Feasibility Investigation of Experimental Visualization Techniques to Study Subcooled Boiling Flow

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Abstract

The purpose of this study is twofold: 1) to explore the feasible implementation of whole-field visualization techniques such as infrared thermometry, particle tracking velocimetry, and high speed shadowgraphy to study subcooled boiling flow through a vertical square channel with a single heated wall and 2) to provide subcooled boiling flow experimental measurements based on the methodology developed in this work. To fulfill the first objective, a series of sensitivity studies and uncertainty analyses was performed, from which recommendations for the proper implementation of these visualization techniques for the study of two-phase flows are given. The purpose of the second objective is to provide reliable information that can be used for the validation of CFD simulations and for the improvement and development of turbulence models under subcooled boiling conditions. Unique in the presented experimental results is the whole-field simultaneous measurement of turbulence characteristics for both the liquid and gas phases and for their interactions. These measurements were made under transitional conditions from a single phase flow region to a two phase boiling flow condition. The presented experimental results provide whole-field, multi-scale measurements that can help improve the accuracy of descriptions of the boiling phenomena.

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1. Introduction

Understanding the influence of two-phase flow parameters on liquid turbulence plays a key role in developing numerical models to describe the complex behavior found in subcooled flow boiling. Model development depends upon the existence of experimental data that can provide detailed information about the liquid and vapor phases at multiple lengths and times scales. Furthermore, it is desirable to quantify the instantaneous and average influences of bubble characteristics on the neighboring liquid turbulence. Although multiple experimental efforts have been directed toward understanding subcooled boiling flow, the complexity of the phenomenon and its high dependence on the experimental conditions have made it difficult to implement whole-field and non-intrusive experimental techniques that can provide the multi-scales required. Therefore, innovative experimental techniques that can fulfill the multi-scale and statistical demands required for the description of the stochastic nature of subcooled boiling flow are needed. This study explores the scope and limitations of innovative measuring techniques to study subcooled boiling flow. Efforts for the simultaneous measurements of liquid and vapor parameters and their interactions are described, with an emphasis on fulfilling the temporal and spatial demands for both: average and fluctuating quantities. The presented measurements are accompanied with sensitivity studies to account for accuracy and repeatability.

1.1. Literature Review

Multiple researchers have made efforts to study subcooled boiling flow experimentally with optical techniques (Abdelmessih et al., 1972; Klausner et al., 1993; Situ et al., 2004; Okawa et al., 2005; Chu et al., 2011). However, only a handful of works have attempted to measure liquid turbulence modifications due to boiling flow parameters (Roy et al., 1997; Lee et al., 2002; Yun et al., 2008, 2010). These experiments use point measurement techniques. Roy et al.

28 (1997) utilized a two-component laser Doppler velocimetry system to measure
 29 both the liquid and boiling bubbles velocities. They also used a dual-sensor
 30 fiber optical probe and a constant temperature hot film anemometer to mea-
 31 sure vapor bubble-related quantities and vapor/liquid temperatures. Lee et al.
 32 (2002) provided measurements of local void fractions and velocity profiles for
 33 both phases. Their measurements were based on a double-sensor conductivity
 34 probe for the local void fraction and vapor velocity and a Pitot tube method
 35 for the local liquid velocity. Situ et al. (2004) measured the flow structure of
 36 subcooled boiling flow in an annulus. They used a double-sensor conductivity
 37 probe to measure local void fraction, interfacial area concentration, and inter-
 38 facial velocities. Yun et al. (2008) performed subcooled boiling experiments in
 39 a 3×3 rod bundle. They used a double-sensor conductivity probe for the va-
 40 por phase measurements and a Pitot tube for the local liquid velocity. Rather
 41 than presenting their results as local profiles, they presented interpolated 2D
 42 maps of liquid velocity, void fraction, interfacial area concentration, interfacial
 43 velocity, and bubble Sauter mean diameter for several conditions. Yun et al.
 44 (2010) performed subcooled boiling experiments through a concentric annulus.
 45 They used a double sensor optical fiber probe for the local measurement of
 46 void fraction, bubbles velocities, Sauter mean diameter, and the interfacial area
 47 concentration. In separate experiments using a specially designed Pitot probe
 48 and a K-type thermocouple, they also measured the local liquid velocity and
 49 temperature.

50 Although the above mentioned experiments delivered relevant information
 51 on the average two-phase flow parameter characteristics, they do not provide
 52 simultaneous measurements of the bubble and liquid characteristics. The tech-
 53 niques used in these experiments depend upon specialized measurements of ei-
 54 ther the gas or the liquid phase parameters, and the obtrusive nature of the
 55 probes and/or probe dimensions make measurements close to the wall a chal-
 56 lenge.

57 To overcome some of the limitations inherent in point measurement tech-
 58 niques, full-field visualization techniques have been used on multiple two-phase

59 flow studies (Hassan et al., 2005; Dominguez-Ontiveros et al., 2006; Ortiz-
 60 Villafuerte and Hassan, 2006; Koyasu et al., 2009). However, there appears
 61 to be a scarcity of subcooled boiling experimental studies that can capture in-
 62 stantaneous whole-field measurements. In response to the need for high quality,
 63 reliable experimental information on subcooled boiling flow, Estrada-Perez and
 64 Hassan (2010) performed whole-field particle tracking velocimetry (PTV) ex-
 65 periments in a square vertical channel with a single heated wall. They focussed
 66 on the liquid turbulence modification due to wall heating. Their results con-
 67 firmed the behavior found in previous studies and provided new information
 68 due to the full-field nature of the technique. The new provided information has
 69 already been used towards the development of a two-phase wall law and for
 70 CFD simulation validation (Končar and Matkovič, 2012).

71 Although a large number of studies have been published, subcooled boiling
 72 flow is still not completely understood. Due to experimental and technical dif-
 73 ficulties, most of these studies are often oriented to measure parameters of only
 74 one phase, i.e., either liquid or vapor parameters, with experimental approaches
 75 limited to either long-term averages such as average void fraction distribution
 76 and average velocity profiles or to instantaneous or fast-occurring events like
 77 bubble departure frequency, bubble growth rate, etc. Furthermore, there have
 78 only been limited attempts to simultaneously capture the full-field wall heat
 79 transfer mechanisms and its interaction with the liquid and vapor dynamics
 80 (Theofanous et al., 2002a; Wang and Sefiane, 2012; Gerardi et al., 2010; The-
 81 ofanous et al., 2002b; Hetsroni et al., 2000; Barber et al., 2011; Golobic et al.,
 82 2012; Kim et al., 2012).

83 The present study is a continuation of the experimental endeavor started by
 84 Estrada-Perez and Hassan (2010) and has the objective of improving the mea-
 85 surement reliability when conducting simultaneous PTV, high speed shadowg-
 86 raphy (HSS) and infrared thermometry (IR-T) for the study of subcooled flow
 87 boiling phenomena. Although these techniques have been previously validated
 88 under multiple experimental conditions (Kähler et al., 2012; Khan, 2012; Kim
 89 et al., 2012), no attempt has been made to use all these techniques simultane-

ously to study subcooled boiling flow. Therefore, issues related to the scope and limitations of these techniques have to be addressed before attempting meaningful subcooled boiling measurements. To this end, a series of sensitivity studies and uncertainty analyses were performed, from which recommendations for the proper implementation of visualization techniques for the study of two-phase flows are given. This work also provides subcooled boiling flow experimental measurements which are based on these recommendations.

This paper is organized as follows. Section 2 presents an overview of the experimental facility, instrumentation, and optical arrangements. Section 3 describes the experimental conditions and the unique features of the proposed measurements. Sections 2 and 3 are especially important because the experimental complexity and induced uncertainties are strongly defined by the experimental arrangement and the way in which the experiments are performed. Section 4 shows the measurement issues found and describes the sensitivity studies performed to quantify the influences of each of the addressed issues. Section 5 defines the uncertainties and discusses how the issues found affect the measurements. Section 6 presents the experimental results of subcooled boiling flow experiments after addressing and correcting for the detected uncertainties, and finally, a brief conclusion as well as recommendations are given in Section 7.

2. Experimental Setup

The experimental facility was designed for the visualization of subcooled boiling flow of refrigerant HFE-301 (3MTMNovec-7000TM) at low system pressures. The facility consisted of a hydraulic loop and a visualization system. Experimental setup details are given in the following subsections.

2.1. Hydraulic Loop

The hydraulic loop consisted of an external loop and a test section, both designed to withstand temperatures in excess of 200°C and pressures up to 100 psi(0.7 MPa). The external loop provided thermal and hydraulic steady-state conditions. The system excess energy was removed with a small plate

119 heat exchanger connected to a chilling system. This allowed us to control the
 120 inlet temperature to the test section. Liquid conditions such as volumetric
 121 flow rate, temperature, and density were measured by a Coriolis flow meter
 122 and controlled by adjusting valves in the test section. The test section was
 123 a rectangular channel made of transparent polycarbonate 30.5 mm long with
 124 a cross-sectional area of 10×10 mm. Energy for boiling was provided through
 125 a transparent indium tin oxide (ITO) heater with a length of 25.5 cm and a
 126 width of 9 mm and a maximum working temperature of about 150°C. The
 127 heater was attached to the lateral interior face of the channel (see fig. 1). The
 128 electric current to the heater was provided and adjusted by a DC power supply.
 129 To reduce ambient heat losses, the test section was covered with an insulation
 130 box. Three walls of the insulation box were made of transparent acrylic and
 131 the fourth wall was a sapphire window. The insulation box materials were
 132 selected to provide visual access for both the infrared camera and the high-
 133 speed cameras. The optical sapphire window provided almost 95% transparency
 134 to the infrared wavelengths of interest. An unheated length of about 61 cm was
 135 installed (i.e., $L/D_h \approx 61$) to ensure fully developed flow. To measure the
 136 heater wall temperature, a mid-wave infrared camera (3-5 μm) was used. To
 137 provide validation for the infrared camera measurements, K-type thermocouples
 138 were attached to the external face of the heater. The test section fluid inlet (T_{in})
 139 and outlet (T_{out}) temperatures were measured with two fast response T-type
 140 thermocouples. Ambient temperature (T_{amb}) fluctuations were measured with
 141 J-type thermocouples. Figure 1 shows the schematics and dimensions of the
 142 test section. To account for the pressure drop throughout the test section,
 143 two differential pressure transducers were used. Also, the gage pressure was
 144 measured at the entrance (P_{in}) and at the outlet (P_{out}) of the test section. The
 145 parameter uncertainties are provided in Table 1.

146 [Figure 1 about here.]

147 [Table 1 about here.]

148 2.2. Visualization System

149 The visualization system consisted of numerous parts. They were three
150 high-speed, high-resolution cameras: two for shadowgraphy experiments and
151 one for the simultaneous PTV-shadowgraphy technique; a high-speed, high-
152 power laser; a high-speed infrared camera; a fast response light emitting diode
153 (LED) system; mirrors; translational stages; lenses; optical filters; particle flow
154 tracers; and a laser power meter. The flow tracers were fluorescent particles with
155 a density range between 1.39 to 1.41 g/cm with an average particle diameter
156 of 5 μm . Illumination for PTV experiments was provided by a Nd:YLF dual-
157 head laser system (ESI, New Wave Research) which offers a nominal energy
158 of 10 mJ of 527-nm light at 1000 Hz. Each laser heads can provide up to
159 5000 pulses per second, allowing PTV measurements up to 10,000 frames per
160 second with lower energies than the nominal. Two optical mirrors and two
161 concave-convex lenses were used to convert the small circular beam from the
162 laser, into a thin sheet of light. The laser light sheet was positioned parallel
163 to the camera focal area. The LED system is externally synchronized to be
164 used as the shadowgraphy illumination. The cameras, mirrors, and lenses were
165 mounted on translational stages in order to have the capability of measuring
166 at different locations within the test section. Figure 2 shows the schematics
167 of the visualization system. The high speed cameras, the laser, and the LED
168 illumination system were synchronized in such a way as to be able to obtain
169 quasi-simultaneous PTV and shadowgraphy measurements.

170 [Figure 2 about here.]

171 2.2.1. Temporal Multi-Scale Approach

172 The configuration shown in Figure 2 was designed to allow multi-orientation
173 and multi-scale measurements. The high-speed PTV/shadowgraphy camera was
174 arranged to provide semi-simultaneous measurements of PTV and shadowgra-
175 phy. This was achieved by synchronizing the camera shutter with alternating
176 pulses of laser and LED illumination. From the temporal multi-scale point of
177 view, the PTV/shadowgraphy camera can be configured to run in continuous

178 or in straddling timing modes. Continuous mode provides a fixed time inter-
 179 val between consecutive frames. In order to properly capture the fast moving
 180 features within the flow, this time interval (Δt_{PTV}) needs to be short, and con-
 181 sequently, the camera needs to be run at high speeds. Due to the camera's
 182 memory limitations, continuous timing mode provides measuring times on the
 183 order of seconds. This limited measuring time also limits the capability of ac-
 184 curately measure time-averaged flow quantities. The straddling timing mode
 185 combines short time interval (sort Δt_{PTV}) between image pairs plus a waiting
 186 period which will be called straddling time ($\Delta t_{straddling}$). This waiting period
 187 is required in order to achieve a higher number of independent samples for bet-
 188 ter statistics. Similarly, the two high-speed shadowgraphy cameras can also be
 189 configured to work in either continuous or in straddling timing modes. Figure
 190 3 shows schematics of the timing used to achieve semi-simultaneous PTV and
 191 shadowgraphy images. The semi-simultaneous PTV/shadowgraphy experiment
 192 consists of sets of four frames each (Fig. 3), two frames for PTV and two frames
 193 for shadowgraphy. The time interval between a PTV and a shadowgraphy frame
 194 is given by $\Delta t_{PTV}/2$.

195 [Figure 3 about here.]

196 2.3. Spatial Multi-Scale Approach

197 To achieve spatial multi-scale measurements, the PTV/shadowgraphy cam-
 198 era was equipped with a telecentric lens which allowed the selection of two dif-
 199 ferent visualization modes, high and medium magnification modes, which corre-
 200 sponded to resolutions of 4.82 and 17.5 $\mu\text{m}/\text{pixel}$, respectively. The two shadowg-
 201 raphy cameras were configured to have different visualization modes: One cam-
 202 era provided high magnification while the other camera was set at low magnifica-
 203 tion. The low magnification corresponded to a resolution of 187 $\mu\text{m}/\text{pixel}$. Focus
 204 will be given to the results from the medium-magnification PTV/shadowgraphy
 205 camera, which provided simultaneous information from both liquid and vapor
 206 phases.

207 The experimental setup described above allows for a set of unique experimen-
208 tal features relevant for two-phase flow measurements. These are summarized
209 next.

210 Simultaneous whole-field measurements of liquid and bubbles parameters:

- 211 • The simultaneous application of PTV and shadowgraphy techniques pro-
212 vided measurements of the liquid and bubbles velocities along with mea-
213 surements of parameters that describe bubble dynamics. This method-
214 ology simplifies quantification of the local void influence on the liquid
215 turbulence.
- 216 • Improved liquid velocity measurements can be achieved by using the shad-
217 owgraphy information to remove spurious vectors found within the domain
218 occupied by the boiling bubbles, i.e., liquid velocity vectors should not ex-
219 ist within the bubble volume.
- 220 • Fluorescent seedings and optical filters helped reduce bubble-induced laser
221 light reflections. It is known that bubble-induced reflections accounts for
222 a large percentage of undesired noise in the PTV images.

223 The use of a relatively long and transparent heater for boiling:

- 224 • The heater's length provided enough heating distance to obtain thermally
225 and hydraulically fully developed flows within the test section.
- 226 • The heater transparency allowed its use for either, visualization or illumi-
227 nation access.

228 Spatial and temporal multi-scales measurements:

- 229 • The availability of visual access from different camera perspectives allows
230 the quantification of bubble parameters with respect to the $x - y$ and
231 $x - z$ planes, while at the same time providing near-wall liquid velocity
232 measurements in the $x - y$ plane.

233 • The spatial multi-scale visualization configuration allows for liquid turbu-
234 lence measurements to be resolved for both the largest and smallest scales
235 within the test section.

236 • The spatial multi-scale visualization allowed resolution of detailed near-
237 wall liquid velocity measurements and three different scales to study the
238 bubble dynamics during the lifetime of the bubbles.

239 • The continuous and straddling timing modes allowed for temporal multi-
240 scale measurements which helped resolve the fast-happening instantaneous
241 parameters while providing also a venue for resolving the long-term aver-
242 age measurements. This capability proved to be specially important for
243 the average and instantaneous bubbles dynamics measurements.

244 Infrared thermometry:

245 • Infrared thermometry allowed for measurements of 2D temperature fields
246 of the heater wall. Only average temperature fields were considered. The
247 infrared measurements were useful to ensure experimental replicability,
248 because deviations from the normal boiling behavior were identified as
249 outliers in the measured temperature fields.

250 Analysis of a single nucleation site:

251 • By placing the measurement area in the vicinity of a single nucleation
252 site, it was possible to measure the flow development from a single-phase
253 heated condition in its transition to a two-phase bubbly flow condition;
254 i.e., measurements for both upstream and downstream of the nucleation
255 site, covering the complete bubble life-cycle were available.

256 • Measuring a developing bubble through its growth process facilitated the
257 understanding of the influences between bubble parameters and liquid
258 turbulence, such as with the relationship of bubble diameters on the liquid
259 velocity.

260 Improved experimental practices:

- An experimental protocol was developed to reduce the influence of non-condensable gases, laser-induced heat, optical distortions due to temperature gradients, and heater aging. This protocol helped to achieve reasonable replicability and reduced uncertainty.

3. Experiments

3.1. PTV-IR-Shadowgraphy experiments

The PTV/Shadowgraphy camera measurement area was located at about 12.3 cm from the test section inlet. Simultaneous PTV and shadowgraphy measurements were performed at this position. The high-speed camera was set to 4000 frames/s, with an exposure time of $250\mu\text{s}$. The relatively large exposure rate was selected as to allow enough light to reach the camera sensor and achieve satisfactory shadowgraphs of the bubbles. The time between the PTV and the shadowgraphy pairs was $\Delta t_{PTV}=1/2000$. This timing allows to acquire one frame of PIV immediately followed by one frame of shadowgraphy. For the medium magnification experiments, each acquired image consisted of 640×952 pixels and a resolution of $17.5\mu\text{m}/\text{pixel}$. Only one experimental condition was considered, with a Reynolds number of $\text{Re} = 4400$. For this Reynolds number, a heat flux of $q'' = 13.5\text{kW}/\text{m}^2$ was selected and a constant inlet temperature of about 15°C was maintained. This experimental condition allowed for a stable nucleation site behavior, however, as can be seen later, nucleation intermittency was found to be a natural behavior at this conditions. The heater wall temperature was measured with the infrared camera. The infrared camera magnification allowed temperature measurements of the whole length of the test section with a resolution of $265\mu\text{m}/\text{pixel}$. Inlet and outlet fluid temperatures were also measured by means of T-type hypodermic thermocouples.

4. Addressed Issues

As discussed previously, there exist a vast collection of works which focus on subcooled boiling. However, there are not many subcooled boiling experimental studies utilizing visualization techniques to study simultaneously the behavior

290 of both phases and their influence on the heater wall temperature. The reason of
 291 the scarcity of visualization studies dealing with subcooled boiling studies may
 292 be due to the experimental inherent complexity and the relative incompatibility
 293 between these visualization measurement techniques and the boiling phenomena
 294 of interest. For example, if not properly addressed, the visualization instrumen-
 295 tation may induce perturbations into an otherwise statistically stable boiling
 296 system. In this section are summarized the sensitivity analysis of experimental
 297 issues not previously addressed in other studies. These issues are classified in
 298 three categories a) visualization experimental issues, b) error sources due to the
 299 boiling phenomena, and c) data analysis issues. The methodology to quantify
 300 and minimize the experimental uncertainties are presented in the next sections.

301 *4.1. Visualization Experimental Issues*

302 *4.1.1. Illumination Heat Sources*

303 Most of the visualization experimental techniques¹ share the characteristics
 304 of utilizing specialized illumination sources. These illumination sources will
 305 depend on the targeted parameters of interest. The 2D PTV technique utilizes
 306 a high energy 2D laser light sheet for liquid velocity measurements, while the
 307 shadowgraphy technique utilizes volumetric illumination, such as an halogen
 308 or LED lamp, to generate shadows of the objects under investigation. These
 309 illumination sources produce large amounts of heat, and since in this study, the
 310 PTV and the shadowgraphy techniques were utilized simultaneously, the impact
 311 of the illumination instrumentation induced heat on the boiling system was
 312 addressed and quantified. It is important to mention that similar studies were
 313 performed before (Estrada-Perez and Hassan (2010)), however, previous studies
 314 limited their analysis to understand the impact of illumination heat sources on
 315 the wall temperature by means of wall-thermocouples. In the present study the
 316 multi-view, multi-scale visualization and the added advantage of a high-speed
 317 infrared camera allowed to capture the effect of the illumination heat sources

¹Although IR thermoetry technique was also used in this study, it was not considered in this section because IR themometry do not require an external illumination source.

318 in both, the bubbles dynamics and the heater wall temperature. The present
319 sensitivity studies are summarized in the next sections.

320 4.1.2. *Selected timing modes (Straddling vs Continuous)*

321 The illumination system was configured to run in continuous and straddling
322 modes (see section 2) with two illumination sources; a high energy laser and an
323 LED lamp. A sensitivity analysis was performed to quantify the influence of
324 these illumination sources and to explore ways to minimize non-desirable effects.
325 Four tests were considered: a) LED illumination and continuous timing mode,
326 b) LED illumination and straddling timing mode, c) LED+laser illumination
327 and Continuous timing mode, and d) LED+laser illumination and Straddling
328 timing mode. The effect of the illumination timing modes was studied from
329 the measurement results of bubbles dynamics and from the Infrared heater wall
330 temperature measurements.

331 4.1.3. *Effect on Bubbles Dynamics*

332 For this analysis, we focused on the bubbles dynamics behavior. Figure 4
333 shows the comparison of the near-nucleation site bubble dynamics between the
334 different illumination and timing modes. Figure 4 shows a two dimensional plot
335 of the bubbles centroid location for each case (X is the axial direction, while Y
336 is the wall-normal direction). For these conditions the bubbles rarely detached
337 from the wall, therefore the bubbles centroid location gives a very good indica-
338 tion of the bubble radius. It is noticeable that for almost all cases the bubbles
339 paths followed a similar trajectory. However, the Laser+LED Continuous case
340 showed to be different from the other test cases. The added amount of heat by
341 the laser running in Continuous timing mode, produced bubbles even upstream
342 the nucleation site under investigation. These laser-induce bubbles, while slid-
343 ing through the wall, travel on top of the nucleation site causing it to deactivate
344 or making it intermittent. Of special interest are the comparisons between LED
345 Straddling and Laser+LED Straddling cases, in both cases the bubbles paths
346 seem virtually the same. This gives a clear indication that the laser induced
347 effects are minimal when the Straddling timing mode is used. It is important

348 to note that although the LED Continuous case presents very similar bubble
349 behaviors, the bubbles most probable paths are not captured. This may be
350 due because in the Continuous timing mode, fewer independent samples are ac-
351 quired hindering the overall statistics of the measurements, i.e., a single bubble
352 is captured in multiple frames, therefore reducing the sampling number. With
353 the Continuous timing mode, outliers bubbles may impact more the statistics.

354 [Figure 4 about here.]

355 Figure 5 compares the estimated bubbles diameters measured in each of
356 the experimental modes. From the box plots is noticeable that even when the
357 average bubble diameter is about the same (0.52 mm) much more outliers are
358 found in the Laser+LED Continuous mode. From these plots can be concluded
359 that if the straddling timing mode is selected it can be ensured similar behavior
360 in repeated experiments. The shadow illumination continuous mode provides
361 similar characteristics but with a higher number of outliers.

362 [Figure 5 about here.]

363 From this analysis it was concluded that as long as the straddling timing
364 mode is used, non-desirable influences from the illumination sources are consid-
365 ered to be negligible small.

366 4.1.4. *Effect on the heater wall temperature.*

367 As mentioned previously, the effects of the illumination sources and timing
368 modes have a significant effect on the bubbles dynamics. In a similar way, illu-
369 mination sources also affect the heater wall temperature, and when considering
370 that boiling bubbles dynamics are intimately linked to heater wall heat transfer,
371 these effects become more evident. Two mechanisms were found on which illu-
372 mination sources may change the heater wall temperatures, the first mechanism
373 is the direct energy deposition from the illumination sources to the heater wall.
374 The direct energy deposition may be absorbed uniformly by the whole heater,
375 as in the case of halogen and LED lamps for shadowgraphy measurements, or

376 it may be absorbed only in particular locations, such as in the case of PTV, on
 377 which the laser light sheet was restricted to a line of 0.8 mm thickness impinging
 378 on the heater wall. From infrared measurements, the direct deposition of energy
 379 from illumination sources appeared to be negligibly small, and was barely de-
 380 tected when single phase experiments were performed. The second mechanism
 381 were noticeable only in the boiling experiments, and significantly changed the
 382 heater wall temperature. The wall temperature distorting mechanism is indirect
 383 in nature and initiate due to small perturbations of the heater wall tempera-
 384 ture. The small temperature perturbations lead to modification of the bubbles
 385 dynamics in the form of illumination induced boiling. The illumination induced
 386 boiling brought about significant changes in the heater wall temperature, as can
 387 be seen in figure 6. Figure 6 shows the results of a sensitivity study on which
 388 four cases were considered: a) No illumination, b) LED illumination and Strad-
 389 dling timing mode, c) LED+laser illumination and Straddling timing mode and
 390 d) LED+laser illumination and Continuous timing mode. From these results is
 391 clear that the LED+laser illumination with continuous timing mode produced
 392 significant changes when comparing to the no illumination case. The tempera-
 393 ture changes were not so significant in the single-phase region, there seems to
 394 be a constant temperature increase up until the vicinity of the nucleation site
 395 (about 130 mm from the inlet electrode). The laser induce bubbles acted as a
 396 heat sink in the nucleation site region, making it intermittent. The nucleation
 397 site intermittency reduced the heat removal due to a reduced bubble frequency,
 398 which is translated in a temperature increase downstream of the nucleation site
 399 as seen in figure 6. All other illumination cases on which the laser light illu-
 400 mination in a continuous timing mode were not used, provided reasonable and
 401 repeatable results.

402 [Figure 6 about here.]

403 4.2. Error Sources of Subcooled Boiling

404 4.2.1. Thermally induced optical distortions

405 Thermally induced optical distortions (TOD) in subcooled boiling systems
406 are typically found nearby interfaces on which large temperature gradients oc-
407 cur. Of special interest on subcooled boiling are the heater wall-liquid interface
408 and the boiling bubbles-liquid interfaces. The TOD phenomenon is specially rel-
409 evant on organic fluids on which the refractive index is strongly dependent on
410 the local fluid temperature (Elsinga et al. (2005)), as is the case for the present
411 study. The working fluid selected for the current experiments is relatively new,
412 and the temperature dependance of the refractive index is unknown. Therefore
413 an experimental characterization was performed to test the influence of refrac-
414 tive index changes on the optical "performance" of the visualization techniques.
415 From the analysis, it was found that the thermally induced optical distortions
416 have three main effects, one bias effect, and two random effects: one due to den-
417 sity changes and the other due to optical distortions produced by the boiling
418 bubbles. These effects can be accounted to be included part of the bias (β_{TOD})
419 and random uncertainty (σ_{TOD}) of the PTV centroid location algorithm. The
420 quantification of these effects were performed in situ, with the following process:
421 A calibration grid with circular patterns was located coinciding with the focal
422 plane of the PTV/Shadowgraphy camera. In this configuration, the grid pattern
423 is normal to the heater wall, having one edge in the near wall region (right side
424 of figure 7) and the other edge in the bulk liquid region. This grid was gen-
425 erated with a distance of 0.5 mm between each circular pattern centroid. The
426 flow loop was ran at the conditions of interest, namely at a Reynolds number of
427 $Re = 4400$, a heat flux range from 0 to 13.5 kW/m^2 and a subcooling level of
428 $\Delta T_{sub} = 15^\circ\text{C}$. The PIV/Shadowgraphy camera frame rate was set to 2000 fps,
429 the same frame rate as the one used for the "continuous" timing condition (see
430 section 2.2.1). The experimental conditions of the uncertainty analysis emulate
431 exactly the boiling experimental conditions, with the exception of the camera
432 focal plane location. In this analysis, the camera was focused on the calibration
433 grid, rather than on the nucleation site. The calibration grid was located on

the outer face of the channel, at about 6.5 mm from the nucleation site (the nucleation site was located at about 3.5 mm from the inner wall). This location was selected as to maximize the illumination light path length through the medium with variable refractive index (the heated refrigerant) on its travel from the target (the calibration grid) to the camera sensor.

Shadowgraphy pictures of the calibration grid were acquired at five different heat fluxes. 1000 images were stored per condition. The acquired calibration grid images were pre-processed to match the requirements of the PTV centroid location algorithm, which receives as input an image with white objects embedded in a black background. The PTV centroid location algorithm was applied for all images within each set. Figure 7 shows the centroid location process applied to the calibration grid. Figure 7 (a) shows the inverted (or negative) version of the original calibration grid image which is the input of the PTV centroid algorithm, figure 7 (b) shows the output of the PTV centroid location algorithm. The PTV centroid location algorithm is based on a particle mask correlation method (Takehara and Etoh (1999)), on which every pixel is correlated to an “ideal” object image, in this case, a white circle embedded in a black background. The blue pixels in the output image indicate pixels near the vicinity of the centroid, while the light yellow pixels indicate the centroid position itself.

[Figure 7 about here.]

Random uncertainty due to thermally induced optical distortions (σ_{TOD}). As mentioned previously, the random component of the thermally induced optical distortion can be divided in two, those due to density fluctuations without phase change (σ_{TOD_ρ}) and those due to the bubbles passing through the measurement region (σ_{TOD_b}), therefore, the total TOD random uncertainty can be expressed as $\sigma_{TOD} = \sigma_{TOD_\rho} + \sigma_{TOD_b}$. These random components of the thermally induced optical distortions were estimated from the calibration grid images. The random distortions without phase change (σ_{TOD_ρ}) showed a concomitant behavior with the heat flux. As expected, these distortions showed to be larger

464 for the higher heat flux cases, and for the regions within the vicinity of the
 465 heated wall. The effect of the random distortions on the calibration grid im-
 466 ages appeared as image deforming patches which moved in the flow direction.
 467 These patches varied in length and width affecting differently the appearance of
 468 the grid images. Ultimately, the grid points location estimation was randomly
 469 changed by these patches. To clarify this effect figure 8 shows the centroid lo-
 470 cation estimation of the calibration grid points. These results are shown for the
 471 non-heated and boiling conditions ($q'' = 0$ and $q'' = 13.5 \text{ kW/m}^2$ respectively).
 472 It is important to mention that the boiling bubbles are outside of the camera
 473 focal plane, reducing in this way their optical distortion influence, therefore it is
 474 safe to say that the present analysis quantifies only the uncertainty due to the
 475 effect of the liquid density changes. Figure 8 shows the calibration grid points
 476 centroid location estimation for all 1000 images for both, the unheated and boil-
 477 ing conditions. It is clear that the centroid location fluctuations are larger for
 478 the boiling condition, which is represented by the black crosses, while the red
 479 crosses represent the centroid location estimation on the unheated condition. It
 480 is important to mention that although no variations on the grid points centroid
 481 locations were expected for the unheated case, small variations were found of
 482 about 0.1 pixels. These variations are mostly attributed to the LED illumi-
 483 nation fluctuations and due to the fact that the PTV algorithm will produce
 484 larger uncertainties for centroid estimation of big objects (Estrada-Perez and
 485 Hassan (2010)). Therefore we define here a random error inherent to the PTV
 486 algorithm for big objects as $\sigma_{PTV} = 0.1$ pixels.

487 [Figure 8 about here.]

488 Further conclusions may be drawn from the wall-normal RMS profiles of the
 489 centroid location estimation. These profiles are shown in figure 9. The centroid
 490 location RMS of the boiling case is a function of the wall-normal position, while
 491 the single non-heated case shows to be position independent. The boiling case
 492 showed to have a maximum RMS of about 0.6 pixels on the near-wall region,
 493 decreasing asymptotically for regions far from the heated wall towards a value

494 of about 0.15 pixels. Noting that the boiling asymptotic RMS value is slightly
 495 different to 0.1 (which is representative of the single phase case), lead us to
 496 conclude that the influence of the thermally induced optical distortions affect
 497 the whole measurement view and need to be accounted for. Another conclusion
 498 from this analysis was the fact that the centroid location random uncertainties
 499 due to thermally induced optical distortions has an equal effect on both, the
 500 wall-normal and the wall-parallel directions.

501 From figure 9 we can obtain a maximum value for $\sigma_{TOD_\rho} \approx 0.5$ pixels (con-
 502 sidering that about 0.1 pixels is attributed to the algorithm uncertainty at this
 503 conditions). However, considering that this value is only valid at the location of
 504 the calibration grid, a correction is required for positions nearby the nucleation
 505 site. Assuming a linear dependency with the distance, and considering that the
 506 nucleation site region is one third from the calibration grid region, the uncer-
 507 tainty in the region of interest is considered to be also one third. Therefore,
 508 $\sigma_{TOD_\rho} = 0.16$ pixels. This assumption will be validated in a later section.

509 [Figure 9 about here.]

510 *Bias uncertainty due to thermally induced optical distortions (β_{TOD})..* An ap-
 511 parent displacement of the calibration grid points was observed as a consequence
 512 of heat flux increments. This displacement was uniformly distributed through
 513 the whole image with a wall-normal preferential direction. The overall trend
 514 was that for every increment on heat flux, the whole image seemed to shift
 515 towards the direction where the heated wall was located. This effect was so un-
 516 expected and large, that it was wrongly thought that the camera or the channel
 517 were displaced in some way. The apparent displacement can be observed, when
 518 comparing the grid points centroid estimation of the boiling and unheated con-
 519 ditions from figure 8. To clarify this effect, figure 10 shows a single row of grid
 520 points for the five different heat fluxes considered for this analysis. This appar-
 521 ent displacement (Δy_o) is stable once a steady state condition is reached, after
 522 which an estimation of β_{TOD} can be easily obtained and a correction for each
 523 heat flux is readily available.

[Figure 10 about here.]

Random uncertainty due to the bubbles passing through the measurement region
(σ_{TOD_b}). From all the thermally induced optical distorting effects, the one that brought about the largest uncertainties was the boiling bubbles effects. To quantify the effect of the boiling bubbles, a calibration grid was located exactly on top of the nucleation site. The camera focal plane was located in the calibration grid position so as to have the calibration grid on focus. From the camera perspective, the boiling bubbles passed in front and behind of the calibration grid. Only the bubbles passing in front of the calibration grid produced optical distortions. To clarify this procedure, figure 11(a) shows the optical distortions that a seemingly transparent boiling bubble produce on its path in front of four calibration grid points. The boiling bubble is sliding along the heater moving up in the direction of the flow. The frames at times $t = 0.0$ and $t = 4.0$ ms shows examples when the influence of the bubble was minimal. It is clear that at those particular times the centroid estimation of the four points were accurately captured. However at different times, the bubbles domain was nearby of the measured area, and the bubbles influence was clear. The curvature of the bubbles interface produce a lens-like effect which produced the optical aberrations of the calibration grid points.

[Figure 11 about here.]

A more quantitative approach may be observed on figure 12, where the black dots represent the centroid location estimation from a row of the calibration grid. The bubbles influence is confined to near-wall regions, on which the boiling bubbles are located. The bubbles induced uncertainties showed a similar behavior as the liquid density fluctuation uncertainties in the sense that there is not an influence preferential direction. The centroid location of grid points varied within a range of 15 pixels which in the context of PIV/PTV is unacceptable. Therefore an approach to reduce this influence is strongly recommended. In this work we removed all the bubbles induced optical distortions by using

553 the bubbles images as masks to remove this undesired effect. The process of
 554 bubbles masking was facilitated due to the fact that we performed simultaneous
 555 PIV and Shadowgraphy visualizations, this meant that we can use the bubbles
 556 information from the shadowgraphs to remove the unreliable particles found
 557 within the domain of the bubbles. Figure 11(b) shows the bubbles masking
 558 procedure to reduce the effect of the bubbles passing. In this case the bubbles
 559 body is considered to be no longer transparent, therefore the lensing-effect is
 560 totally removed. However, bubbles influence still prevails in the vicinity of the
 561 bubbles. In these regions, large density changes are still producing considerably
 562 large effect. However it has to be recalled that in the PIV/PTV experiment,
 563 the objects to be tracked are tinny particles that are following the liquid flow.
 564 Both of these characteristics (small size and moving with the flow) will reduce
 565 greatly the bubbles influence. The present analysis is quite conservative, and it
 566 is expected that both, the density fluctuations and bubbles influences will af-
 567 fect the PIV/PTV particle tracers centroid location in a reduced manner. The
 568 process of removing the information within the domain of the bubbles is shown
 569 in figure 12. The red dots represent the resulting centroid location estimation
 570 after removing the undesired bubbles induced information. It is clear that the
 571 bubbles removal process drastically reduced the centroid location range from
 572 about 15 pixels to about only 2 pixels.

573 It is important to mention that following the aforementioned procedure, we
 574 can keep the bubbles induced uncertainty low even for high void fraction cases.
 575 The only impact on the liquid velocity measurements at high void fractions
 576 will be reflected on the sampling number. Only those particles which view is
 577 not blocked by a bubble are considered. Therefore many more images will be
 578 required to compute reliable statistics for high void fraction cases.

579 [Figure 12 about here.]

580 Figure 13 shows the centroid location RMS comparisons between three cases,
 581 the unheated case, the boiling case with raw data, and the boiling case without
 582 the bubbles unreliable information. The bubbles brought about a huge RMS

583 on the order of 2.5 pixels which was reduced to about 0.4 pixels just after
 584 removing the bubbles information. From the comparison of these two cases,
 585 it is clear that the bubbles removal correction extends to the first four points
 586 (from left to right) of the profile. These points are closer to the heated wall. The
 587 fifth and sixth points show a significant discrepancy compared to the unheated
 588 case. This discrepancy may be explained by the density fluctuations effects or
 589 by the distorting effect located on the vicinity of the bubbles interface. From
 590 this information the maximum bubbles induced optical distortion for the near-
 591 wall measurements accounts for about $\sigma_{TOD_b} = 0.2$ pixels. This value does not
 592 take into account the density fluctuation influence which accounts for about
 593 0.2 pixels, a similar value was obtained for the density fluctuations induced
 594 uncertainty estimated in previous sections, which accounted for $\sigma_{TOD_\rho} = 0.16$
 595 pixels, therefore the assumption of a linear dependency of the density induced
 596 uncertainty with respect to location seems to be reasonable.

597 [Figure 13 about here.]

598 4.3. Data Analysis Issues

599 4.3.1. PTV Related

600 The previous sections showed critical issues that have to be addressed when
 601 using PTV for the analysis of subcooled boiling experimental images. These
 602 issues were mainly related to optical distortions due to density gradients and
 603 due to the existence of boiling bubbles in the measurement region. Based on this
 604 information, it was decided that careful removal of bubbles induced vectors was
 605 a necessity to ensure reliable liquid velocity measurements. The bubbles induced
 606 vectors removal can be performed in two distinct ways: The first one, which will
 607 be called Bubble Image Masking (BIM), is an image processing algorithm that
 608 removes or masks the pixels that are within the domain of the bubbles. The
 609 second one, which will be called Bubbles Velocity Masking (BVM), is a post-
 610 processing algorithm that removes or masks the velocity vectors that are within
 611 the domain of the bubbles. In both cases, the bubble domain is determined
 612 from the shadowgraphy images acquired simultaneously with the PTV images.

Figure 14 shows the comparison of the average liquid velocity profiles using three different PTV analysis procedures, including the Raw data analysis, on which no bubble information was removed, the PTV analysis on which BIM was used to remove undesired noise from bubbles images, and the PTV analysis with BVM, to remove undesired velocity vectors within the bubbles domain. These results are compared at different axial positions ($x = 0.0$ mm, 1.2 mm, and 6.2 mm) from the nucleation site. From these results, it is clear that the PTV analysis with BIM produces an overestimation of the liquid velocity at the axial location $x = 6.2$ mm. Investigation of these results showed that the bubbles image removal of the BIM process hindered the particle centroid location of the PTV algorithm, resulting on spurious particles on the vicinity of masked regions. The spurious particles location corresponded to the bubbles interfaces, which lead to erroneously measure the bubbles velocities. This explains the overestimation of the liquid velocity at the location $x = 6.2$ mm, at this location the bubbles are fully developed and have larger velocities. Based on these results, it was determined that the BVM performed better, not only the spurious particles detection was reduced with the BVM process, but also provided higher quality vectors due to the aid of the bubbles information on the particle matching process.

[Figure 14 about here.]

4.3.2. Bubble intermittency

Although it appeared that at this experimental condition a stable bubble nucleation behavior was achieved, the influence of the additional power supplied by the laser showed to be large. When performing PIV experiments in a continuous mode (see timing configuration explanation), the nucleation site behavior changed drastically (these effect were explained in previous sections). Therefore it was decided to perform the PIV experiments only in straddling mode configuration. In straddling mode, the laser induced power was largely reduced, and the effect of the laser in the nucleation behavior was not longer noticeable. However, some intermittency was observed in the activity of the

nucleation site. As shown in Figure 15, this intermittency was detected directly from the experimental images. Ten percent of the 10,000 PIV images were considered as “intermittent” instances on which a lower void fraction was found. Examples of what was considered an “intermittent” image are shown in Figure 15 (A), (B), and (C). Intermittent images were removed from the analysis of flow statistics because they were not representative of the “stable” behavior of the nucleation site. Figure 15 (D) and (E) are examples of the experimental data that was considered in the statistical analysis. As of today, is not known with certainty the reasons of this intermittency.

[Figure 15 about here.]

Further insights are obtained when comparing the liquid velocity measurements between the stable case and the intermittent instances. Figure 16 shows the average velocity profiles at three axial positions ($x=6.2$, $x=1.19$, $x=0.0$) from the nucleation site. The black filled symbols represent the stable case or in the context of this condition, it represents instances of high void fraction on which the bubble number was larger than six, the red hollow circles represent the intermittent cases on which low void fraction was found. Low void fraction cases were those on which less than 6 bubbles were present. Comparing the results obtained between the intermittent and the stable cases, the influence of the bubbles parameters is clear. For the intermittent cases, the small void presence barely influence the liquid velocity, in fact the deviation from a single phase behavior was small. However for the stable case on which the bubble layer was fully developed, the influence of the high void fraction brought about a large acceleration of the liquid velocity.

[Figure 16 about here.]

4.3.3. Sampling number influence on velocity measurements.

To ensure that the measured flow statistics have been computed with a high statistical significance, an analysis was performed to test the influence of sampling number on the statistical parameters of interest. In this case we were

672 interested on the wall-normal velocity profiles along the heater, to this end, the
 673 velocity fields from the PIV images were divided in bins, 200 vertical bins in
 674 the wall-parallel direction, and 50 horizontal bins in the wall-normal direction.
 675 This allowed us to provide velocity profiles representing the flow development
 676 along the heater.

677 For the uncertainty analysis, we focused on a single horizontal bin and per-
 678 formed the average wall-normal velocity profile estimation depending on differ-
 679 ent sampling numbers. The selected sampling numbers ranged from 10 to 4000.
 680 This analysis was repeated five times, ensuring that each time different samples
 681 were selected out of the total sample pool which was about 4800 velocity fields.
 682 Figure 17 shows the results of this procedure. For small sample numbers, or in
 683 this case for small number of vector fields, the discrepancies of the five estimated
 684 velocity profiles are significant. These discrepancies gradually die down by in-
 685 creasing the number of vector fields, until reaching a point on which increasing
 686 the number of vector fields no longer affects the estimated average profile. This
 687 point is said to have sufficient samples, enough to provide the velocity profile
 688 with high statistical significance. The point of high statistical significance for
 689 the wall-normal velocity profile corresponded to a value of about 3000 vector
 690 fields.

691 [Figure 17 about here.]

692 5. Uncertainty Analysis

693 The uncertainty analysis on this work focus on the particle tracking velocime-
 694 try methodology. In this context, velocity measurements uncertainties strongly
 695 depend on the accurate centroid location of the tracked objects (Kähler et al.
 696 (2012)). PTV velocity measurements are obtained from individual particle lo-
 697 cations at different time intervals, and are given by $V_{i,x} = (x_{i,2} - x_{i,1})/\Delta t_{PIV}$
 698 where $V_{i,x}$ is the axial velocity component of the i -th particle, $x_{i,2}$ is the axial
 699 position of particle i in the second frame, while $x_{i,1}$ is the axial position in the
 700 first frame, and Δt_{PTV} is the time interval between two PTV frames. Similar

expressions are required for the other velocity components, however, for sake of simplicity, only the axial component is treated. From this expression, and assuming that the timing uncertainty is negligible, it is clear that the centroid location uncertainty plays a key role on accurate velocity measurements. Two types of uncertainties were quantified, bias and random uncertainties. The next sections highlight the relevant aspects of these uncertainties.

5.1. Bias uncertainties

From the calibration grid experiments the bias uncertainty due to the thermal optical distortions (β_{TOD}) was quantified. It was found that β_{TOD} is a function of the heat flux, liquid velocity, and subcooling level, and that it remained constant for steady state conditions. For each test condition, bias uncertainties can be easily quantified in terms of a correction factor (y_o). The correction of this bias becomes specially important for close to the wall measurements. Close to the wall velocity measurements are sensitive to image distortions which can induce significant uncertainties on the average and instantaneous velocities. The bias uncertainty had been addressed previously in optical or visualization studies dealing with strong density gradients and boiling (Roy et al. (2002); Hsieh et al. (2003)), however these studies did not address the fluctuating components of the uncertainties which are induced either by the random density fluctuations or by the bubbles influence, these are discussed next.

5.2. Random uncertainties

In previous sections, it has been found that the uncertainty associated with the centroid location estimation were those induced by thermally induced optical distortions (TOD), and those inherent of the PTV centroid location algorithm. Then, the centroid location uncertainties under boiling conditions can be expressed as $\sigma_x = \sigma_{TOD_\rho} + \sigma_{TOD_b} + \sigma_{PTV}$ (see section 4 for the definitions of each term). From the calibration grid experiments it was found that the uncertainty due to the random liquid density changes is a function of the position from the heated wall, with a maximum value at $y = 0$ of $\sigma_{TOD_\rho}(0) = 1.14$ pixels. The maximum uncertainty due to bubbles aberrations was found to be $\sigma_{TOD_b} = 2.5$

pixels. Previous studies had shown that, for objects similar in size as the cali-
 bration grid points, the centroid location uncertainty of the PTV algorithm is
 $\sigma_{PTV} = 0.05$ pixels (Estrada-Perez (2004); Estrada-Perez and Hassan (2010)).
 In order to apply these results in our flow boiling experiments, a correction
 was required to account for the size discrepancies. The calibration grid points
 used for the uncertainty analysis accounted for about 25 pixels in diameter,
 while, in the flow boiling experiments, a maximum particle image size of about 2
 pixels was found. Previous sensitivity studies had shown that the PTV centroid
 location performance is a strong function of particle size Estrada-Perez (2004);
 Estrada-Perez and Hassan (2010). After correcting for the size discrepancies, the
 maximum uncertainties suitable for the boiling experiments are: $\sigma_{TOD_p}(0) =$
 0.091 pixels, $\sigma_{TOD_b} = 0.200$ pixels and $\sigma_{PTV} = 0.004$ pixels, which adds up to a
 maximum centroid location uncertainty of $\sigma_x = 0.295$ pixels. Using the calibra-
 tion for the boiling experiments (a resolution of $17.5 \mu m/\text{pixel}$), $\sigma_x = 5.17 \mu m$.
 In terms of the axial velocity, the uncertainty propagation rules (Kähler et al.
 (2012); Kline and McClintock (1953)) gives $\sigma_{V_x} = (\sigma_{x_1}^2/\Delta_{t_{PIV}}^2 + \sigma_{x_2}^2/\Delta_{t_{PIV}}^2)^{1/2}$,
 assuming that $\sigma_{x_1} = \sigma_{x_2}$ we end up with $\sigma_{V_x} = (2\sigma_x^2/\Delta_{t_{PIV}}^2)^{1/2} = 0.014$ m/s,
 which is about 7% of the maximum axial velocity. As explained in section 4 the
 dominant uncertainty is induced by spurious particles and vectors due to the
 bubbles influence. The bubbles induced uncertainties are reduced by neglecting
 the information within the bubbles domain from the liquid velocity fields. The
 remaining bubbles induced uncertainty after the removal procedure was esti-
 mated to be $\sigma_{TOD_b}^* = 0.016$ pixels, which gives $\sigma_x^* = 0.111$ pixels or $\sigma_x^* = 1.95$
 μm , which in terms of the velocity gives $\sigma_{V_x}^* = 0.006$ m/s or 3% of the max-
 imum axial velocity. This analysis provides insight of the maximum possible
 uncertainties, those which will happen close to the heater wall in a boiling ex-
 periment. Far from the heated wall, the effect of the density fluctuations and
 bubbles influences will be negligible. For sake of comparison the uncertainty
 with the bubbles effect and after these effects are reduced are depicted in figure
 18. For these profiles, it was allowed for the bubbles influences to extend to
 the whole profile, instead of being confined to the near-wall region. This to

include cases of higher void fractions, or cases that the bubbles are uniformly distributed through the channel, such as in the case of isothermal bubbly flows.

In figure 18, the uncertainty before removing bubbles effects are depicted as black error bars, while the uncertainties after removing the bubbles effects are shown in red. It is important to mention that both, horizontal and vertical error bars were obtained with this analysis. Horizontal error bars for the position uncertainty, and vertical error bars for the velocity uncertainty. In Table 2, are summarized the uncertainties estimated in this study showing comparisons for the bubbles effect and object size scaling corrections.

[Figure 18 about here.]

[Table 2 about here.]

6. Results

Velocity Measurements

After addressing the issues found in section 4 to reduce uncertainty and to enhance the statistics reliability, we focused on the liquid and bubbles statistics. The velocity of both phases was obtained by means of particle tracking velocimetry (PTV). The PTV algorithm is able to track small objects such as the PIV particle tracers or large objects such as the boiling bubbles. The results of the tracking algorithm are shown in Figure 19. The picture in the left of Figure 19 shows an instantaneous velocity field on top of the shadowgraphy image, the right picture in Figure 19 shows the PTV results of the boiling bubbles.

[Figure 19 about here.]

Figure 19 shows the advantages of using the single nucleation site approach. This approach provides the capability of measuring at the same experimental condition, the flow development from a heated single phase to the transition to two-phase boiling flow. Furthermore, the bubbles dynamics can be accurately characterized at every point along the heater, this allows to explore the influence of multiple bubble dynamics conditions on the average liquid velocity behavior.

790 From a set of instantaneous information, like the ones shown in figure 19, average
 791 flow statistical quantities can be estimated, for example, in figure 20 are shown
 792 the average void residence time fraction (left) and average liquid velocity profiles
 793 (right). The void residence time fraction was obtained from the average of a
 794 set of binary shadowgraphy images on which black pixels represented the liquid
 795 phase and white pixels represents the gas phase. This procedure enabled us to
 796 consider each pixel as a single void probe for the estimation of the local void
 797 fraction. Similarly from a set of instantaneous velocity fields, average velocity
 798 profiles can be obtained. Figure 20 shows the liquid and bubbles average velocity
 799 profiles along the axial direction (right picture). it is clear that the effect of the
 800 nucleated bubbles brought significant changes on the liquid behavior: Upstream
 801 of the nucleation site, in the single-phase region, the liquid velocity is virtually
 802 not affected, the liquid statistics remain the same at different axial positions.
 803 Such behavior remain constant up until the region on which the nucleation
 804 site is located. Downstream the nucleation site, there is a liquid axial velocity
 805 increase which seems to be concomitant to the bubbles sizes and velocities.
 806 From the present observations it appears that the liquid velocity increase with
 807 the distance is maintained up until about a distance of 7 to 8 mm, after which,
 808 the local peak of liquid velocity tend to a terminal value of 0.2 m/s. A similar
 809 behavior was observed for the boiling sliding bubbles, bubbles diameters and
 810 velocities increased concomitantly with the distance. This increase on bubble
 811 diameter is attributed to the bubble sliding through the heated wall. It was also
 812 observed that the rate of bubble growth is much larger near the vicinity of the
 813 nucleation site, and that after few millimeters (~ 4 mm), the bubbles dimensions
 814 reached a value that was kept relatively constant. Bubbles velocity depended
 815 entirely on the bubbles sizes along the heater. The bubbles dynamics behavior
 816 is studied in more detailed in following sections.

817 [Figure 20 about here.]

818 6.1. Bubbles Dynamics

819 Figure 21 shows the high magnification shadowgraphy results (resolution of
820 $4.82\ \mu\text{m}$). The high magnification results allowed a detailed examination of
821 the average bubble behavior along the bubble path. Four profiles are shown
822 in Figure 21: bubbles width, height, axial velocity, and normal velocity. It is
823 important to note that more than 20000 bubbles were considered so as to show
824 the most probables behavioral bubble paths along the heater wall. Furthermore,
825 these results were obtained with the straddling timing mode, which provides an
826 independent measuring sample for each image pair. As observed in Figure 21,
827 large changes in the bubbles dimensions came about the first half millimeter
828 after nucleation. Bubbles at the nucleation site increased rapidly both in width
829 and height. The nucleated bubbles showed to follow two preferable growing
830 paths, namely: Path A and Path B. Path A is characterized by a sharp increase
831 on bubble size, following two typical behavior. The first behavior of bubbles
832 following path A is a rapid bubble growth which causes bubble detachment.
833 Most of the detached bubbles reduced in size and were pushed back to reattach
834 to the wall. The second common behavior of bubbles that follow Path A, were
835 those bubbles that coalesced with the leading bubble. The motion fluctuations
836 induced by the coalescing process promoted as well bubble detachment. Bubbles
837 that followed path B, consisted on nucleated bubbles that did not detach from
838 the wall, and presented a smooth growing rate as they slid through the wall. The
839 bubbles velocity was intimately related to the bubbles growing behavior. Several
840 points are worth noting: First, the bubbles seems to have an almost constant
841 acceleration at least in the first 3.5 mm after nucleation. However, the axial
842 velocity within 0.25 to 0.75 mm showed to be largely fluctuating. This behavior
843 is explained when considering that at this location, most of the coalescence,
844 detachment and reattachment happens. Another interesting behavior is the
845 normal bubbles velocity at the nucleation site. The force acting on the bubbles
846 induced by the rapid growing at the nucleation site produced bubbles velocities,
847 in the wall-normal direction, as large as 0.4 m/s. This velocity is large compared
848 to the maximum axial velocity that was not larger than 0.25 m/s. After this

849 very large velocity increase, the normal velocity tends rapidly to zero.

850 [Figure 21 about here.]

851 Insight into the benefits of performing multi-scale measurements can be
852 gained when comparing the results from Figure 21 and Figure 22. Figure
853 22 shows the synchronized measurements at the same conditions as the ones
854 shown in 21 but from different view point and magnification. Figure 21 shows
855 the high-magnification side-view results, while in Figure 22 are shown the low-
856 magnification front-view results. Figure 21 provides detailed bubble dynamics
857 information, however this measurement is limited to only 3.5 mm from the nu-
858 cleation site. Figure 22 shows less detailed information but in a larger scale. To
859 make the differences of scales between these measurements clearer, a small rect-
860 angle close to the nucleation site in Figure 22 depicts the measurement region
861 from the side-view high-magnification camera. The first plot of Figure 22 shows
862 the evolution of the probable paths nucleated bubbles may take while sliding
863 through the wall, a uniform dispersion is observed, similar to the spreading of
864 a bubble plume. The second plot of Figure 22 shows the axial velocity of the
865 bubbles, from this plot can be inferred that the terminal velocity of the bubbles
866 is about 0.2 m/s. Bubbles reach to these velocities fairly rapidly, within the
867 first 10mm after nucleation. The velocity component on the direction parallel
868 to the heater (Z direction) is shown in the third plot of Figure 22, This velocity
869 component is very close to zero, however there is a significant increase of this
870 velocity with distance. Sliding bubbles increasing in size reach rapidly to a ter-
871 minal axial velocity, and show to increase their zigzag motion in the direction
872 parallel to the wall.

873 [Figure 22 about here.]

874 6.2. Liquid Velocity Statistics

875 One of the main objectives of the PTV measurements is to obtain detailed
876 information of the liquid velocity close to the heated wall under subcooled boil-
877 ing conditions. Figure 23 shows the average axial velocity profile at different

axial locations. The color bar indicate the axial distance from the nucleation site, starting with a blue color for locations on which only single phase flow is found, the red color represents the location after 7 mm downstream the nucleation site. The influence of the boiling bubbles on the liquid velocity is clear. There is a local peak in the region close to the wall. This local peak is related to the average bubble radius measured at each axial location.

[Figure 23 about here.]

To have a better understanding of the liquid behavior, it is always convenient to present these results in dimensionless form. The characteristic length and velocity used for the non-dimensionalization are $y^+ = (yu_\tau) / \nu$ for the characteristic length and u_τ for the characteristic velocity, u_τ is the friction velocity defined as $u_\tau = \sqrt{(\tau_w / \rho)}$. The wall shear stress (τ_w) is obtained experimentally using the approximation for regions close to the wall $\tau_w = \mu \left. du/dy \right|_{y=0}$. From the previous definitions we found a frictional velocity of $u_\tau = 0.0125$ m/s. It is important to note that the heated single phase friction velocity was considered as the characteristic velocity. Figure 24 shows the non-dimensional form utilizing the single phase heated frictional velocity $u_\tau = 0.0125$ m/s. From this plot, significant discrepancies from the law of the wall (continuous line in red) were observed even for the heated single phase cases. These discrepancies, rather than being experimental uncertainties, are attributed to the buoyancy driven flow induced in the vicinity of the heated wall. The single phase unheated experimental results have been shown (Estrada-Perez and Hassan, 2010) to match faithfully the law of the wall for locations above $y^+ = 1.0$ in a similar configuration. Also, the effect of the boiling level has been previously observed by Estrada-Perez and Hassan (2010). However, the present experiments focused in a single nucleation site, allowing to have different void fractions which depend on the location. Therefore, a single heat flux condition will provide different local void fractions, which simplified greatly the experimental and analysis work. In Figure 24 the red and gray lines represent the limits of the viscous sublayer and that of the buffer layer. Also, it is clear that the largest influence of the

908 boiling bubbles is confined in the region between these two lines.

909 [Figure 24 about here.]

910 7. Conclusions

911 In this work, a sensitivity study was performed to explore the feasible imple-
912 mentation of whole-field visualization techniques such as Infrared Thermometry,
913 Particle Tracking Velocimetry, and High speed Shadowgraphy to study sub-
914 cooled flow boiling through a vertical square channel with a single heated wall.
915 It was found that although each independent technique requires very specific
916 technical demands, with careful experimental system arrangements, the simul-
917 taneous implementation of these techniques to study subcooled flow boiling is
918 viable with reasonable uncertainties and high repeatability.

919 From the PTV perspective several findings/recommendations are highlighted:
920 For typical PTV boiling experiments, the use of high energy lasers in a contin-
921 uous timing mode has to be used with caution. Laser induced perturbations
922 changed what was considered a stable boiling condition.

923 Therefore, the use of the straddling timing mode is recommended. The
924 straddling timing mode showed to be superior not only due to the reduced
925 laser induced perturbations, but also provided higher quality flow statistics.
926 The straddling timing allowed more independent samples to be used on the
927 estimation of the time average quantities. This fact was specially important for
928 the shadowgraphy measurements due to the relatively small number of bubbles.

929 The sensitivity studies performed in this work provided insight into the PTV
930 uncertainties when studying boiling. It was found that other than the typical
931 uncertainties of the technique², additional uncertainties inherent to the boil-
932 ing phenomena were found. These included uncertainties due to thermo-optical
933 distortions, which are highly dependent on position and on experimental condi-
934 tions. Thermo-optical distortions manifested as a bias uncertainty β_{TOD} and by

²Uncertainties quantified by means of artificial images and idealized characteristics

two random uncertainties σ_{TOD_p} and σ_{TOD_b} . The random uncertainties originate from random density fluctuations and due to the boiling bubbles. The bias uncertainty is easily corrected by means of side experiments involving a calibration grid, the uncertainty due to random density fluctuations σ_{TOD_p} can not be easily corrected, but for the studied conditions did not largely affect the measurements.

It was also found that large uncertainties on the PTV measurements were induced by the boiling bubbles, therefore it is recommended to perform simultaneous PTV/Shadowgraphy experiments. The shadowgraphy experiments will dictate the bubbles domain, from which spurious velocity vectors can be removed to reduce this uncertainties.

The experimental methodology developed in this work, provided whole-field velocity fields of the two phases, bubbles dynamics quantification and heater wall temperature fields in a simultaneous manner with acceptable accuracy and repeatability. The data gathered using this methodology can be used as an experimental benchmark for validation of CFD codes and for the improvement and development of models and correlations for a better description of subcooled boiling flow.

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1045 List of Figures

1046	1	Test section schematics and dimensions.	39
1047	2	Visualization system schematics	40
1048	3	Timing configuration for semi-simultaneous PTV/shadowgraphy	
1049		measurements, with square's color representing: green, illumina-	
1050		tion by laser; gray, illumination by LED lamp; white, waiting or	
1051		straddling period.	41
1052	4	Bubble dynamics behavior at different illumination and timing	
1053		conditions a) LED Straddling, b) LED Continuous, c) Laser+LED	
1054		Straddling, d) Laser+LED Continuous.	42
1055	5	Bubbles diameters comparison between the different illumination	
1056		and timing modes.	43
1057	6	Wall temperature influence due to different illuminations and tim-	
1058		ing conditions.	44
1059	7	Centroid location process	45
1060	8	Estimated location of grid points	46
1061	9	Location uncertainty due to refractive index fluctuations	47
1062	10	Apparent position displacement due to temperature driven re-	
1063		fractive index changes.	48
1064	11	Example of centroid location variation due to a bubble optical	
1065		distortion.	49
1066	12	Centroid location variation due to bubbles induced distortions. .	50
1067	13	Centroid location estimation RMS variation due to bubbles in-	
1068		duced distortions	51
1069	14	Bubbles images effect on the average liquid velocity measurements.	52
1070	15	Intermittency of nucleation site activity.	53
1071	16	Intermittency of nucleation site activity.	54
1072	17	Sampling number effect on the velocity profile.	55
1073	18	Uncertainty associated with the average velocity profiles compar-	
1074		ing two cases: a) with the bubbles effects (black error bars) and	
1075		without the bubbles effects (red error bars).	56
1076	19	Liquid and bubbles velocity fields and profiles	57
1077	20	Void residence time and velocity profiles	58
1078	21	Side view high magnification bubble dynamics measurments. . .	59
1079	22	Low magnification shadowgraphy visualization for bubble dy-	
1080		namics measurements	60
1081	23	Axial liquid velocity profile at different axial positions from the	
1082		nucleation site.	61
1083	24	non-dimensional axial liquid velocity profile at different axial po-	
1084		sitions from the nucleation site (using the single- phase friction	
1085		velocity u^*), and the single phase unheated law of the wall (red). .	62

Figure 1: Test section schematics and dimensions.

Figure 2: Visualization system schematics

Figure 3: Timing configuration for semi-simultaneous PTV/shadowgraphy measurements, with square's color representing: green, illumination by laser; gray, illumination by LED lamp; white, waiting or straddling period.

Figure 4: Bubble dynamics behavior at different illumination and timing conditions a) LED Straddling, b) LED Continuous, c) Laser+LED Straddling, d) Laser+LED Continuous.

Figure 5: Bubbles diameters comparison between the different illumination and timing modes.

Figure 6: Wall temperature influence due to different illuminations and timing conditions.

Figure 7: Centroid location process

Figure 8: Estimated location of grid points

Figure 9: Location uncertainty due to refractive index fluctuations

Figure 10: Apparent position displacement due to temperature driven refractive index changes.

Figure 11: Example of centroid location variation due to a bubble optical distortion.

Figure 12: Centroid location variation due to bubbles induced distortions.

Figure 13: Centroid location estimation RMS variation due to bubbles induced distortions

Figure 14: Bubbles images effect on the average liquid velocity measurements.

Figure 15: Intermittency of nucleation site activity.

Figure 16: Intermittency of nucleation site activity.

Figure 17: Sampling number effect on the velocity profile.

Figure 18: Uncertainty associated with the average velocity profiles comparing two cases: a) with the bubbles effects (black error bars) and without the bubbles effects (red error bars).

Figure 19: Liquid and bubbles velocity fields and profiles

Figure 20: Void residence time and velocity profiles

Figure 21: Side view high magnification bubble dynamics measurements.

Figure 22: Low magnification shadowgraphy visualization for bubble dynamics measurements

Figure 23: Axial liquid velocity profile at different axial positions from the nucleation site.

Figure 24: non-dimensional axial liquid velocity profile at different axial positions from the nucleation site (using the single- phase friction velocity u^*), and the single phase unheated law of the wall (red).

1086 List of Tables

1087	1	Measurement equipment ranges and uncertainties	64
1088	2	Uncertainty Study Results	65

Table 1: Measurement equipment ranges and uncertainties

Parameter		Uncertainty
Liquid flow rate	[m ³ /s]	$\dot{Q}_l \pm 0.05 \%$
Temperature	[°C]	$T_{amb} \pm 0.50$
		$T_{in} \pm 0.50$
		$T_{out} \pm 0.50$
Differential Pressure	[Pa]	$dP_1 \pm 0.25 \%$
		$dP_2 \pm 0.50 \%$
System Pressure	[Pa]	$P_{in} \pm 0.25 \%$
		$P_{out} \pm 0.25 \%$
Heater power	[W]	$\dot{q} \pm 1.10 \%$

Table 2: Uncertainty Study Results
With bubbles effects

σ_{TOD_b}	2.50 pixels 43.8 μm	0.200 pixels 3.5 μm
σ_x	3.69 pixels 64.6 μm	0.295 pixels 5.17 μm
σ_{V_x}	5.21 pixels/ Δt_{PIV} 0.18 m/s	0.42 pixels/ Δt_{PIV} 0.015 m/s
Without bubbles effects		
$\sigma_{TOD_b}^*$	0.2 pixels 3.5 μm	0.016 pixels 0.28 μm
σ_x^*	1.39 pixels 24.3 μm	0.111 pixels 1.95 μm
$\sigma_{V_x}^*$	1.97 pixels/ Δt_{PIV} 0.069 m/s	0.16 pixels/ Δt_{PIV} 0.006 m/s