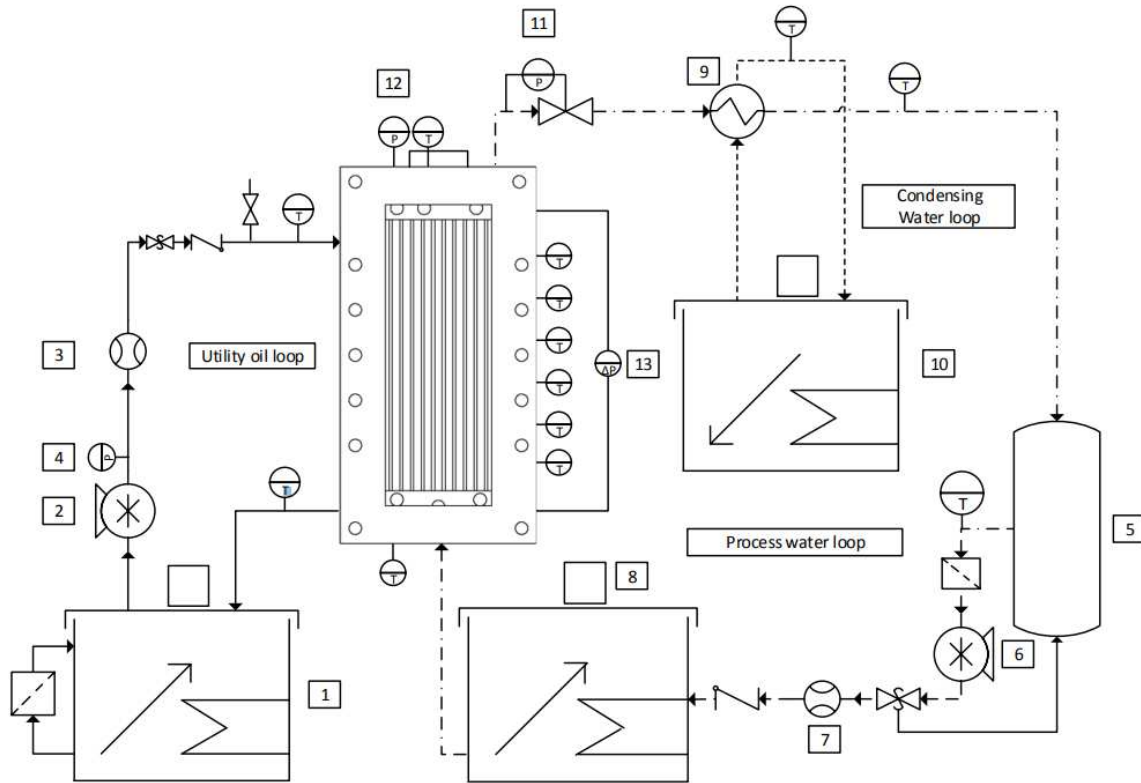
## 122 **2. Material**

### 123 *2.1. Experimental set-up*

124 For this work, a dedicated test bench was built to operate intensified industrial waste heat  
125 boiler at laboratory scale; its Process & Instrumentation Diagram (P&ID) is presented in  
126 *Figure 1*. The spatial organization of the test bench is presented in *Figure 2*. Three different  
127 loops of fluids are required: a hot utility loop to provide heat, another one for the process fluid  
128 (water) being preheated and vaporized and the last one to condensate the produced vapor. The  
129 hot loop uses a silicon oil flow as the heat-transfer fluid. Instead of using a classical electrical  
130 resistance, a silicon oil as heating source has been preferred in order to limit the wall  
131 temperature on the water side. Indeed, an electrical resistance cannot reproduce the thermal  
132 exchange between two fluids since its temperature and its heat flux cannot be controlled  
133 separately.

134 A JULABO SE-6 temperature-controlled bath (20 – 300 °C; 3 kW; n° 1) heats Julabo  
135 Thermal HS silicon oil. The hot oil is pumped by a MAAG Refinex 22/22 gear pump (1 – 10  
136 L/min; n° 2) and its flow rate is measured by a YOKOGAWA Rotamass Nano Coriolis  
137 flowmeter (0 – 950 kg/h; n° 3). The discharge pressure of the pump is measured by a  
138 YOKOGAWA absolute pressure sensor (0 - 20 bars; n°4) to ensure safe operation of the  
139 pump.

140



141

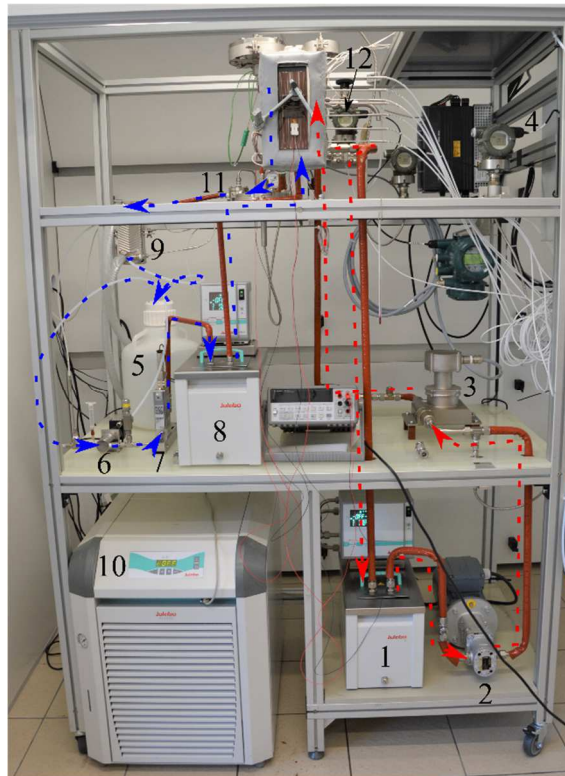
142 *Figure 1: Process & Instrumentation Diagram of the test bench (1: oil bath; 2: oil pump; 3:*  
 143 *oil flowmeter; 4: oil pressure sensor; 5: water tank; 6: process water pump; 7: water*  
 144 *flowmeter; 8: process water preheater; 9: condenser heat-exchanger; 10: cooler; 11:*  
 145 *pressure controller; 12: absolute pressure sensor; 13: differential pressure sensor).*

146 The process fluid, demineralized water, is stored in a tank at room temperature (n° 5). The  
 147 fluid is pumped by a HNP Mikrosystem mzs-7205 gear pump (0.048 – 248 mL/min; n° 6) and  
 148 the flow rate is measured by a BRONKHORST mini CORI-FLOW Coriolis flowmeter (0.4 –  
 149 20 kg/h; n° 7). Before entering the test section, the flow is preheated through helical spires by  
 150 silicon oil in a JULABO ME-6 temperature-controlled bath (20 – 200 °C; 2 kW; n° 8). At the  
 151 test section outlet, the two-phase flow is condensed in a plate heat exchanger (n° 9) cooled by  
 152 cold water provided by a JULABO FL-1201 cooler (-20 – 40 °C; 1.2 kW; n° 10). The  
 153 pressure inside the test section is regulated by a QBS Equilibar discharge pressure controller  
 154 (1 – 5 bars; n° 11).



155 Temperatures are measured at various locations in the test bench by 1/10 DIN PT 100 sensors.  
156 In the hot oil fluid loop, the sensors are located at the inlet and outlet of the test section in  
157 order to estimate the heat flux provided by the oil flow. In the process fluid loop, the  
158 temperature is measured in the test section, and at the outlet of the condenser to control its  
159 cooling efficiency.

160 The test bench operates the test section called vaporizer, which is a milli-structured plate heat  
161 exchanger manufactured in house. The vaporizer (130 mm x 250 mm x 50 mm), presented in  
162 *Figure 3*, is composed of four different parts: a borosilicate glass and three stainless steel  
163 engraved plates. Both water and oil flows enter the vaporizer through the multi-tasks block:  
164 the water just flows through the block via chambers whereas the oil flow is contained in the  
165 rectangular cross-section channel (2.5 mm x 9 mm) in the middle of the block. More  
166 precisely, the water enters at the bottom of the multi-task block inside the distribution  
167 chamber, then the water flow is vaporized along ten vertical semi-circular cross-section  
168 channels (diameter 2 mm) mechanically engraved with a total length of 180 mm. Finally, the  
169 two-phase water flow is gathered in the collection chamber located at the top of the plate and  
170 the multi-task block before leaving the vaporizer. Hydrodynamics in the channels can be  
171 observed through the borosilicate window (11 mm thick) maintained by the lid. This  
172 vaporizer was designed to operate a boiling flow under a maximum pressure of five bars. In  
173 order to ensure the insulation of the vaporizer, a custom insulating coat, made from  
174 MATELIS 500 material (glass fibers fabric, thickness 6 mm), encapsulates the test section.

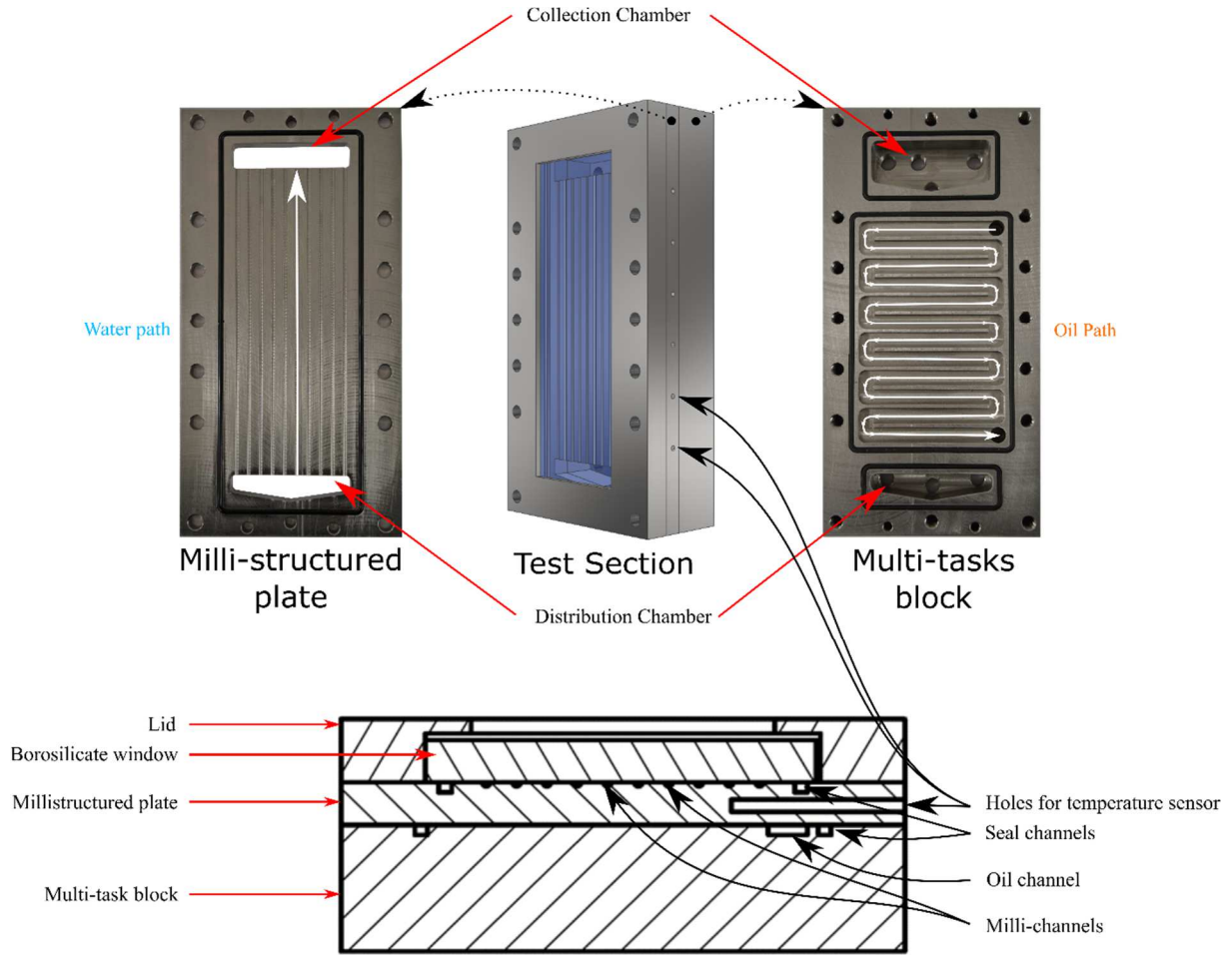


175

176 *Figure 2: Spatial organization of the test bench (numbers refer to caption of Figure 1)*

177 Some data are directly measured in the test section, namely the temperature with PT100  
 178 sensors in both chambers, the pressure in the collection chamber by a YOKOGAWA absolute  
 179 pressure sensor (0 - 20 bars, n° 12) and the differential pressure along channels by a  
 180 YOKOGAWA differential pressure sensor (0 – 5 bars, n° 13). The temperature at the center  
 181 of the dividing wall between the hot oil and the boiling water is measured along the milli-  
 182 structured plate by PT100 sensors placed in dedicated holes (*Figure 3*). In addition, heat  
 183 losses are measured during specific experiments with two heat flux meters FHF02 from  
 184 HUKSEFLUX, positioned on the borosilicate window and on the back of the vaporizer, on  
 185 the insulating coat. The heat flux meter on the window is visible in *Figure 2*, it is maintained  
 186 with a metallic clamp. The thermal contact between the patch and the surface is ensured by a  
 187 thermal conductor sheet.

188



190

191 *Figure 3: Detailed view of the test section (vaporizer): assembled (middle), milli-structured*  
 192 *plate (left), multi-task block (right) and horizontal cross-sectional view of the vaporizer*  
 193 *(bottom).*

194 **2.2. Experimental operating conditions**

195 The possible ranges of the operating parameters are summarized in *Table 1*.

<b><i>Operating parameter</i></b>	<b><i>Range</i></b>	<b><i>Unit</i></b>
Hot oil flow rate	180 (0.05)	kg/h (kg/s)
Water flow rate	0.3 – 6 ( $8.3 \cdot 10^{-8}$ – $1.67 \cdot 10^{-6}$ )	L/h ( $m^3/s$ )
Corresponding to a specific water flow rate	5 – 53	kg/m <sup>2</sup> s

Oil temperature	130 – 180	°C
Water pre-heating temperature	30 – 130	°C
Pressure	1 (10 <sup>5</sup> )	Bar (Pa)

196 *Table 1: Experimental operating parameters ranges.*

197 In this work, only experiments performed at atmospheric pressure are presented. Moreover,  
 198 the oil flow rate is fixed at 180 kg/h since specific experiments highlighted the small influence  
 199 of the oil flow rate on the vapor quality produced ( $\pm 12\%$  over an oil flow rate range from 75  
 200 to 180kg/h). These experiments are not presented here for the sake of concision.

201 *2.3. High-speed camera*

202 Hydrodynamics of the flow in the channels is recorded by a high-frequency MIKROTRON  
 203 EoSense mini 2© camera (up to 523 frames per second). The test section is illuminated by  
 204 three light sources, covered by a layer of tracing paper for more homogeneous illumination.  
 205 Since the internal data storage of the camera is limited, the shooting duration is influenced by  
 206 two main parameters: the framerate of capture and the size of the Region Of Interest (ROI).  
 207 This size impacts the size (in bytes) of each frame captured, therefore, it impacts the global  
 208 number of frames that can be stored in the camera memory. Here, we chose a fixed framerate  
 209 of 420 fps for an acquisition time between 5 and 10 seconds, depending on the size of the  
 210 ROI.

211 *2.4. Experimental procedure*

212 The first step of the experimental procedure consists in setting all operating parameters, then  
 213 all the measurable data on the test bench are picked up at steady state when the temperatures  
 214 of the test section are stabilized (which takes about one hour and a half for the first  
 215 experiment starting at ambient temperature and about half an hour after a change of one of the  
 216 operating parameters for each further experiment). The picked-up data are: the inlet and outlet

217 temperatures of both oil and water flows, the temperatures of the milli-structured plate, the  
 218 vaporizer pressure, and the mass flow rates of water and oil. A film of the boiling water is  
 219 then recorded.

### 220 3. Experimental methods and data treatment for analysis of flow regimes

#### 221 3.1. Spatio-Temporal Diagrams

222 Stacking images coming from high-speed movies is a simple and an easy method to present  
 223 the evolution of the boiling flow inside a channel. However, it can only show a short extract  
 224 of the movies for sake of clarity. In this work, a new film post processing based on the  
 225 creation of Spatio-Temporal Diagrams has been developed in order to enlarge duration of the  
 226 high-speed movie presented. It is elementarily described in *Figure 4*. A simplified film is  
 227 studied in this example to allow for a better understanding of the method.

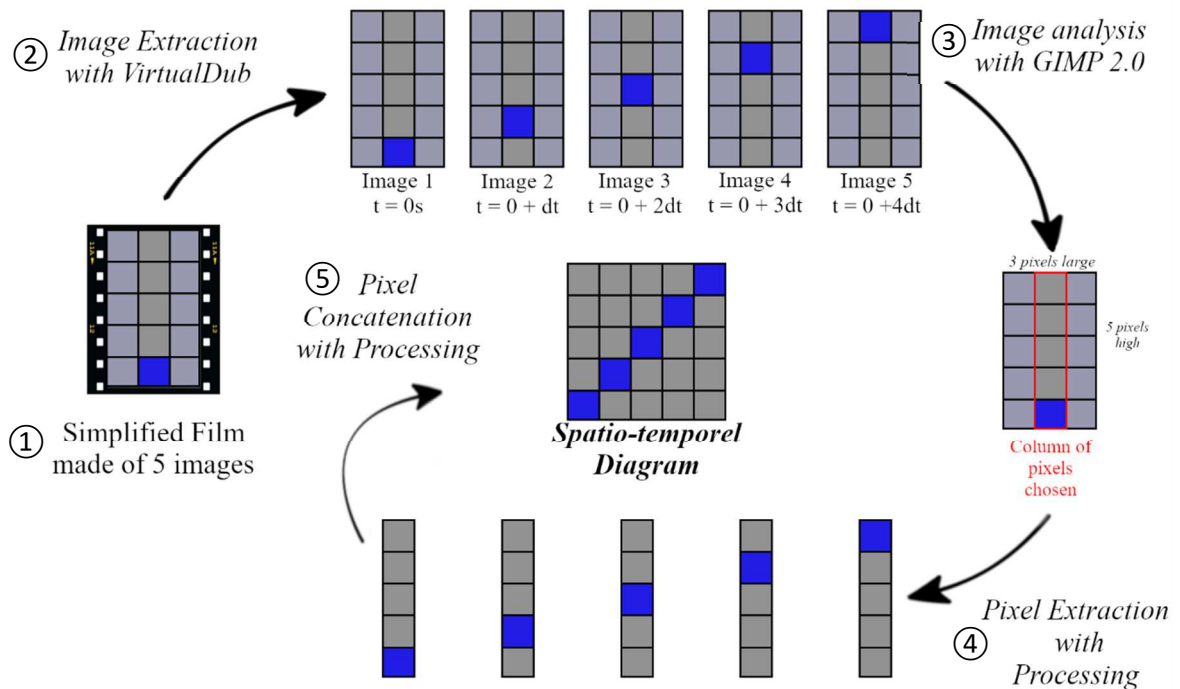


Figure 4: Method used to create spatio-temporal diagrams applied on a simple case.

230 A film is composed of many images scrolling at a chosen framerate. The software VirtualDub  
231 (step 2) is used to extract the image sequence from the film, composed by  $k$  images ( $k = 5$   
232 for the example). Each extracted image has the same dimensions corresponding to a matrix of  
233 ( $m$  lines  $\times$   $n$  columns) pixels ( $m = 5$  and  $n = 3$  in the example). In this study, since the  
234 camera is fixed on a tripod, the recorded film represents a static view of channels engraved in  
235 the milli-structured plate. It means that channels in the plate can be linked to columns of  
236 pixels in the images composing the film. To do that (step 3), the software GNU Image  
237 Manipulation Program (GIMP 2.0) is used to spot columns of pixels corresponding to  
238 channels. The average width of each channel on pictures is about 20 pixels. Among these 20  
239 columns, only one column is chosen for post-treatment, it is generally extracted in the middle  
240 of the channel where a better exposure is recorded (step 4).

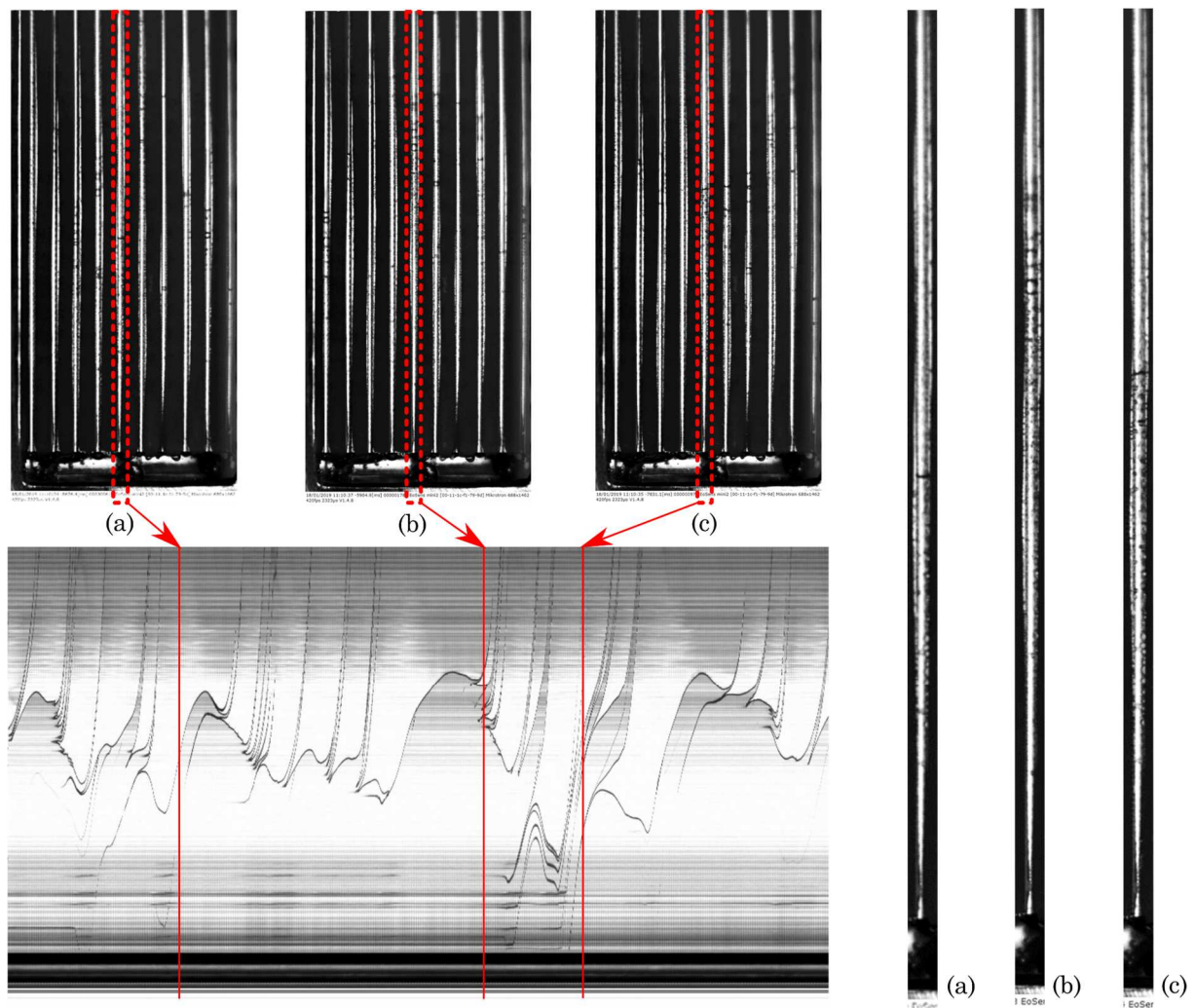
241 When the channels positions, e.g. the columns of pixels positions, are picked up, a third  
242 software, Processing, is used to create spatio-temporal diagram (step 5). The process consists  
243 in a loop over all the images of a video. For each image, the following steps are performed:

- 244 • The image is opened by the software,
- 245 • The chosen column of pixels corresponding to the channel of interest is copied,
- 246 • This column is incrementally pasted on the spatio-temporal diagram.

247 By pasting the same column of the successive images of the video, diagrams can be read from  
248 left to right to follow the chronology of events happening in the channel.

249 The same procedure is applied iteratively to each channel of the plate. At the end of the  
250 process, ten different spatio-temporal diagrams are obtained, one for each channel. The size of  
251 each diagram is ( $m$  lines  $\times$   $k$  columns) pixels. The X-axis of diagrams represents time  
252 whereas the Y-axis represents the position in the channels.

253 In *Figure 5*, one diagram created by the method described above is presented. It shows events  
 254 occurring in the fifth channel from the left of the milli-structured plate. Several images  
 255 extracted from the film at various time steps are presented above the diagram. In this case, the  
 256 choice of the fifth channel is done on the best exposure conditions criterion. Except for both  
 257 channels at the extremity of the plate (number 1 and 10), the same behavior is observed in the  
 258 other channels of the milli-structured plate but it is not presented here for sake of concision.



259  
 260 *Figure 5: Full images of the 10-channels plate at three different moments (top left), zoomed-*  
 261 *in views on the fifth channel at these same moments (right) while occurrence of the single-*  
 262 *phase flow (a), the nucleation in cascade (b), the spontaneous nucleation (c) and the*  
 263 *corresponding spatio-temporal diagram (bottom left) of the fifth channel; Oil flow rate 80*

264 *L/h, oil temperature 130°C, water flow rate 33 mL/min, water pre-heating temperature 50°C*  
265 *and atmospheric pressure.*

266 In this experiment, the 10 diagrams corresponding to the 10 channels are composed of 4218  
267 columns of pixels, with a height of 1746 pixels. It means that the original video was  
268 composed of 4218 images, and lasted approximately 10 seconds since the framerate chosen  
269 for recording was 420 fps.

270 This new method for the post-treatment of high-speed videos is not a silver bullet, it has some  
271 pros and cons that need to be discussed. On one hand, this innovative method enables the  
272 quick visualization of boiling phenomena over long durations (more than dozens of second if  
273 needed), it also enables a better understanding of the chronology and the causal links between  
274 phenomena. However, on the other hand, since the creation of these Spatio-Temporal  
275 Diagrams only focuses on one column of pixels extracted from the video, the diagram is not  
276 exhaustive. This issue can be tackled by calculating the average grey scale on the channel  
277 width, but both techniques are very sensitive to the video exposure conditions.

### 278 *3.2. Dynamic vapor quality*

279 The vapor quality is defined as the vapor mass fraction in the flow at the outlet of the test  
280 section:

$$x = \dot{m}_v / (\dot{m}_v + \dot{m}_l) \quad (1)$$

281 Where  $\dot{m}_v$  denotes the mass flow rate of the vapor phase (kg/s) and  $\dot{m}_l$  the mass flow rate of  
282 the liquid phase (kg/s).

283 When the heat is provided by an electrical cartridge, the specific flux can be considered  
284 uniform so that a local vapor quality can be assessed (Wang et al. [25], Lu et al. [16] and  
285 Sempértégui-Tapia et al. [9]). In this study, it is only possible to evaluate a global vapor



286 quality, i.e. the quality at the outlet of the test section, by writing the heat balance over the  
 287 whole vaporizer:

$$\dot{Q}_{oil} = \dot{Q}_{water} + \dot{Q}_{loss} \quad (2)$$

288 Where  $\dot{Q}_{oil}$  denotes the power transferred by the hot oil to the vaporizer (W),  $\dot{Q}_{water}$  the  
 289 received power by the water flow in the vaporizer (W) and  $\dot{Q}_{loss}$  the heat losses of the  
 290 vaporizer to the environment (W). The power transferred by the oil flow is defined by:

$$\dot{Q}_{oil} = \dot{m}_{oil} C_{p,oil} (T_{oil}^{in} - T_{oil}^{out}) \quad (3)$$

291 Where  $\dot{m}_{oil}$  denotes the oil mass flow rate (kg/s),  $C_{p,oil}$  the oil mass heat capacity (J/kg/K)  
 292 and  $T_{oil}^{in}$  and  $T_{oil}^{out}$  the inlet and outlet oil temperatures in the vaporizer respectively (°C).

293 The power received by the water flow can be divided in two different terms, by differentiating  
 294 the single-phase flow from the two-phase flow. A part of this power,  $\dot{Q}_{sp}$ , heats up the water  
 295 to reach its boiling point:

$$\dot{Q}_{sp} = \dot{m}_w C_{p,w} (T_w^{eb} - T_w^{in}) \quad (4)$$

296 Where  $\dot{m}_w$  denotes the mass flow rate of the water flow (kg/s),  $C_{p,w}$  the water mass heat  
 297 capacity (J/kg/K),  $T_w^{eb}$  the boiling temperature of water (°C) and  $T_w^{in}$  the inlet water  
 298 temperature in the vaporizer (°C). For the particular case of the inlet water temperature in the  
 299 vaporizer, the inlet water temperature is assumed equal to the temperature set in the pre-  
 300 heating bath by neglecting heat losses along the pipe between the pre-heating bath and the  
 301 vaporizer. The temperature probe measuring the water temperature in the distribution  
 302 chamber is only used to estimate the temperature of the water flow entering the channels. The  
 303 second part of the received power,  $\dot{Q}_{tp}$ , is dedicated to the partial vaporization of water:

$$\dot{Q}_{tp} = \dot{m}_w x \overline{\Delta H_v} \quad (5)$$

304 Where  $x$  denotes the global dynamic vapor quality and  $\overline{\Delta H_v}$  the water mass latent heat of  
 305 vaporization (J/kg). By substituting equations (3)-(4)-(5) in equation (2), the global vapor  
 306 quality calculation becomes:

$$x = \left( \dot{m}_{oil} C_{p,oil} (T_{oil}^{in} - T_{oil}^{out}) - \dot{Q}_{losses} - \dot{m}_w C_{p,w} (T_w^{eb} - T_w^{in}) \right) / (\dot{m}_w \overline{\Delta H_v}) \quad (6)$$

307 According to equation 6, the vapor quality value is closely related to heat losses. Heat losses  
 308 can be assessed using an overall convective heat-transfer coefficient using the measured mean  
 309 temperature of the plate (see Appendix A).

### 310 3.3. Uncertainty

311 The uncertainty presented in each plot in this study is calculated by the differential method,  
 312 according to the following equation:

$$e_{F(P_1, \dots, P_n)}^2 = \sum_{i=1}^n \left( \frac{\partial F(P_1, \dots, P_n)}{\partial P_i} e_{P_i} \right)^2 \quad (7)$$

313 Where  $F(P_1, \dots, P_n)$  is the considered function of  $n$  parameters  $P_i$ ,  $e_{F(P_1, \dots, P_n)}^2$  the estimated  
 314 square error of the function and  $e_{P_i}$  the uncertainty of the parameter  $P_i$ .

315 All the temperature probes have an accuracy of  $\pm 0.15$  °C. The oil flowmeter has an accuracy  
 316 of  $\pm 0.1$  kg/h, the water flowmeter of  $\pm 0.012$  L/h and the tension measured in the heat flux  
 317 meter of  $\pm 0.5$  mV. The uncertainty of heat losses is estimated to 20% of the total value (cf.  
 318 Appendix A). The estimation of the external surface of the test section is done by multiplying  
 319 two measured dimensions. Since the insulation of the vaporizer is made of fabric, the  
 320 measured dimension has an accuracy of  $\pm 1$  cm because of the fabric looseness. The major  
 321 source of uncertainty on the vapor quality is the temperature reading, more specifically the  
 322 calculation of the difference of temperature in the heat balance, with typical relative  
 323 uncertainties on the order of 35%.

324        3.4. Local vapor quality from local void fraction

325        Despite the lack of local data in the test section, a local void fraction can be determined using  
326        the spatio-temporal diagrams. The void fraction  $\alpha$  is defined by:

$$\alpha = A_v / (A_v + A_l) \quad (8)$$

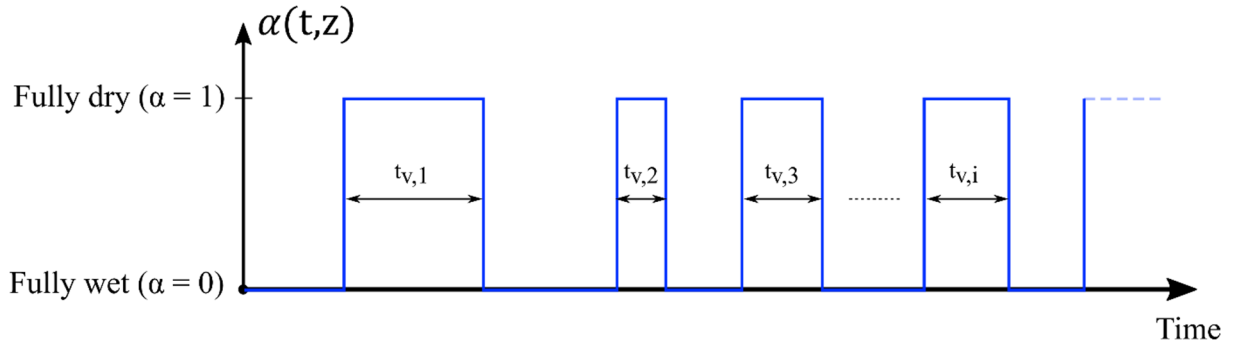
327        Where  $A_v$  (m<sup>2</sup>) and  $A_l$  (m<sup>2</sup>) are the cross-sectional areas occupied respectively by the vapor  
328        phase and the liquid phase.

329        A diagram allows the estimation of the local void fraction (at a given position in a channel) as  
330        a function of time. A time-averaged value is obtained by integrating over time:

$$\alpha_{av}(z) = 1/t_{tot} \int_0^{t_{tot}} \alpha(t, z) dt \quad (9)$$

331        Where  $\alpha_{av}(z)$  is the mean local void fraction at position  $z$ ,  $\alpha(t, z)$  the local void fraction as a  
332        function of time at this position, and  $t_{tot}$  the total duration considered to calculate the mean  
333        value (s).

334        As shown in *Figure 6*, an ideal slug flow would produce alternating light and dark patches at  
335        a given location along the channel (corresponding to a given horizontal line of the diagram).  
336        The darker patches correspond to periods when the channel is full of liquid (liquid slug) and  
337        the lighter patches to the flow of vapor (bubble). According to the color of patches, the local  
338        void fraction, namely 0 when the channel is full of liquid and 1 when it is full of vapor, can be  
339        associated at each time to determine the function  $\alpha_{av}(t, z)$ .



340

341 *Figure 6: Simplified evolution of the void fraction at a given position in a milli-channel under*  
 342 *slug flow conditions*

343 In other terms, at each moment in time, and for this location, the void fraction is equal either  
 344 to 0 or to 1 so that the mean void fraction over time can be computed as:

$$\alpha_{av}(z) = \sum_i t_{v,i}/t_{tot} \quad (10)$$

345 Where  $t_{v,i}$  denotes the duration of a phase where the considered location is completely dry  
 346 (s). This ideal case is not so often encountered in the obtained diagrams. Some others patches  
 347 are visible with intermediary brightnesses and associated with local void fractions included  
 348 between 0 and 1. The calculation of the average void fraction of these patches is discussed in  
 349 the section 4.4.2.

350 Another quantity is required to estimate the local vapor quality: the slip ratio  $S_r$  (or velocity  
 351 ratio). This ratio compares the velocities of the liquid phase and the vapor phase and is  
 352 defined as:

$$S_r = v_v/v_l \quad (11)$$

353 Where  $v_v$  (m/s) and  $v_l$  (m/s) are the velocities respectively of the vapor phase and the liquid  
 354 phase. It exists various methods for the calculation of this ratio, in this work an indirect  
 355 method is used and detailed in section 4.4.2.

356 According to equation (1), the vapor quality can also be developed as:

$$x_{local} = v_v A_v \rho_v / (v_v A_v \rho_v + v_l A_l \rho_l) \quad (12)$$

357 Where  $\rho_v$  (kg/m<sup>3</sup>) and  $\rho_l$  (kg/m<sup>3</sup>) denote the densities respectively of the vapor phase and the  
358 liquid phase. By substituting equations (8) and (11) in equation (12), the calculation of the  
359 local quality becomes:

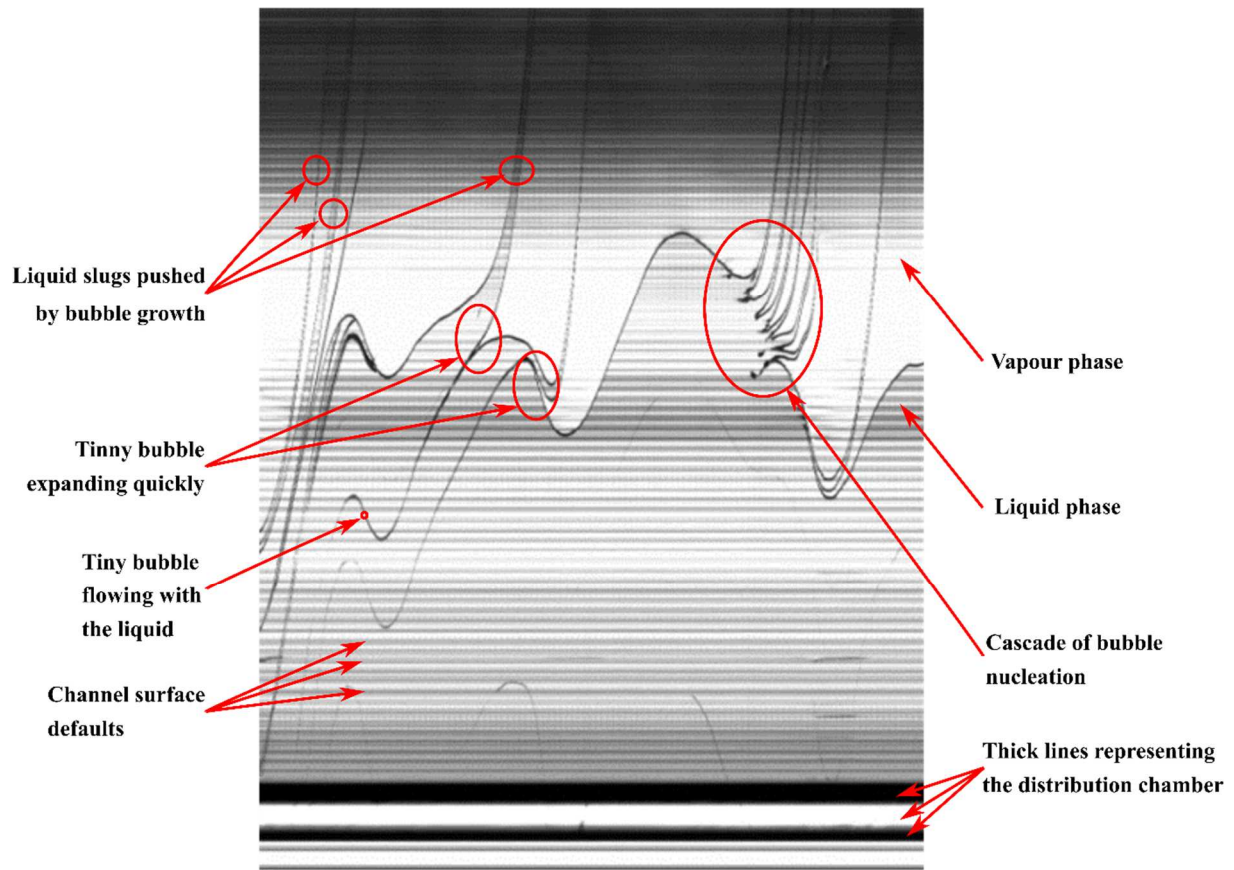
$$x_{local} = 1 / (1 + (1 - \alpha) / \alpha * \rho_l / \rho_g * 1 / S_r) \quad (13)$$

360 In this study, the mean void fraction over time and at a given position ( $\alpha_{av}(z)$ ) is taken into  
361 account to estimate the local quality.

## 362 **4. Results and Discussion**

### 363 *4.1. Diagrams interpretation*

364 Some elementary patterns are observed in these complex diagrams such as brightness  
365 changes, multiple lines (curvy lines or straight horizontal lines). In *Figure 7*, a part of a  
366 diagram is zoomed in and some elements are explained.



367

368

*Figure 7: Focus on a spatio-temporal diagram part.*

369

First invariant horizontal lines are visible over the entire diagram. Two cases can be

370

distinguished: massive black and white lines at the bottom and other grey horizontal striae.

371

Massive lines correspond to the “representation” of the distribution chamber whereas striae

372

are caused by the channel surface machining defaults. Both these patterns are the direct result

373

of the method used to create diagrams: since the same column of pixels is picked up from all

374

images composing the film, invariant patterns caused by the geometry of the plate are

375

reproduced in every column of the diagram.

376

Domains with various brightnesses are also visible in the diagrams, they represent either

377

liquid or vapor phases of the boiling flow in the channel. Indeed, the brightness difference is

378

related to light reflection either on the metal plate or through the liquid. The liquid and the

379

produced vapor do not have the same behavior on the light path. Since the single-phase liquid

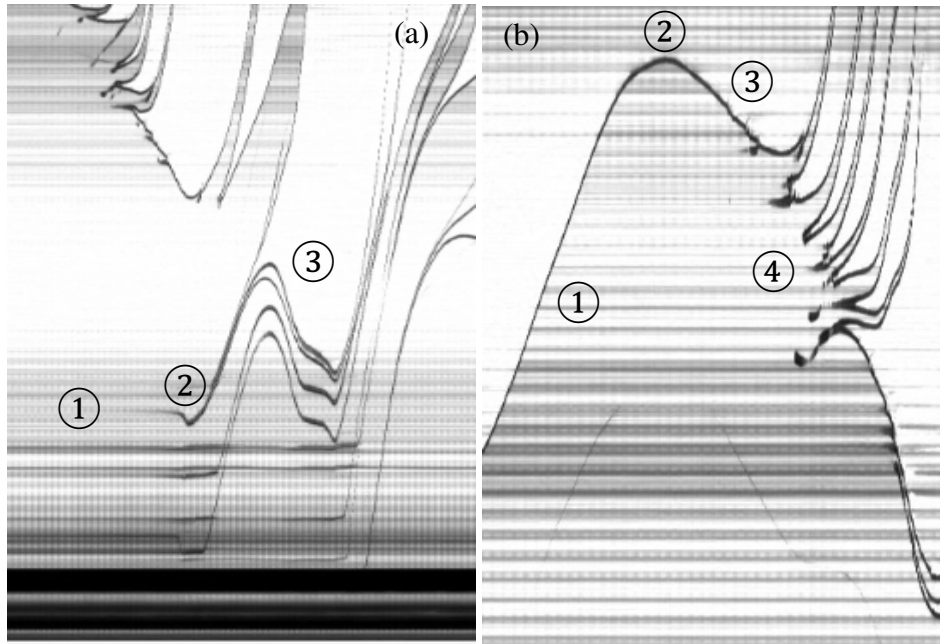
380 flow enters the channel at the bottom through the distribution chamber, darkest domains  
381 represent the liquid phase. Therefore, brightest domains represent the vapor phase. As a  
382 consequence, continuous black curves are the interfaces between phases:

- 383 • Black curves separating two domains with different exposures correspond to menisci  
384 between the liquid and vapor phases,
- 385 • Thin black curves in the darkest domain, e.g. the liquid phase, are tiny bubbles driven  
386 by the liquid and growing. These curves generally divide themselves into two lines: at  
387 this point, the bubble diameter is matching the cross section of the channel, leading to  
388 a fast expansion.

389 Numerous quasi-vertical filaments are observed in the upper side of the diagrams. A further  
390 observation shows two menisci at the upper and lower bounds of the dark domain  
391 composing these filaments. According the previous explanations, those filaments are the  
392 temporal visualization of a liquid slug expelled by a bubble growth.

#### 393 *4.2. Hydrodynamics phenomena*

394 In the presented diagrams, two main phenomena can be distinguished: a spontaneous  
395 nucleation (see *Figure 8 (a)*) and a periodic phenomenon (see *Figure 8 (b)*).



396

397 *Figure 8: Focus on the diagram representation of the spontaneous nucleation (a) and the*  
 398 *periodic phenomenon (b). (Oil flow rate 75 kg/h, oil temperature 130°C, water flow rate 2*  
 399 *L/h, water pre-heating temperature 130°C and atmospheric pressure).*

400 Each phenomenon can be described step by step. For the spontaneous nucleation:

- 401 1. There is a sufficient amount of energy located on a nucleation site to enable the bubble  
 402 nucleation. Bubble grows while remaining stuck on a channel wall.
- 403 2. The bubble grows until its size is sufficient to quit the nucleation site. Bubble take off  
 404 is probably related to shear caused by the liquid up flow or down flow.
- 405 3. The bubble is driven by the liquid flow along the channel until it reaches a spot where  
 406 it grows quickly. This fast size change induces reverse flow of the liquid upstream  
 407 (below the bubble) and liquid slug ejection downstream (above the bubble).

408 For the periodic phenomenon:

- 409 1. The boiling activity of adjacent channels raises quickly the liquid level in the  
 410 considered channel. The liquid then receives heat from the wall by convection.
- 411 2. The liquid level reaches a local maximum.



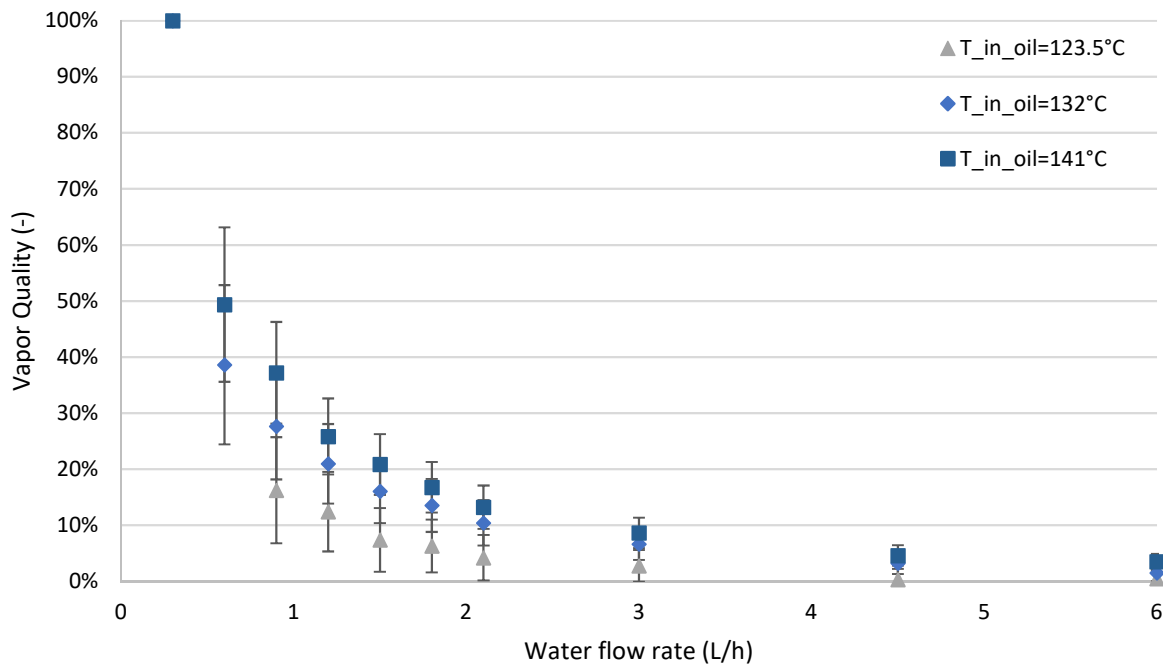
- 412 3. Events causing the previous level raise in other channels stop. The liquid level drops  
413 meanwhile the liquid flow still receives heat from the wall.
- 414 4. The heat received by the liquid during these movements enables a chain nucleation  
415 during the level drop. An average number of 5 or 6 strong bubble growths with  
416 subsequent ejection of slugs is generally observed. The level of liquid, which naturally  
417 drops, is further pushed down, accentuating the reverse flow observed.

418

#### 419 *4.3. Global vapor quality*

420 *Figure 9* presents the influence of the water flow rate and the oil inlet temperature on the  
421 global vapor quality. The quality of the vapor produced in the vaporizer decreases with the  
422 water flow rate and increases with the oil inlet temperature. A total vaporization of the water  
423 flow is observed when the oil inlet temperature is above 141°C.

424 This behavior is explained by the fact that heat transfer is limited on the oil side (this  
425 assumption has been validated through additional experiments not detailed here for a sake of  
426 brevity). For a given oil inlet temperature, the power provided by the oil to the test section is  
427 independent of water flow rate. Considering that heat losses are roughly constant and  
428 according to the heat balances (equations (2) and (4)), the higher the water flow rate, the  
429 higher the power required for pre-heating. As a consequence, the vapor quality decreases with  
430 the power available for vaporization.



431

432 *Figure 9: Influence of water flow rate and oil inlet temperature on vapor quality. (Oil flow*  
 433 *rate 180kg/h, inlet water temperature 80°C and atmospheric pressure).*

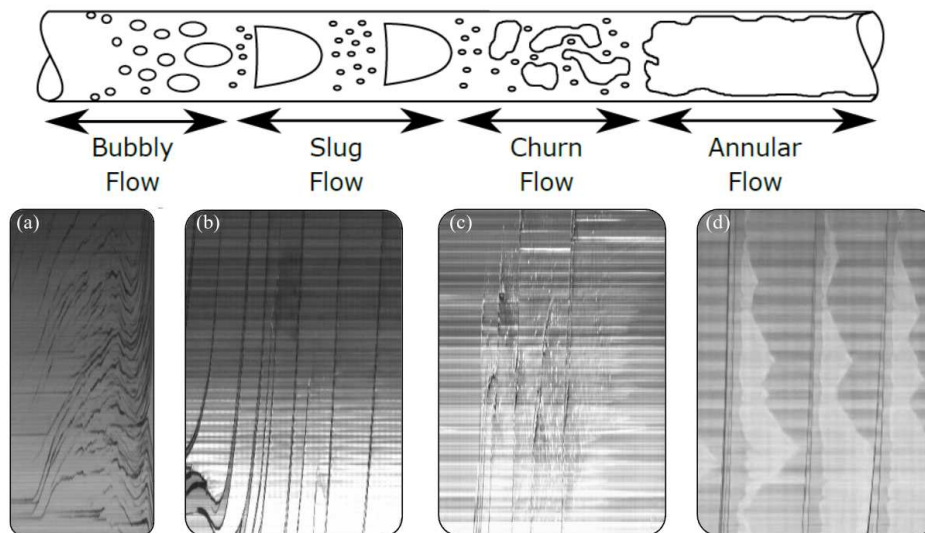
434 Additionally, considering that for a given water flow rate, and therefore a given pressure drop,  
 435 the water boiling temperature remains the same, a higher oil inlet temperature leads to a  
 436 higher exchanged power. Consequently, the available power for vaporization increases as well  
 437 as the vapor quality.

#### 438 4.4. Flow regimes and flow map

##### 439 4.4.1. Flow regimes identification

440 As shown in *Figure 10*, four different flow regimes can be identified in the diagrams: the  
 441 bubbly flow, the slug flow, the churn flow and the annular flow. It is important to notice that  
 442 these regimes are not observed at the same time nor at the same position in the channel as the  
 443 sketch in the top of *Figure 10* might suggest. Focusing the analysis on each flow regime  
 444 observed, the bubbly flow regime (a) starts in the subcooled liquid flow, where the first  
 445 bubbles nucleate. In the diagrams, these bubbles are spotted as thin black filaments in dark  
 446 domains, and their movement follows the liquid flow. The slug flow (b) starts when the cross

447 section of a growing tiny bubble diameter meets the cross section of the channel. When that  
 448 happens, the growth of the bubble accelerates, pushing down the liquid upstream and ejecting  
 449 the liquid slug downstream. Depending on the inlet water flow rate, the slug can leave a trail,  
 450 with more or less liquid. If the trail is significant, the churn flow (c) is observed on diagrams:  
 451 it appears as a “turbulent” zone where slugs and projections are visible. Some small white  
 452 spots are clearly visible and are a characteristic feature of this flow regime. On the contrary, if  
 453 the liquid trail is thinner, the annular flow (d) is observed. On diagrams, bright sail shapes are  
 454 visible on the right of every slug ejection patterns. The thin film of liquid evaporates with  
 455 time until a new ejection of a slug happens.



456  
 457 *Figure 10: Flow regime identification in the Spatio-Temporal Diagrams: Bubbly flow (a),*  
 458 *Slug flow (b), Churn flow (c) and Annular flow (d)*

459 The next step of this work is repast these regimes on a map as a function of the liquid flow  
 460 rate and the local vapor quality. Unfortunately, this latter feature is not measured directly: the  
 461 next section demonstrates how the local quality can be estimated by a proper analysis of the  
 462 diagrams.

463 *4.4.2. Local vapor quality*

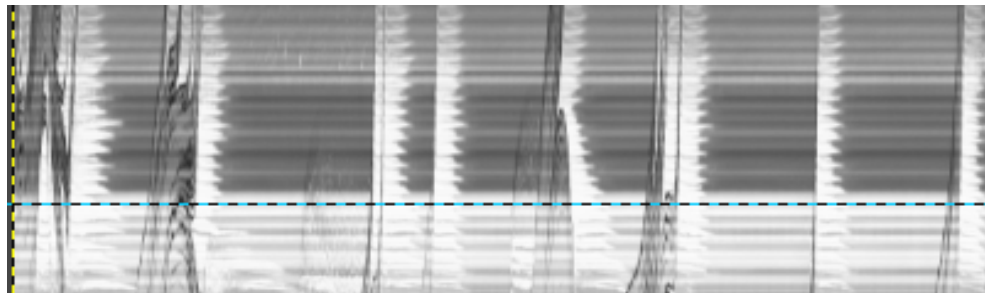
464

#### 4.4.2.1. Estimation of the void fraction

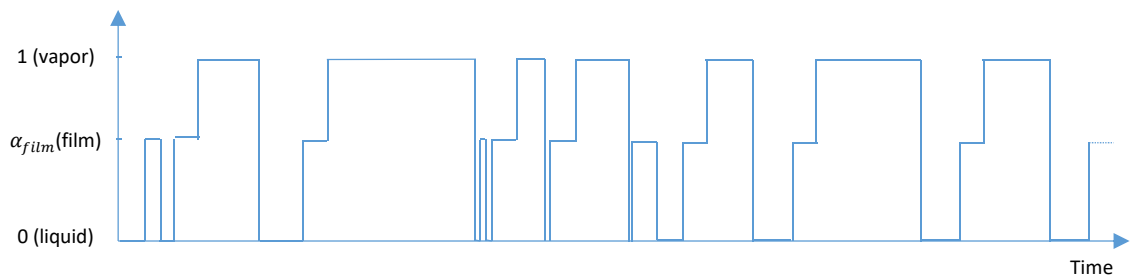
465 The first step in the determination of the local quality is to assess the mean void fraction over  
466 time thanks to spatio-temporal diagrams. *Figure 11* presents the local void fraction evolution  
467 according to patterns present on the diagram along a horizontal line corresponding to a  
468 strategic chosen position in the channel: below and above this position only bubbly flow or  
469 slug and annular flows are observed. On diagrams, these three flow regimes are associated  
470 with three patterns. Each pattern can be related to a value of the void fraction among:

- 471 • 0: only water is present in the channel.
- 472 • 1: only vapor is present in the channel.
- 473 •  $0 < \alpha_{film} < 1$ : since the film left by the ejected liquid slug is slowly vaporized, the  
474 mean value of the void fraction for the annular flow is not null. The default value was  
475 set at 0.5 awaiting validation.

476



477



478

479 *Figure 11: Evolution of the local void fraction along the limit defined between the bubbly flow*  
480 *and the slug flow. (Oil flow rate 180 kg/h, oil temperature 140°C, water flow rate 2 L/h, water*  
481 *pre-heating temperature 80°C and atmospheric pressure).*

482 In *Figure 11* is presented an example of the method used to determine the value of the local  
483 void fraction from the analysis of a spatio-temporal diagram. Using equation (9) on the plot  
484 created in *Figure 11*, the mean value over time at the given position  $\alpha_{av}(z)$  is calculated.

#### 485 4.4.2.2. *Estimation of the slip ratio*

486 According to equation (13), the value of the slip ratio is needed for the calculation of the local  
487 quality from the local void fraction. Its value could be large enough to have a great influence  
488 on that calculation. In this study, the slip ratio is assumed constant, uniform and equal to a  
489 mean value in channels. This strong assumption is also used by some authors in the literature  
490 in models of void fraction using the local quality and a constant slip ratio. For instance, the  
491 Chen [26] model can be cited as a non-exhaustive example.

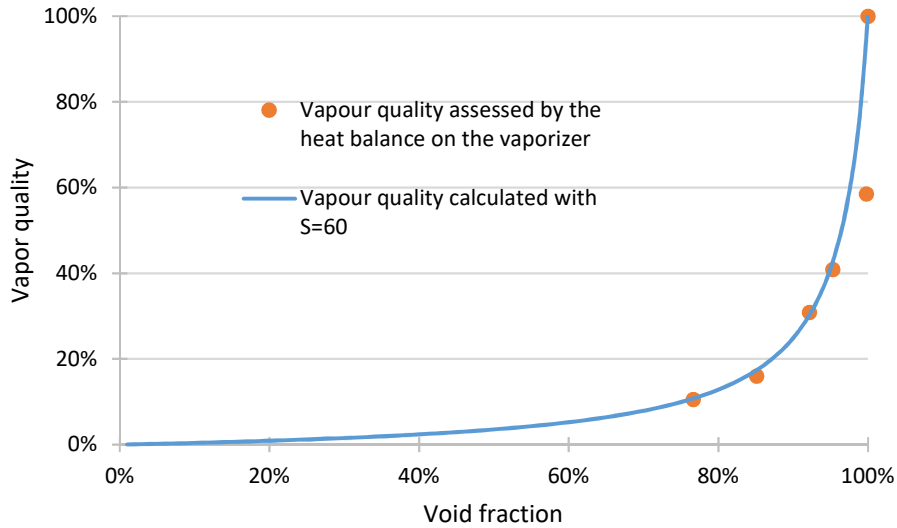
492 We set its value by comparing the global quality computed by the present method to the  
493 value inferred by heat balance (equation (6)). More precisely, an optimization on the slip ratio  
494 to reduce the quadratic error calculated by equation (14) is performed.

$$quadratic\ error = \sum_i \left( (x_{thermal,i} - x_{local,i}) / x_{thermal,i} \right)^2 \quad (14)$$

495 Where  $x_{thermal,i}$  and  $x_{local,i}$  are respectively the global quality estimated through the heat  
496 balance and the local quality calculated by equation (13) at the channel outlet. The quadratic  
497 error is computed over the entire set of data for the following experimental conditions (index  
498 “i” represents each particular experiment): oil flow rate 180 kg/h, oil temperature 140°C,  
499 water flow rate [0.3 – 6] L/h, water pre-heating temperature 80°C and atmospheric pressure.

500 *Figure 12* presents the optimized slip ratio calculated to fit properly the experimental data. In  
 501 that particular case, the optimal value of  $S_r$  is equal to 60 for an assumed value of  $\alpha_{film}$  of 0.5.

502



503

504 *Figure 12: Optimized slip ratio for local quality assessment. (Oil flow rate 180 kg/h, oil*  
 505 *temperature 140°C, water flow rate [0.3 – 6] L/h, water pre-heating temperature 80°C and*  
 506 *atmospheric pressure).*

#### 507 4.4.2.3. Study of the relation between $\alpha_{film}$ and $S_r$

508 As alluded to, an assumption had to be made on the value of  $\alpha_{film}$  to complete calculations in  
 509 the previous section. The mean value of 0.5 was chosen since the film results from a liquid  
 510 slug (void fraction = 1) and is finally totally vaporized (void fraction = 0). In this section, the  
 511 effect of a change in the assumed value of  $\alpha_{film}$  on the optimized value of  $S_r$  is discussed.  
 512 First of all, a change in  $\alpha_{film}$  affects the mean void fraction  $\alpha_{av}$ . Using equation (9) on the  
 513 plot of *Figure 12* leads to a simple calculation of  $\alpha_{av}$  presented in equation (15) where the  
 514 variation of  $\alpha_{av}(z)$  with  $\alpha_{film}$  is linear.

$$\alpha_{av}(z) = \frac{t_{vap}}{t_{tot}} + \frac{t_{film}}{t_{tot}} * \alpha_{film}, \begin{cases} t_{vap} = \sum_i t_{v,i} \\ t_{film} = t_{tot} - t_{vap} \end{cases} \quad (15)$$

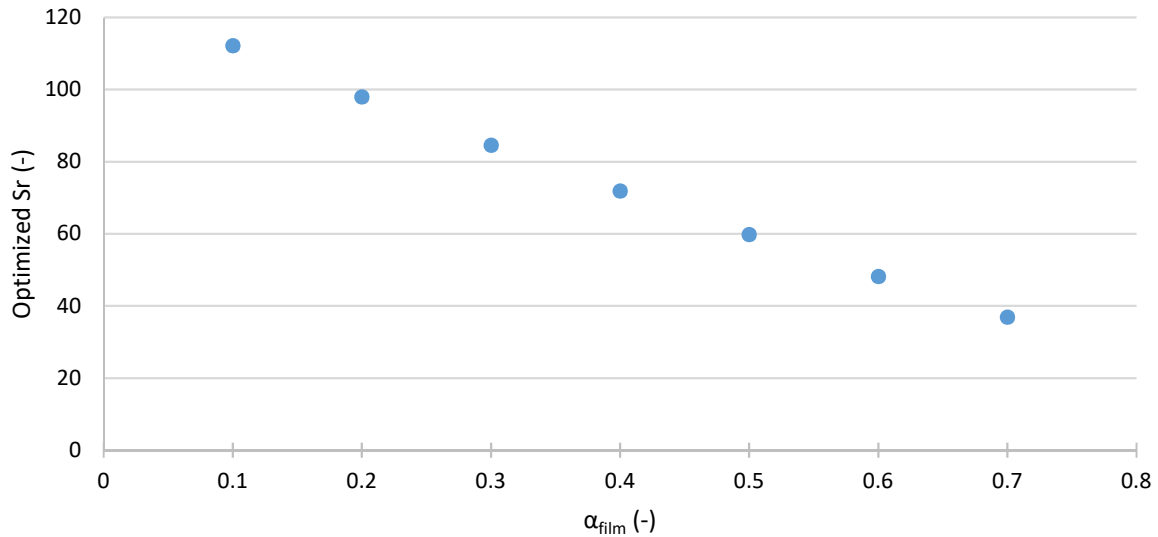
515 Where  $t_{vap}$  and  $t_{film}$  are namely the duration of the vapor state and the duration of the film  
 516 state (s) at position  $z$  and  $t_{tot}$  the total duration of the sequence considered for the integration  
 517 (s).

518 The relation between  $S_r$  and  $\alpha_{film}$  can be seen by using equation (13), introducing  $B_1$  and  $B_2$   
 519 respectively the constant ratios  $t_{film}/t_{tot}$  and  $t_{vap}/t_{tot}$  presented in equation (15):

$$S_r = x/(1 - x) * (1/(B_1\alpha_{film} + B_2) - 1) * \rho_l/\rho_g \quad (16)$$

520 In particular, since the slip ratio is optimized by using the quality  $x_{thermal}$  estimated by heat  
 521 balance, the ratio  $x_{thermal}/(1 - x_{thermal})$  is independent of  $\alpha_{film}$ . Equation (16) shows that  
 522 there exists an infinity of couples  $\{S_r; \alpha_{film}\}$  that can be a solution of this equality.

523 For a chosen value of  $\alpha_{film}$ , the slip ratio used for the calculation of the local quality can have  
 524 a significant influence on how the model fits the experimental data. However, for each value  
 525 of  $\alpha_{film}$ , an optimized slip ratio can be found to fit data, the remaining quadratic error is  
 526 consistent for every couple  $\{\alpha_{film}; S_r^{optimized}\}$  put to the test. Therefore, the optimized slip  
 527 ratio obtained for a chosen  $\alpha_{film}$  can be considered as a relevant value. To go further, the  
 528 optimized  $S_r$  is plotted as a function of the chosen  $\alpha_{film}$  in *Figure 13*.



529

530

*Figure 13: Evolution of the optimized  $S_r$  with an increasing  $\alpha_{film}$*

531 The linear relation between the optimized  $S_r$  with an increasing  $\alpha_{film}$  is at first sight  
 532 surprising. However, a closer look at equation (16) gives the explanation: since the magnitude  
 533 of variation of  $\alpha_{film}$  is small, the function giving  $S$  can be assimilated to its asymptote for  
 534 this magnitude of variation.

535 The magnitude of optimized slip ratios is larger than the value calculated from models  
 536 available in the literature. The models determined by Zivi [27] or Smith [28] predict a slip  
 537 ratio depending on the vapor quality respectively up to 9.6 or 24.6. This difference of  
 538 magnitude can be explained by the reduction of the size of the flow. Ferret et al. [29]  
 539 attempted to measure experimentally slip ratios by image analysis. They found slip ratios  
 540 between 680 and 25 942, much higher than the predicted slip ratio using the Hewitt [30]  
 541 correlation between 3.6 and 9.5. Boiling water in 2 mm diameter vertical semi-circular  
 542 channels leads to a predominant slug flow regime causing liquid slug ejection and reverse  
 543 flow. These phenomena seem to lead towards higher mean slip ratios and this trend has to be  
 544 confirmed by additional works.

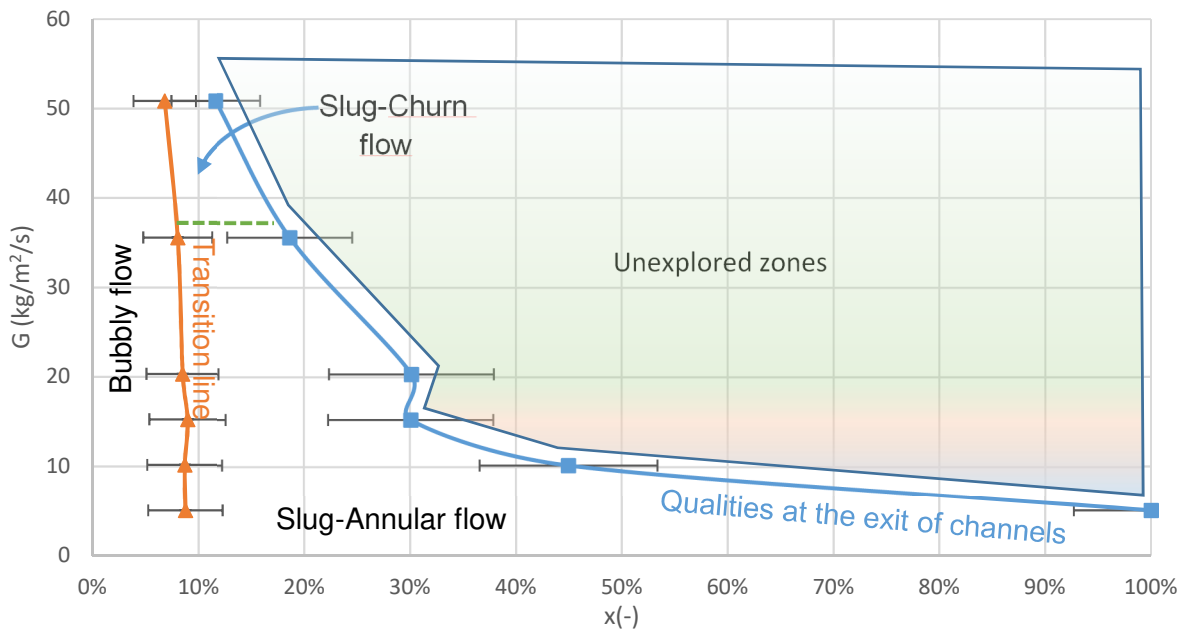


545 In conclusion, for the calculation of the average void fraction (equation (9)), there is no  
 546 restriction on the value of  $\alpha_{film}$  chosen, as long as its corresponding optimized slip ratio is  
 547 used in the calculation of the local quality by equation (13). The local quality estimated  
 548 thanks to this method can be used to draw the flow regimes maps developed in the next  
 549 section.

550 *4.4.3. Flow regimes map*

551 *Figure 14* presents the regimes map obtained by exploiting spatio-temporal diagrams  
 552 extracted from the experiments.

553



554

555 *Figure 14: Flow regimes map (water flow rate [5 – 50.8]  $\text{kg/m}^2/\text{s}$ , inlet water temperature*  
 556 *80°C, inlet oil temperature 132 °C, oil flow rate 179.3  $\text{kg/h}$ .)*

557 In this series of experiments, only one real transition line can be drawn between the  
 558 bubble/slug flow and the slug/churn and annular flow. This transition occurs when the vapor  
 559 quality reaches approximately 9%, which is consistent with Revellin and Thome [31]  
 560 observation. In their work on the R-314a boiling flow, their flow regime map presents a

561 similar transition line for same specific flow rates but at a lower quality. There exists another  
562 transition in the “slug” zone: above a specific flow rate of around 38 kg/m<sup>2</sup>/s, the churn flow  
563 appears in the list of flow regimes visible in the diagrams among the annular and the slug  
564 flow. Unfortunately, the transition line between bubbly flow and the mix of bubbly and slug  
565 flow is not observed here as it can be seen in Revellin and Thome. Indeed the reverse flow is  
566 so important in the channels that vapor pushes violently the liquid down to the distribution  
567 chamber avoiding a permanent subcooled liquid flow at the entrance of channels. The  
568 unexplored zone is due to the limitation of the test section on the vapor quality produced  
569 inside the channels. Since the slug flow ejects a significant amount of liquid, the maximal  
570 quality drops quickly by increasing the water flow rate.

571

## 572 **5. Conclusions**

573 Water flow boiling in ten milli-channels apparatus for steam production was experimentally  
574 investigated in this work. The boiling phenomena were observed using a high-speed camera  
575 to study flow patterns, flow regimes maps and vapor quality. The conclusions of the present  
576 investigation are as follows:

- 577 • The innovative method using spatio-temporal diagrams is a useful tool for  
578 understanding flow boiling inside milli-channels. It enables a quick overview of the  
579 events occurring in channels and allows an estimation of local data such as the average  
580 local void fraction at a given position in the channel.
- 581 • The boiling flow can be described by two main events: a spontaneous bubble  
582 nucleation inside the liquid flow and a periodic oscillation inducing multiple  
583 nucleation near the interface liquid/vapor.

- 584 • Every bubble created in channels induces a reverse flow and the ejection of a liquid  
585 slug out of the channel. This phenomenon is a real issue for the improvement of the  
586 vapor quality produced. Since the liquid is prematurely ejected from the channel by  
587 the bubble growth, the transferred heat is not sufficient to ensure total vaporization.
- 588 • Flow regimes in channels were determined thanks to a parallel analysis of both spatio-  
589 temporal diagrams and high-speed films. Four different regimes were identified:  
590 bubbly, slug, churn and annular flows. Contrary to the case of a boiling flow in a  
591 single channel, flow regimes are observed successively in the channel. The turnover of  
592 flow regime is caused by the quick growth of bubbles in channels creating reverse  
593 flow. It disturbs hydrodynamics in other channels via connected-vessel effect.  
594 Nevertheless, a flow regime map can be drawn and it shows that the transition  
595 between the bubbly flow and other flow regimes lies at 10% quality.
- 596 • The vapor quality produced in the vaporizer depends mostly on the water flow rate  
597 and the inlet oil temperature. Total vaporization is possible in the vaporizer but at low  
598 water flow rate.

599 For further understanding of flow boiling in small channels, new experiments are needed to  
600 complete the exploration of the flow regime map presented in this work. The issue of liquid  
601 slugs ejection caused by bubble growth also has to be tackled. To do that, new designs of  
602 milli-channels with variable cross-sections should be designed in order to let the possibility  
603 for the vapor to freely flow up to the outlet of the channels. Last but not least, the effect of  
604 pressure on the boiling flow in such structure has to be studied through spatio-temporal  
605 diagrams.

## 606 **6. Nomenclature**

$A$  : Cross-sectional area (m<sup>2</sup>)

$C_p$  : Mass calorific capacity (J/K/kg)  
 $e$  : Uncertainty  
 $F$  : Function (-)  
 $\overline{\Delta H_{vap}}$  : Mass latent heat of vaporization (J/kg)  
 $P$  : Parameter (-)  
 $\dot{m}$  : Mass flow rate (kg/s)  
 $n$  : index (-)  
 $\dot{Q}$  : Power (W)  
 $\dot{q}$  : Heat flux (W/m<sup>2</sup>)  
 $S$  : Surface (m<sup>2</sup>)  
 $S_r$  : Slip ratio (-)  
 $t$  : Time (s)  
 $T$  : Temperature (°C)  
 $v$  : Phase velocity (m/s)  
 $x$  : Vapor quality (-)

#### Greek symbols

$\alpha$  : Void fraction (-)  
 $\rho$  : Density (kg/m<sup>3</sup>)

#### Subscripts

$film$  : Liquid film  
 $l$  : Liquid phase  
 $local$  : Calculated locally  
 $oil$  : Oil flow  
 $sp$  : Single-phase  
 $thermal$  : Calculated via the heat balance  
 $tot$  : Total  
 $tp$  : Two-phase  
 $v/vap$  : Vapor phase  
 $w$  : Wall  
 $water$  : Water flow

#### Superscripts

*eb* : Boiling point

*in* : Inlet

*out* : Outlet

607

## 608 **7. Acknowledgments**

609 Authors acknowledge BPI France for their financial support of the FAIR Project (“Fabrication  
610 Additive pour l’Intensification des Réacteurs”; n°2015-PRSP-16), in the frame of the  
611 “Programme d’investissements d’avenir”, and the ENERBATIN Project supported by Région  
612 Grand-Est through CPER 2015-2020. In addition, authors acknowledge the mechanical  
613 workshop and the electronic service (SIEL) of the Reactions and Chemical Engineering  
614 Laboratory in Nancy for their precious help during the construction and the instrumentation of  
615 the test bench and the test section.

## 616 **8. References**

- 617 [1] A. Stankiewicz, J.A. Moulijn, Re-Engineering the Chemical Processing Plant: Process  
618 Intensification, CRC Press, 2003.
- 619 [2] T.R. Dietrich, ed., Microchemical Engineering in Practice, WILEY, 2009.
- 620 [3] V. Hessel, A. Renken, J.C. Schouten, J. Yoshida, Micro Process Engineering, 2009.
- 621 [4] K. Surla, Hydrogène, Tech. l’ingénieur. TIB319DUO. (2019). [https://www.techniques-  
622 ingenieur.fr/base-documentaire/procedes-chimie-bio-agro-th2/fabrication-des-grands-  
623 produits-industriels-en-chimie-et-petrochimie-42319210/hydrogene-j6368/](https://www.techniques-ingenieur.fr/base-documentaire/procedes-chimie-bio-agro-th2/fabrication-des-grands-produits-industriels-en-chimie-et-petrochimie-42319210/hydrogene-j6368/).
- 624 [5] F. Giroudière, A. Le Gall, Production des gaz de synthèse, Tech. l’Ingénieur.  
625 TIB329DUO. (2012). [https://www.techniques-ingenieur.fr/base-  
626 documentaire/procedes-chimie-bio-agro-th2/procedes-industriels-de-base-en-chimie-et-  
627 petrochimie-42329210/production-des-gaz-de-synthese-par-vaporeformage-j5480/](https://www.techniques-ingenieur.fr/base-documentaire/procedes-chimie-bio-agro-th2/procedes-industriels-de-base-en-chimie-et-petrochimie-42329210/production-des-gaz-de-synthese-par-vaporeformage-j5480/).
- 628 [6] J. Frauhammer, G. Eigenberger, L. V. Hippel, D. Arntz, A new reactor concept for  
629 endothermic high-temperature reactions, Chem. Eng. Sci. 54 (1999) 3661–3670.  
630 doi:10.1016/S0009-2509(98)00454-0.
- 631 [7] J. Bhat, Shrikant A.; Sadhukhan, Process Intensification Aspects for Steam Methane  
632 Reforming: An Overview, Am. Inst. Chem. Eng. AIChE J. 55 (2009) 408–422.  
633 doi:10.1002/aic.11687.
- 634 [8] V. Solotych, D. Lee, J. Kim, R.L. Amalfi, J.R. Thome, Boiling heat transfer and two-  
635 phase pressure drops within compact plate heat exchangers: Experiments and flow  
636 visualizations, Int. J. Heat Mass Transf. 94 (2016) 239–253.  
637 doi:10.1016/j.ijheatmasstransfer.2015.11.037.

- 638 [9] F.D. Sempértegui-Tapia, G. Ribatski, Flow boiling heat transfer of R134a and low  
639 GWP refrigerants in a horizontal micro-scale channel, *Int. J. Heat Mass Transf.* 109  
640 (2017) 938–948. doi:10.1016/j.ijheatmasstransfer.2017.02.066.
- 641 [10] G.M. Lazarek, S.H. Black, Evaporative heat transfer, pressure drop and critical heat  
642 flux in a small vertical tube with R-113, *Int. J. Heat Mass Transf.* 25 (1982) 945–960.  
643 doi:10.1016/0017-9310(82)90070-9.
- 644 [11] P.A. Kew, K. Cornwell, CORRELATIONS FOR THE PREDICTION OF BOILING  
645 HEAT TRANSFER IN SMALL-DIAMETER CHANNELS, *Appl. Therm. Eng.* 17  
646 (1997) 705–715.
- 647 [12] A.S. Pamitran, K. Il Choi, J.T. Oh, H.K. Oh, Forced convective boiling heat transfer of  
648 R-410A in horizontal minichannels, *Int. J. Refrig.* 30 (2007) 155–165.  
649 doi:10.1016/j.ijrefrig.2006.06.005.
- 650 [13] L. Cheng, G. Xia, Fundamental issues, mechanisms and models of flow boiling heat  
651 transfer in microscale channels, *Int. J. Heat Mass Transf.* 108 (2017) 97–127.  
652 doi:10.1016/j.ijheatmasstransfer.2016.12.003.
- 653 [14] X. Fang, Y. Yuan, A. Xu, L. Tian, Q. Wu, Review of correlations for subcooled flow  
654 boiling heat transfer and assessment of their applicability to water, *Fusion Eng. Des.*  
655 122 (2017) 52–63. doi:10.1016/j.fusengdes.2017.09.008.
- 656 [15] L. Yin, R. Xu, P. Jiang, H. Cai, L. Jia, Subcooled flow boiling of water in a large  
657 aspect ratio microchannel, *Int. J. Heat Mass Transf.* 112 (2017) 1081–1089.  
658 doi:10.1016/j.ijheatmasstransfer.2017.05.028.
- 659 [16] Q. Lu, D. Chen, C. Li, X. He, Experimental investigation on flow boiling heat transfer  
660 in conventional and mini vertical channels, *Int. J. Heat Mass Transf.* 107 (2017) 225–  
661 243. doi:10.1016/j.ijheatmasstransfer.2016.11.020.
- 662 [17] S.M. Kim, I. Mudawar, Review of databases and predictive methods for heat transfer in  
663 condensing and boiling mini/micro-channel flows, *Int. J. Heat Mass Transf.* 77 (2014)  
664 627–652. doi:10.1016/j.ijheatmasstransfer.2014.05.036.
- 665 [18] J.C. Chen, Correlation for boiling heat transfer to saturated fluids in convective flow,  
666 *Ind. Eng. Chem. Process Des. Dev.* 5 (1966) 322–329. doi:10.1021/i260019a023.
- 667 [19] J. Yan, Q. Bi, Z. Liu, G. Zhu, L. Cai, Subcooled flow boiling heat transfer of water in a  
668 circular tube under high heat fluxes and high mass fluxes, *Fusion Eng. Des.* 100 (2015)  
669 406–418. doi:10.1016/j.fusengdes.2015.07.007.
- 670 [20] S.G. Kandlikar, Fundamental issues related to flow boiling in minichannels and  
671 microchannels, *Exp. Therm. Fluid Sci.* 26 (2002) 389–407. doi:10.1016/S0894-  
672 1777(02)00150-4.
- 673 [21] J.R. Thome, State-of-the-art overview of boiling and two-phase flows in  
674 microchannels, *Heat Transf. Eng.* 27 (2006) 4–19. doi:10.1080/01457630600845481.
- 675 [22] V. Kumar, Vikash, K.D.P. Nigam, Multiphase fluid flow and heat transfer  
676 characteristics in microchannels, *Chem. Eng. Sci.* 169 (2017) 34–66.  
677 doi:10.1016/j.ces.2017.01.018.
- 678 [23] L. Chen, Y.S. Tian, T.G. Karayiannis, The effect of tube diameter on vertical two-  
679 phase flow regimes in small tubes, *Int. J. Heat Mass Transf.* 49 (2006) 4220–4230.  
680 doi:10.1016/j.ijheatmasstransfer.2006.03.025.
- 681 [24] M.E. Steinke, S.G. Kandlikar, An Experimental Investigation of Flow Boiling  
682 Characteristics of Water in Parallel Microchannels, *J. Heat Transfer.* 126 (2004) 518.

- 683 doi:10.1115/1.1778187.
- 684 [25] S. Wang, X. Bi, S. Wang, Boiling heat transfer in small rectangular channels at low  
685 Reynolds number and mass flux, *Exp. Therm. Fluid Sci.* 77 (2016) 234–245.  
686 doi:10.1016/j.expthermflusci.2016.04.022.
- 687 [26] J.J.J. Chen, A further examination of void fraction in annular two-phase flow, *Int. J.*  
688 *Heat Mass Transf.* 29 (1986) 1760–1763. doi:10.1016/0017-9310(86)90116-X.
- 689 [27] S.M. Zivi, Estimation of steady state steam void fraction by means of the principle of  
690 minimum entropy production, *Trans. ASME, J. Heat Transf.* 86 (1964) 247–252.
- 691 [28] S.L. Smith, Void fractions in two- phase flow. A correlation based upon an equal  
692 velocity head model, 18 (1969) 647–664. doi:10.1243/pime\_proc\_1969\_184\_051\_02.
- 693 [29] C. Ferret, L. Falk, U. D’Ortona, A. Chenu, T.T. Veenstra, Introduction of image  
694 analysis for the quantification of the boiling flow heat transfer, *Chem. Eng. J.* 101  
695 (2004) 357–365. doi:10.1016/j.cej.2003.10.028.
- 696 [30] G. Hetsroni, G.F. Hewitt, Void Fraction, in: M. Graw-Hill (Ed.), *Handb. Multiph. Syst.*  
697 *Chapter 2.3.*, New York, 1982. doi:10.1615/AtoZ.v.void\_fraction.
- 698 [31] R. Revellin, J.R. Thome, A new type of diabatic flow pattern map for boiling heat  
699 transfer in microchannels, *J. Micromechanics Microengineering.* 17 (2007) 788–796.  
700 doi:10.1088/0960-1317/17/4/016.
- 701

## 702 **Appendix A: Heat losses experiments**

703 This section develops the methodology adopted for the estimation of the convective heat-  
704 transfer coefficient presented in this work for the assessment of heat losses. Two series of  
705 experiments were carried out on the test bench in order to estimate this coefficient: one by  
706 using heat-flux meters and a second one by exploiting cooling kinetics of the test section.

### 707 *1. Heat losses measured by heat-flux meter*

708 Since one of the heat flux meters is glued on the glass window, it prevents visualizing  
709 phenomena in the test section. As the present work is focused on the visualization and the  
710 characterization of the flow regimes and their influence on the vapor quality, it has been  
711 chosen to assess heat losses by using an overall convective heat-transfer coefficient at the  
712 external surface of the vaporizer. For this campaign, only an oil flow is used to provide heat to  
713 the test section. The experimental operating conditions used are gathered in *Table 1*:

Parameter	Range	Unity
Oil flow rate	46 – 157	kg/h
Inlet Oil temperature	38.8 - 147	°C

714 *Table A.1 Ranges of operating conditions used for the heat losses measurement by heat-flux*  
715 *meters*

716 The heat flux of both sensors are picked up and heat losses are calculated by:

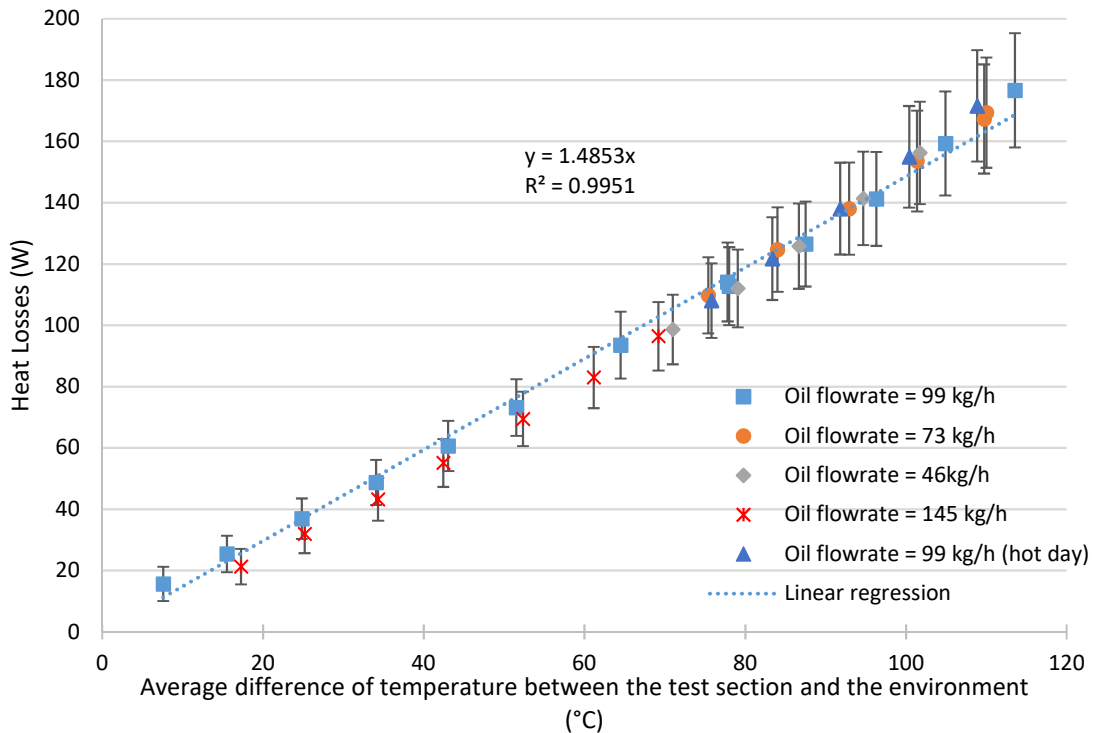
$$\dot{Q}_{losses} = \dot{q}_{window}S_{window} + \dot{q}_{insulator}S_{insulator} \quad (A.1)$$

717 Where  $\dot{q}$  denotes the heat flux of the considered surface (W/m<sup>2</sup>), and  $S$  its area (m<sup>2</sup>).

718 The raw results are presented in *Figure A.1*; uncertainties are estimated by equation (7). Since  
719 the external area of the test section is known (0.11 m<sup>2</sup>), the heat-transfer coefficient can be



720 estimated by dividing the slope by the external area. The convective heat-transfer coefficient  
 721 calculated by this way is equal to 13.5 W/m<sup>2</sup>/K

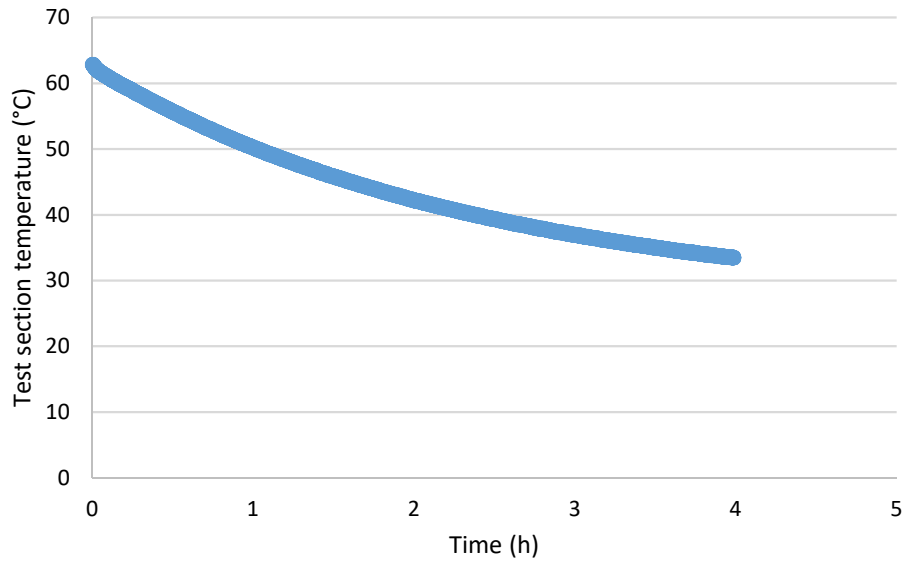


722

723 *Figure A.1: Heat losses measured on the test bench by heat-flux meters.*

724 *2. Heat-transfer coefficient estimated from the cooling kinetics of the test bench*

725 For this campaign, the oil and the water flow temperatures are set on the same value to speed  
 726 up the heating of the test section. When all temperatures of the test section are stabilized, the  
 727 circulation of both fluids is stopped. Then, temperatures are picked up every 2 seconds until  
 728 the ambient temperature is reached. The initial temperatures tested are: {62.8; 72; 80.8; 98.7;  
 729 107.9} °C. Since there are 6 temperatures picked in the milli-structured plate, the decreasing  
 730 mean value of these temperatures as a function of time is considered. An example of this  
 731 evolution is plotted in *Figure A.2*.



732

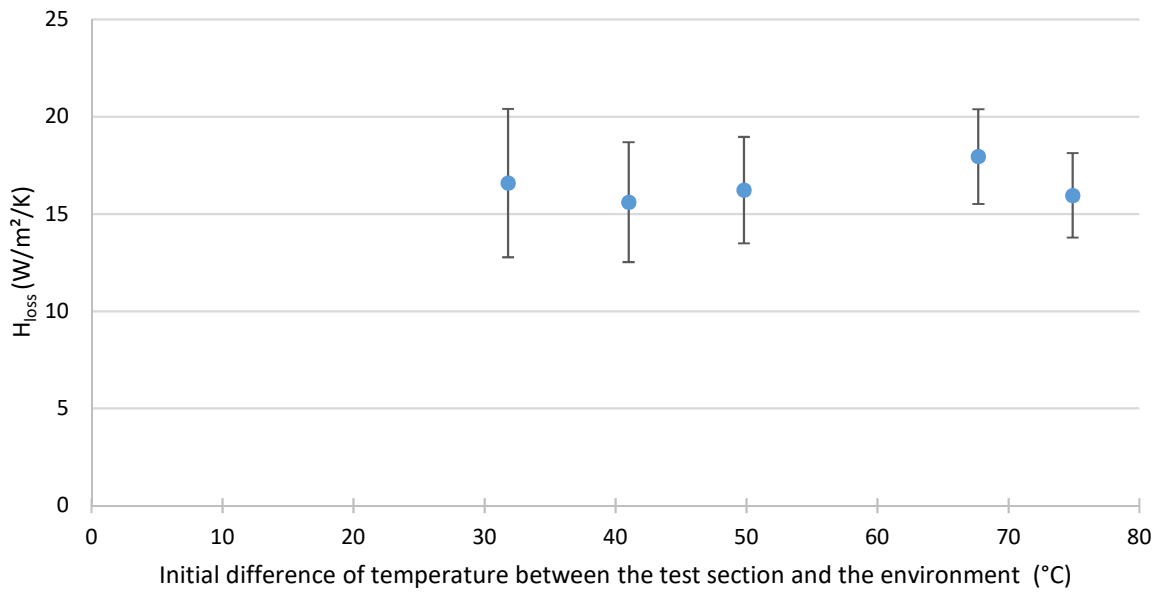
733 *Figure A.2: Cooling kinetics of the test section from an initial temperature of 62.8°C*

734 The pick-up process is in fact stopped before the end of the cooling. Only the initial slope is  
 735 considered for the estimation of the convective heat-transfer coefficient. A heat balance on the  
 736 test section during the cooling process gives:

$$dT/dt = -h_{loss}S/(m_{test\ section}C_p\ test\ section) * (T - T_{environment}) \quad (A.2)$$

737 Where  $h_{loss}$  (W/m<sup>2</sup>/K) is the convective heat-transfer coefficient.

738 Thanks to the external area, the mass and the heat capacity of the test section, the initial  
 739 difference of temperature between the test section and the environment and the initial slope of  
 740 the curve, the heat-transfer coefficient can be calculated. The results are consigned in *Figure*  
 741 *A.3.*



742

743 *Figure A.3: Convective heat-transfer coefficient calculated from the cooling kinetics of the*  
 744 *test section.*

745 According to uncertainty of measurements, both methods lead to close results, it has been  
 746 decided that the convective heat-transfer coefficient is set to 15 W/m<sup>2</sup>/K considering an  
 747 uncertainty of 20% of the calculated value.

Image Extraction  
with VirtualDub

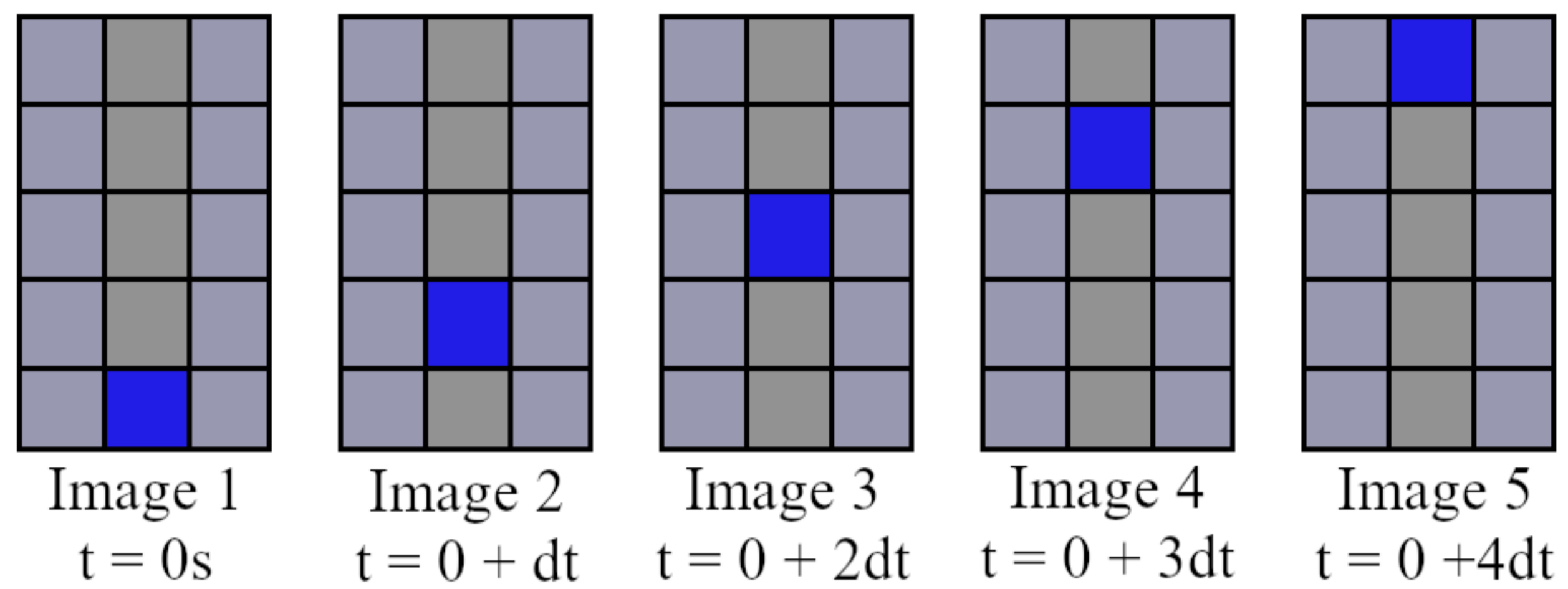
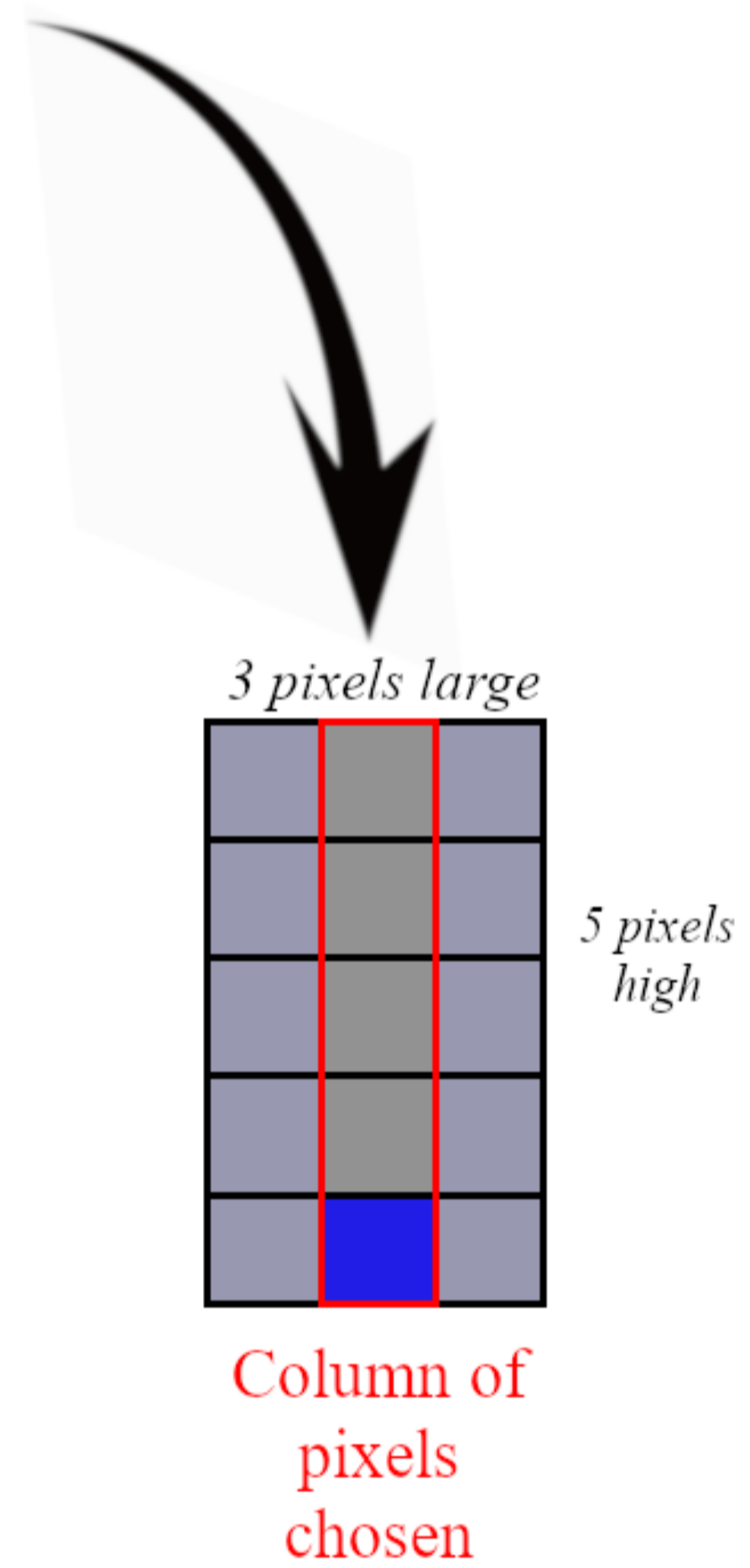
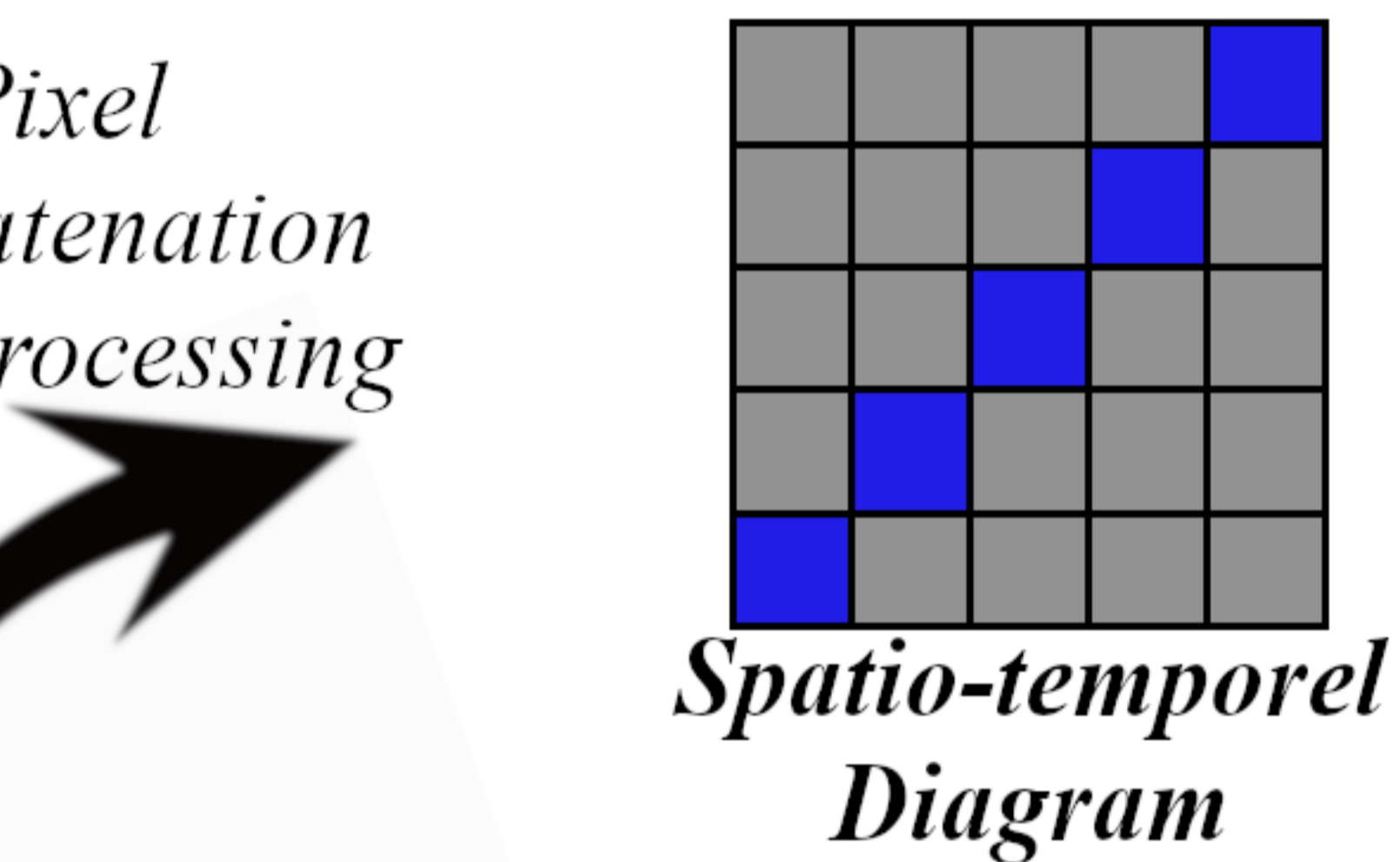


Image analysis  
with GIMP 2.0

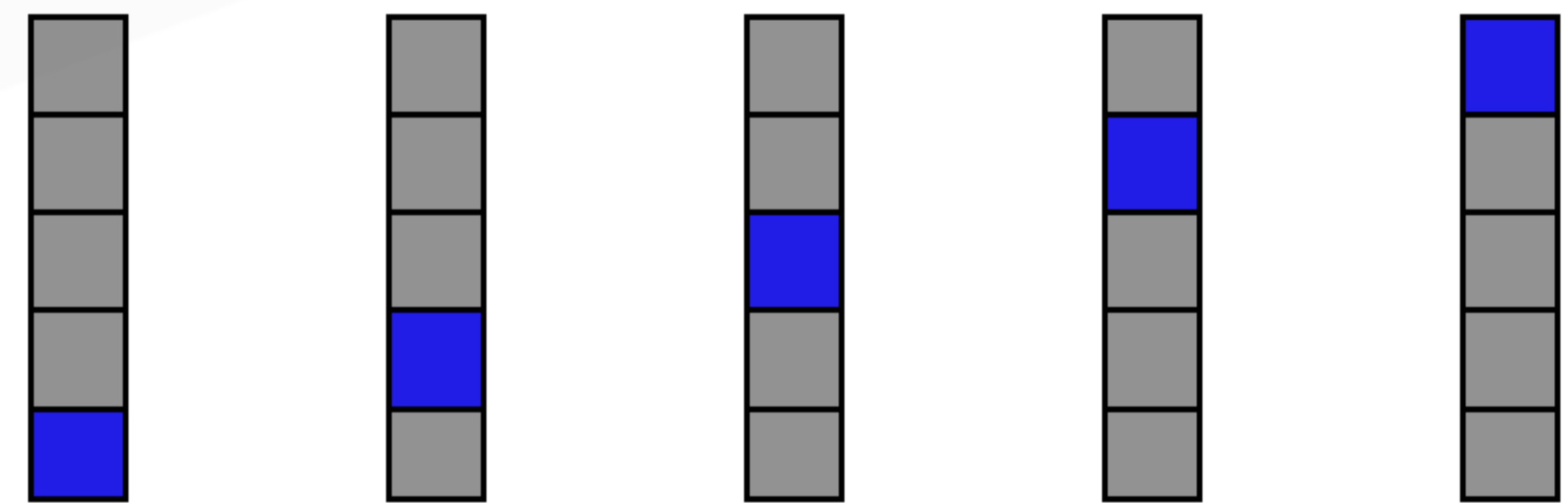


Simplified Film  
made of 5 images

Pixel  
Concatenation  
with Processing



Pixel Extraction  
with  
Processing



Liquid slugs pushed  
by bubble growth

Tinny bubble  
expanding quickly

Tiny bubble  
flowing with  
the liquid

Channel surface  
defaults

Vapour phase

Liquid phase

Cascade of bubble  
nucleation

Thick lines representing  
the distribution chamber

