

Temperature and velocity field measurements of pool boiling using two-colour laser-induced fluorescence, infrared thermometry and particle image velocimetry

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Abstract

We study nucleate pool boiling in water at saturation temperature and ambient pressure under low heat fluxes. A combination of high-speed and spatially-resolved diagnostic tools are developed and applied to provide detailed insight into the flow and heat transfer mechanisms during bubble life cycle. Two fluorescent dyes with non-overlapping spectra are seeded into the water and are excited by a Nd:YLF laser sheet at 527 nm. A two-colour laser-induced fluorescence method is employed to individually track the fluorescence of each dye by connecting two cameras, equipped with separate optical filters, to a beamsplitter and a lens. Tracer particles are also introduced in the water to perform simultaneous particle image velocimetry measurements. Finally, synchronised high-speed infrared thermometry is conducted to acquire the surface temperature field over the heater. The links between the interfacial/bubble dynamics, flow and heat transfer are investigated. Superheated liquid from the thermal boundary layer adjacent to the heater is displaced upwards, due to the growth and departure of the bubbles. Two counteracting vortices form on each side of the bubbles during their departure and rise, which contribute to the scavenging and mixing of the bulk water, resulting in a trail of superheated liquid below them.

1 Introduction

Nucleate boiling is a very effective mode of heat transfer and is therefore employed in a wide range of industrial applications, from nuclear reactors (1; 2) to emerging high-performance micro-systems (3). A comprehensive understanding of the heat and fluid flow processes during the phenomenon is hence crucial as it can unlock new avenues for the more efficient use of thermal energy. However, complex and dynamic two-phase transport phenomena are involved in nucleate boiling, which require further research.

Empirical methods have been predominantly developed so far to try to explain these coupled and interacting mechanisms, which are, however, inherently limited to a narrow range of operational conditions. Recently, the rise of mechanistic methods (4; 5) and the advances and increasing detail of computational efforts (6; 7) have resulted in a need for detailed space and time-resolved experimental measurements for validation and model development purposes.

Several experimental techniques have been employed to investigate the flow and heat transfer during pool boiling in the past. Earlier efforts extracted local temperature information with thermocouples and microsensors (8), while more recent efforts have emerged that can provide whole field information on the temperature distribution over the heater with infrared (IR) diagnostics (9; 10) and the temperature in

the liquid bulk with rainbow Schlieren (11; 12), which are intrinsically averaged along the depth of field of the imaging system.

Here, we combine advanced infrared- and laser-based diagnostic tools (13; 14; 15) for the first time, in order to extract spatiotemporally resolved temperature and velocity information during the bubble life cycle and to investigate any associated phenomena during pool boiling. A high-speed IR technique, previously developed by Bucci et al. (10), is used to obtain the temperature and heat flux distributions over the heater surface and is employed in conjunction with two-colour laser-induced fluorescence (2cLIF) (16) and particle image velocimetry (PIV) methods, which are able to provide simultaneous local temperature and velocity-field information in the water phase, respectively. The current work has a technical experimental nature and is focused on the application of such techniques in a pool boiling system. The physics of the phenomena will be discussed in more detail as we progress in this study.

2 Experimental Methodology

2.1 Apparatus

The apparatus used for the pool boiling experiments is illustrated in Fig. 1. The cell was filled with DI water and was brought to saturation temperature, T_{sat} , via a circulating

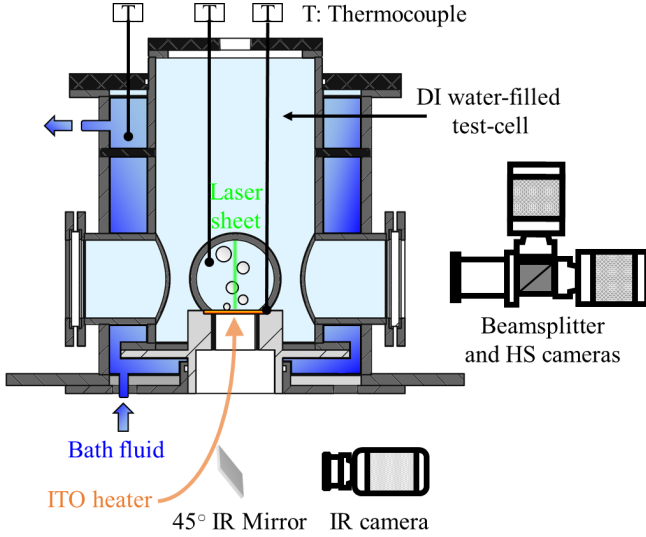


Figure 1: Schematic of the apparatus and instruments used for the experiments.

heating bath. The temperature of the water, T , was monitored with K-type thermocouples located at bespoke positions, close to the heater and at the top of the side-view window. Once the bulk water reached its saturation temperature, i.e. $T = T_{\text{sat}}$ was established, current was supplied to a thin-film indium tin oxide (ITO) heater coated on a IR transparent sapphire glass, providing the heat flux to initiate boiling.

We coated a $\sim 100 \mu\text{m}^2$ area at the centre of the heater with hydrophobic material (PTFE) to artificially control the nucleation topology and generate isolated bubble at a desired location (centre of the heater). Bubbles nucleating along the path of the laser beam and the camera's depth of field, would obstruct the implementation of the laser diagnostic techniques.

2.2 Experimental techniques

We employed a ratiometric 2cLIF method to obtain the temperature field of the water by tracking the emission of two fluorescent dyes dissolved in it, namely fluorescein disodium (FL) and sulforhodamine101 (SR). The concentration of each dye was equal to $C_{\text{FL}} = 4 \cdot 10^{-5} \text{ M}$ and $C_{\text{SR}} = 1.4 \cdot 10^{-7} \text{ M}$. Two high-speed (HS) cameras were connected to a pellicle beamsplitter (R45%: T55%) and a Nikon 105 mm lens (cf. Fig. 1). An extension tube was connected between each camera and the beamsplitter, which also acted as a holder for the optical filters. Different optical filter arrangements (combinations of short, long and notch filters) were used for each camera to visualise each fluorescent dye separately.

Additionally, fluorescent tracer particles of mean size $10 \mu\text{m}$ at a concentration below 0.01 M emitting primarily above $\lambda > 550 \text{ nm}$ (where λ denotes the wavelength) were also introduced in the water. Tracking their displacement with PIV allows for velocity field measurements. Figure 2 illustrates the optical wavelength bands visualised by each camera, along with the spectra of the dyes and particles used.

The first camera, CAM_{FL} (Phantom V12.1), recorded the fluorescent intensity of the temperature-sensitive FL dye (Band 1 in Fig. 2), while the second camera, CAM_{SR} (Phantom V25.12), recorded the intensity of the temperature-

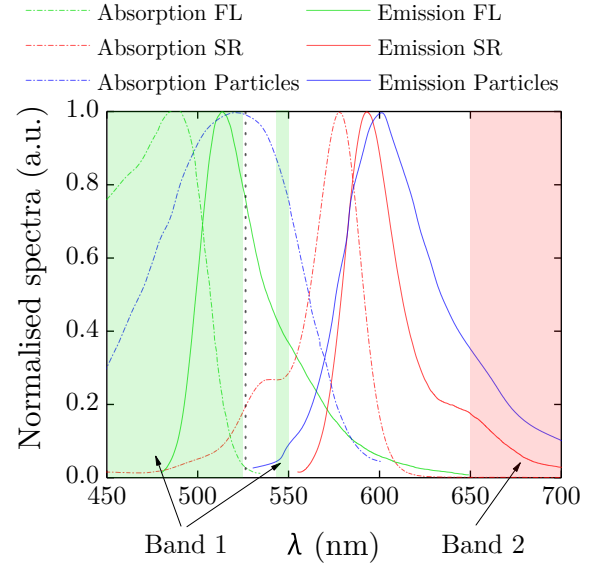


Figure 2: Normalised excitation and emission spectra of FL, SR and the fluorescent tracer PIV particles. The spectral bands recorded with each camera are illustrated with the shaded rectangles. The dotted black line denotes the laser light at $\lambda = 527 \text{ nm}$.

insensitive SR dye and the PIV tracer particles (Band 2 in Fig. 2). The spectral bands of each camera have been selected to avoid spectral conflicts, which can lead to erroneous results (17; 18). It is imperative for our experiments to use a ratiometric approach, as reflections from the bubble interface can influence the measurements. Also, this approach allowed us to obtain temperature measurements closer to the bubble interface. The 2cLIF method has been used recently by Chaze et al. (16) to measure the temperature field inside of drops impinging on a hot solid surface.

A high-speed Nd:YLF laser was utilised at its second harmonic (527 nm) to excite both dyes and the particles, as shown in the absorption spectra of Fig. 2. One cavity of the laser was used with a pulse repetition frequency of 2.5 kHz and an average power of $\sim 25 \text{ W}$. Dedicated optics were connected to the laser head to generate a thin sheet of light and to define the measurement volume of the PIV and LIF techniques. The laser sheet thickness was measured with a sharp razor blade connected to a plate with a traversing mechanism and coated with a black dye to avoid any laser reflections.

The blade was initially positioned so that it completely blocks the laser sheet, recording zero values of fluorescence at $z \sim 0 \text{ mm}$. As the blade was gradually advanced along the transverse direction and perpendicularly to the laser sheet, the fluorescence signal recorded by both cameras started to increase and reached its maximum value when the blade was no longer blocking the laser sheet. The fluorescence was both space- and time-averaged over 300 images and the resulting distribution of the fluorescence is shown in Fig. 3(a). The fluorescence shown is normalised with the maximum light recorded. The probability distribution $P_I(z)$ and the probability density function $PDF_I(z)$ of the fluorescence I along z were then calculated for each dye as shown in Fig. 3(b), in order to extract the laser sheet thickness.

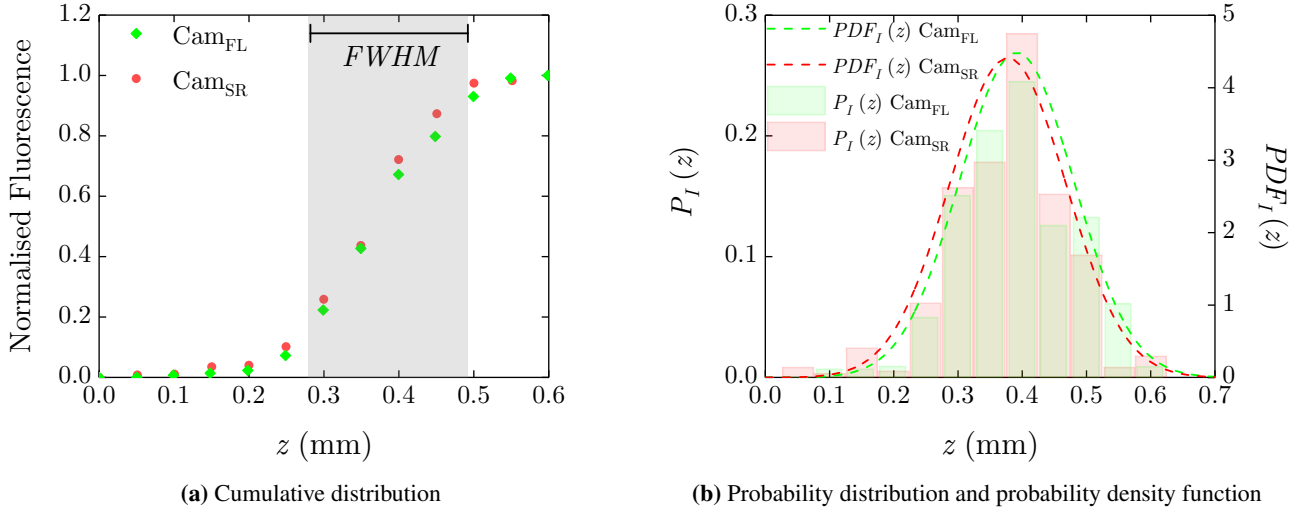


Figure 3: The laser sheet thickness measured from the fluorescence light recorded from the high-speed cameras as the blade traversed along the transverse direction z .

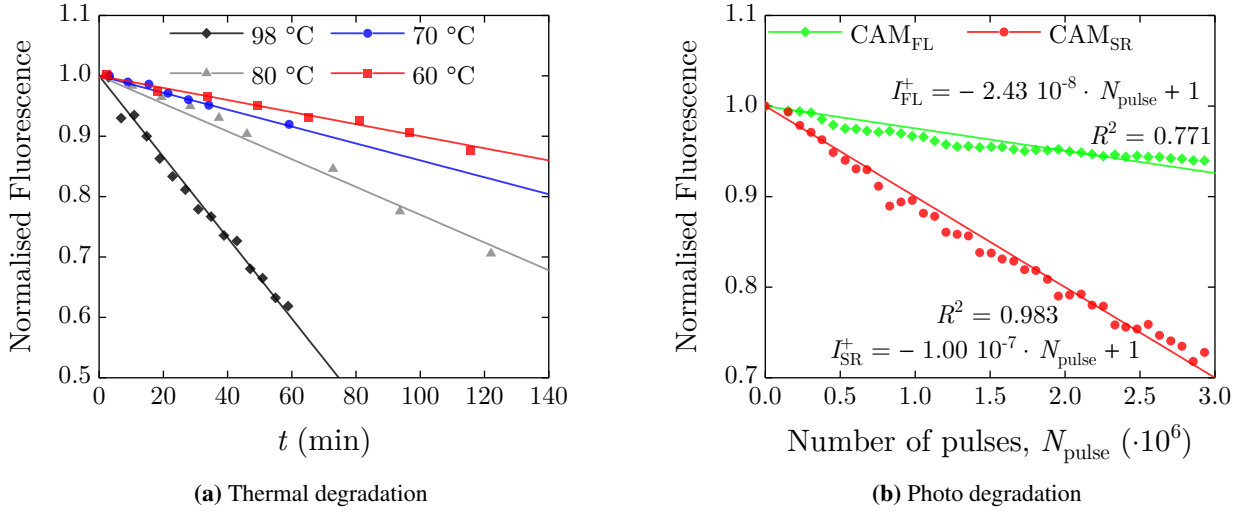


Figure 4: Thermal (for SR) and photo degradation (for both FL and SR) induced by the elevated solution temperature and the laser light, respectively. The data in (a) for 60 to 80 °C have been obtained from Chaze et al. (16).

The laser sheet thickness is reported here as the full width half maximum ($FWHM$) value of the light distribution. The light recorded can be described by a normal $PDF_I(z)$ of the form:

$$PDF_I(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{(z - \mu_z)^2}{2\sigma^2} \right] \quad (1)$$

as illustrated in the PDF s of Fig. 3(b). In the aforementioned relation the standard deviation is noted as σ and the mean as μ_z . The $FWHM$ can be then calculated as:

$$FWHM = 2\sigma (2 \ln 2)^{0.5}, \quad (2)$$

which can be written as $FWHM \approx 2.355\sigma$ or 213 μm and 209 μm for the fluorescence of CAM_{FL} and CAM_{SR} , respectively. The resulting laser sheet thickness is taken as the mean between the two cameras equal to 211 μm .

It has been found that SR can be subject to thermal degradation when its temperature exceeds the ambient (16). In our current work, we induced boiling at water saturated conditions, which resulted in the degradation of SR over time. Figure 4(a) presents the fluorescence of SR over time at four different temperatures, spanning the range of 60 °C to 98 °C. The fluorescence was both space- and time-averaged over 300 images. The different curves are obtained from our experiments and from Chaze et al. (16).

We chose the upper temperature limit below the saturation temperature of water to avoid boiling. The volume of the liquid during the runs remained practically constant so any evaporation effects that would result in an increase of C_{SR} were neglected. The fluorescence appears to be decreasing in a linear manner for all the temperatures shown, therefore we fitted a line with a negative slope passing through each distinct temperature data set. Higher temperatures induce faster

degradation of the dye, resulting in smaller slope values.

We subjected a solution of water containing the dyes at the same concentration as the experiments to a laser light of the same frequency and power as the experiments in order to investigate the effects of the photo degradation on the dyes. We then recorded the fluorescence emitted over time from both dyes. The results are illustrated in Fig. 4(b). A quasi-linear drop in the fluorescence is recorded, similarly to the thermal degradation data. We fitted a linear curve with a negative slope, as presented in Fig. 4(b). The overall experiments and calibration procedure lasted over 30 min, so the curves of Fig. 4 can be used to correct for any thermal and light degradation occurring during the experiments.

Finally, an IR camera (TELOPS Fast M3k) was used to record the thermal radiation emitted by the boiling surface (ITO) during the experiments at a spatial resolution of $50 \mu\text{m pixel}^{-1}$ and an exposure time of 50 ms. All cameras recorded the bubble nucleation events at 2.5 kHz and were synchronised via a high-speed PTU controller (LaVision).

2.3 Image analysis

Spatial calibration and image corrections were applied to the 2cLIF, PIV and IR raw images using in-built functions of DaVis 8.4 (LaVision) and in-house developed MATLAB (Mathworks) algorithms. The image processing steps followed for the 2cLIF and PIV are portrayed in Fig. 5. The images from both cameras are needed to have matching field of views to allow for pixel to pixel correspondence and thus enable the application of ratiometric 2cLIF. Spatial corrections are applied to the images of each camera to minimise any rotation or magnification differences. Images of a calibration target with patterned circles of known distances and dimensions immersed in the cell were taken, and the native spatial calibration algorithm of DaVis 8.4 was applied to the raw images, e.g. Fig. 5(a). A typical corrected image of CAM_{SR} is shown in Fig. 5(b). Both cameras had a resulting resolution of $52 \mu\text{m pixel}^{-1}$ after the spatial calibration.

To avoid any noise from the PIV particle signal of CAM_{SR} on the resulting temperature field, the particles were removed from the images using a similar approach to Voulgaropoulos and Angeli (19; 20) and shown in Fig. 5(c)-(f). First, a moving average filter was applied in 3 by 3 pixel² neighbourhoods to isolate the particles and was followed by a dilatation filter. The dilated images were then binarised using a global threshold and subtracted from the spatially corrected images to give Fig. 5(e). The remaining ‘holes’ that originally contained the particles were interpolated to produce the final images, as shown in Fig. 5(f). The final images were used for the ratiometric 2cLIF temperature measurements.

A similar methodology to Charogiannis et al. (21) was used to obtain the velocity field in the water phase from the subtracted moving average images of Fig. 5(c), which contained the isolated PIV particles. An algorithmic mask was first calculated, which was based on the intensity variations caused at the bubble interface. The mask prevented the calculation of velocity vectors in the gas phase. The DaVis 8.4 PIV cross-correlation algorithm was then used in a three-pass iterative mode with interrogation windows of decreasing size, starting from 64 by 64 pixels² and continuing to 32 by

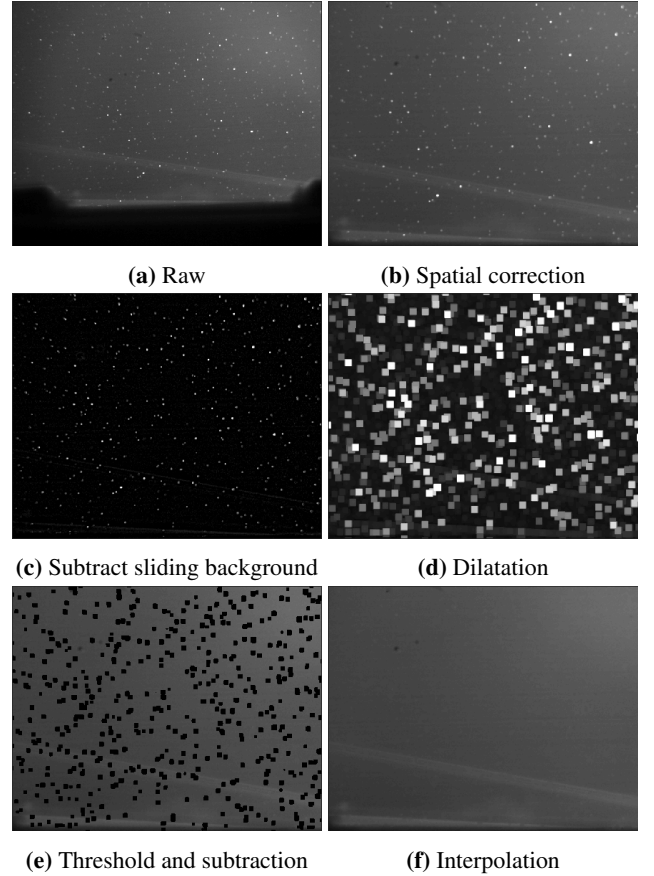


Figure 5: Image processing steps applied to a typical image of CAM_{SR} to spatially correct the image and remove the PIV particles.

32 pixels² with 50% overlap for the last two iterations. The images were finally post-processed with a universal outlier detection filter and any windows containing outliers were removed and interpolated. Finally, the optimal smoothing filter of DaVis 8.4 was applied to better illustrate the results.

The heater temperature and heat flux distribution were calculated from the IR images by solving a coupled three-dimensional heat conduction and two-dimensional radiation inverse problem. The IR camera measures the combined radiation emitted by: (i) the boiling surface, (ii) the substrate and (iii) the reflections of the background radiation. The heat conduction model used here provides the temperature and heat flux distributions over the heater surface. The interested reader is referred to Bucci et al. (10) for a detailed description of the model and the image analysis procedure.

3 Results and Discussion

3.1 Phenomenology

Different nucleation characteristics were encountered during boiling at $T = T_{\text{sat}}$ for various heat fluxes, $\dot{q}''$, supplied from the heater to the liquid. As shown in the images of Fig. 6, the boiling characteristics differ primarily by the density of nucleation sites. The only nucleation site triggered for low enough heat fluxes ($\dot{q}'' < 60 \text{ kW m}^{-2}$) was the artificial nucleation site in the centre of the heater, e.g. Fig. 6(a), while

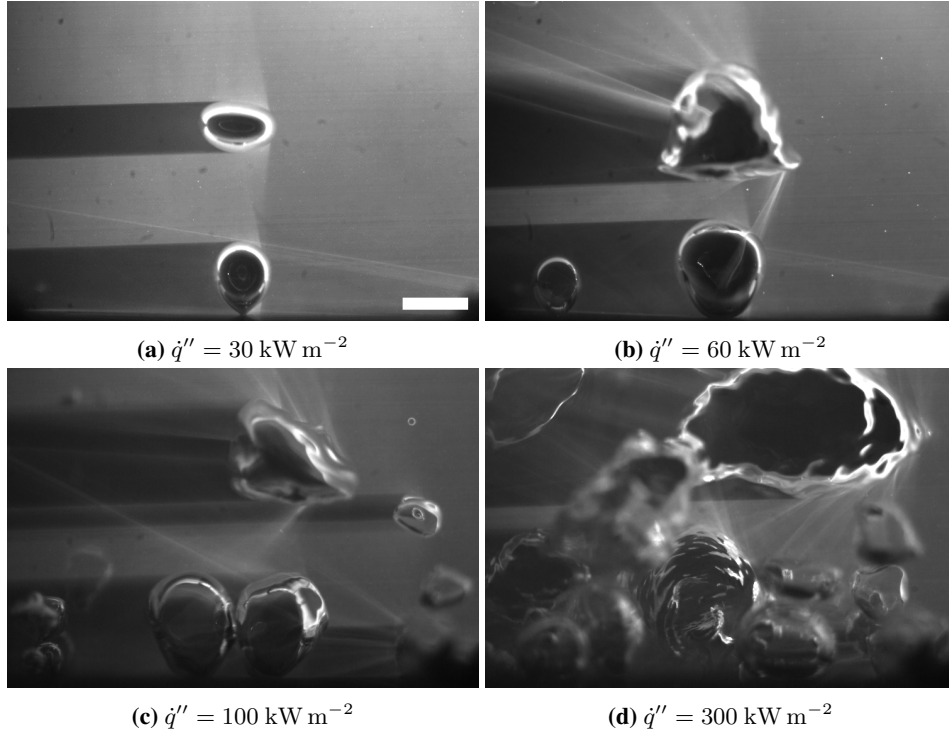


Figure 6: Nucleation characteristics encountered for different heat fluxes at $T = T_{\text{sat}}$. The scale bar is 2 mm long.

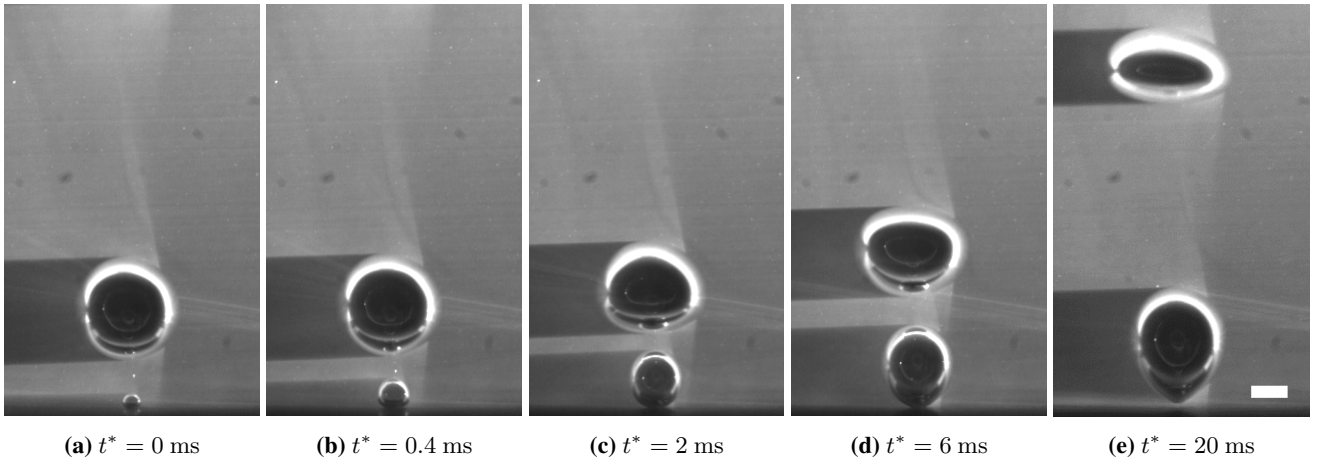


Figure 7: Nucleation characteristics encountered at different time-steps for $q'' = 30 \text{ kW m}^{-2}$ and at $T = T_{\text{sat}}$. The scale bar is 1 mm long.

below $q'' < 30 \text{ kW m}^{-2}$ we did not observe any nucleation taking place. The artificial nucleation site corresponds to the area with the initial hydrophobic PTFE coating.

For $q'' = 60 \text{ kW m}^{-2}$, i.e. Fig. 6(b), we started to observe a secondary bubble nucleating from the edges of the heater. For higher heat fluxes, as in Fig. 6(c), neighbouring bubbles close to the initial nucleation site appeared, and coalescence could be seen. For $q'' > 200 \text{ kW m}^{-2}$ as in Fig. 6(d), we could only observe a bulk cloud of vapour generated from the heater instead of distinct bubbles. Such cases will not be investigated in the current work, due to the refractive index mismatch between the liquid and vapour phase that causes obstructions to the laser sheet. Most conditions investigated with 2cLIF and PIV span the range from 30 to 60 kW m^{-2} .

Five different time-steps of a typical case of a single nucle-

ating bubble are shown in Fig. 7 for $q'' = 30 \text{ kW m}^{-2}$ and at saturation temperature. The images portray the life cycle of a typical single vapour bubble, from its generation to departure. The time in the captions is denoted as t^* , where $t^* = 0$ signals the first frame where a nucleus of the bubble is visible in the images. The bubble is initially spherical and gradually grows as more vapour is generated by the surrounding superheated liquid. During this time, the bubble loses its sphericity and detaches due to the buoyancy forces.

3.2 Effect of additives

We investigated the effects of the added dyes and particles to the water on the nucleation characteristics during pool boiling, by quantifying their effects on: (i) the equivalent diame-

Table 1: Effect of additives on the bubble nucleation characteristics at $T = T_{\text{sat}}$ and for $\dot{q}'' = 30 \text{ kW m}^{-2}$.

Additives	Backlight	LIF	Backlight/LIF
	Diameter, d_{eq} (mm)	Diameter, d_{eq} (mm)	Nucleation Time (s)
None	2.32 ± 0.16	n/a	13.54 ± 2.90
FL	2.38 ± 0.17	2.00 ± 0.25	14.19 ± 2.79
FL + SR	2.62 ± 0.16	2.00 ± 0.09	17.12 ± 6.74
FL + SR + Particles	2.44 ± 0.18	2.09 ± 0.21	14.01 ± 4.33

ter of the bubbles during their departure from the heater and (ii) the nucleation time from their generation to departure. The results are illustrated in Table 1 for $\dot{q}'' = 30 \text{ kW m}^{-2}$ and at $T = T_{\text{sat}}$. The results are averaged over at least five bubbles for each case and the uncertainty of these measurements is taken as one standard deviation.

The equivalent bubble diameter is calculated based on the measured areas of the departing bubbles and assuming symmetry along the vertical axis, namely $d_{\text{eq}} = \sqrt{4A/\pi}$, where A is the area measured. It appears that the addition of the fluorescent dyes, namely FL and SR at their respective concentrations, imposes small changes in the equivalent bubble diameter during departure when compared against the additive-free case. These changes are $< 13\%$ and within one standard deviation. Similar results were obtained for the nucleation times. We recorded deviations of less than 5%, 26% (exhibiting the greatest standard deviation) and 3% from the additive-free solution, respectively. Notably, all deviations fall within one standard deviation. It is thus confirmed that the additives at the concentrations used do not meaningfully alter the nucleate boiling characteristics at our conditions.

It has been recently discussed that total internal reflection effects at the water-air interface can alter the measured thickness of thin films (22). It was found that when the laser light hits a water-air interface at angles greater than the critical angle of total reflection, the LIF thickness measurement can be increased by about 30%. In our experiments, the incident light hits the curved bubble interface at an angle greater than 50° for the majority of the bubble perimeter. We find the equivalent bubble diameters measured with LIF to be about 20% smaller than the measurements using a backlight (Table 1), in agreement with the estimations of Häber et al. (22). To tackle such effects we considered using the structured planar laser-induced fluorescence (s-PLIF) method proposed in Charogiannis et al. (23), by using a Ronchi ruling plate to modulate the structure of the laser light and enabling more accurate identification of the interface. However, such a method was eventually avoided in the present work as it would greatly limit our ability to measure the temperature and velocity field of the water.

3.3 Temperature field: Liquid

The ratios of the fluorescent intensities of CAM_{FL} over CAM_{SR} , $I_{\text{R}} = I_{\text{FL}}/I_{\text{SR}}$, were obtained for different water temperatures below T_{sat} . The resulting relationship is plotted in Fig. 8. The water temperatures were measured with two K-type thermocouples with an estimated error of 0.5°C at two positions, as shown in the schematic of Fig. 1. We considered their mean, despite recording small deviations between

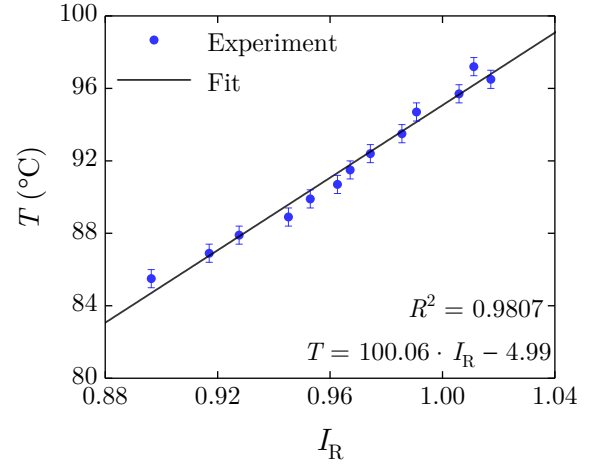


Figure 8: Evolution of the ratio of the fluorescent intensities of CAM_{FL} over CAM_{SR} as a function of temperature.

them ($\Delta T \sim 0.5^\circ\text{C}$). The fluorescence ratio was spatially averaged over the area of interest.

The data exhibit a linear behaviour, with $R^2 = 0.981$, giving a fit of $T = 100.06 \cdot I_{\text{R}} - 4.99$, where T is in $^\circ\text{C}$. To quantify the measurement capabilities of the 2cLIF used here, we introduce a sensitivity coefficient s , which is merely equal to the inverse of the slope of the linear fit, namely $s \sim 1\%^\circ\text{C}^{-1}$. This parameter is lower to the one reported by Chaze et al. (18). The difference could be attributed to the reduced range of temperatures used for the calibration ($\Delta T \approx 15^\circ\text{C}$) and to the high temperatures investigated ($T > 85^\circ\text{C}$) in the present work, compared to the range of 27°C to 80°C investigated by Chaze et al. (18).

Using this ratiometric 2cLIF method we obtained the temperature fields in the bulk and close to the bubble interface, despite the low signal to noise ratios and measurement sensitivity. The resulting temperature fields are smoothed with a Gaussian filter to better illustrate the trends. Figure 9 shows the water temperature fields measured at different time-steps for a typical nucleating bubble for $\dot{q}'' = 30 \text{ kW m}^{-2}$. The blue regions denote the bubble masks, which are overshot by 20% to cover any biases by the LIF-measured interfacial boundaries. Relatively small temperature gradients were recorded in the bulk and away from the bubble, which can be attributed to the natural circulation inside the cell. Superheated liquid of about 2°C above T_{sat} was displaced away from the nucleating site of the bubble during its formation and departure from the heater. The superheated liquid can be

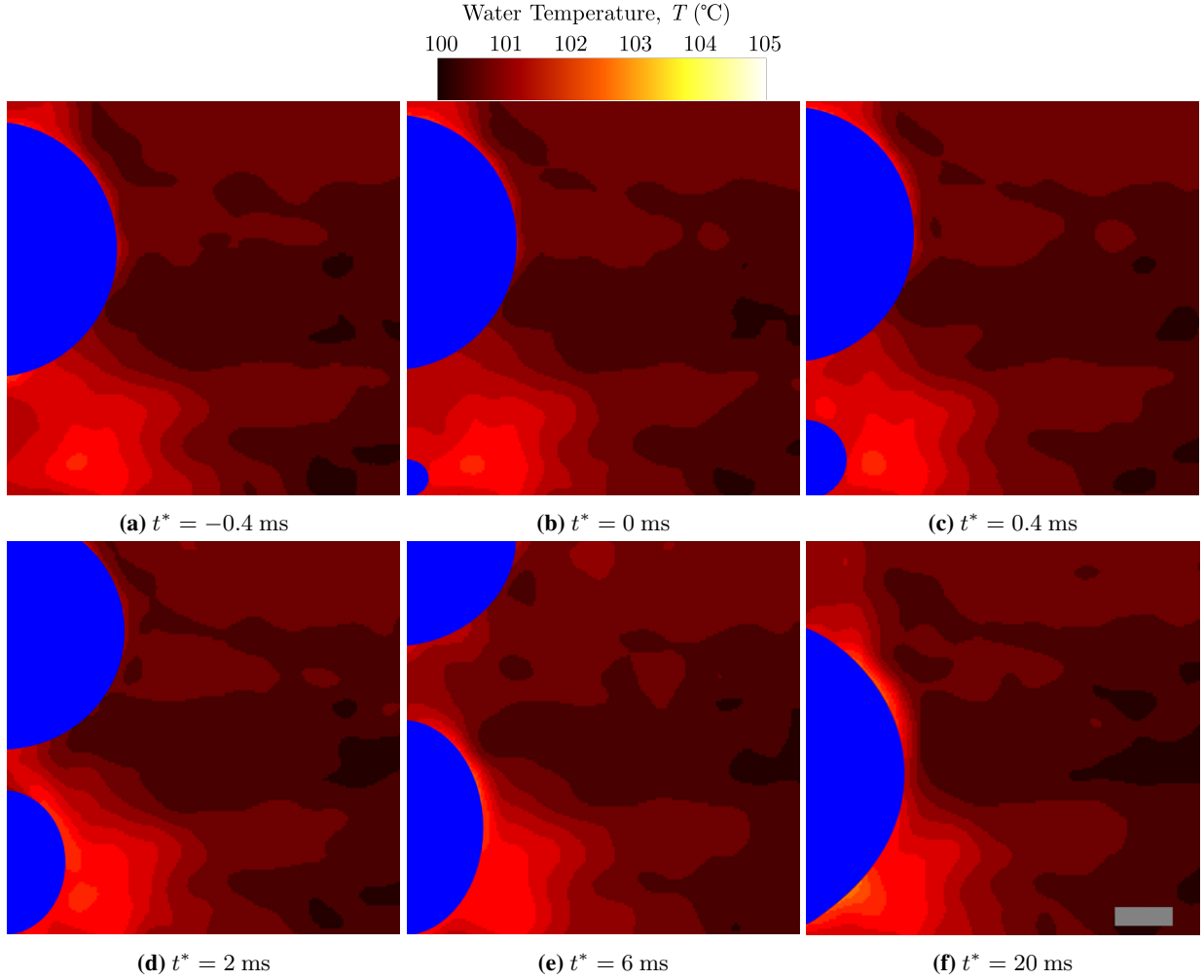


Figure 9: Temperature fields measured with 2cLIF at different time-steps for $\dot{q}'' = 30 \text{ kW m}^{-2}$ and at $T = T_{\text{sat}}$. The surface of the bubbles is illustrated with the blue regions. Each contour level corresponds to 0.5°C . The scale bar is 0.5 mm long.

originating from mixing of the thermal boundary layer. This finding is consistent with the recent results from Schlieren-based measurements of Narayan et al. (11; 12). It must be noted that we did not manage to measure a consistent thermal boundary layer along the heater surface for this condition. For $\dot{q}'' = 30 \text{ kW m}^{-2}$ we expect the thermal boundary layer to be relatively small (approximately a few pixels thick). We plan to perform targeted experiments of higher spatial resolution to accomplish accurate measurements at that region.

3.4 Temperature field: Heater

The IR camera captured the temperature distribution across the heater, T_w , during the bubble nucleation, growth and departure. A typical time-sequence during nucleation for a heat flux of $\dot{q}'' = 30 \text{ kW m}^{-2}$ is presented in Fig. 10. We observe that the local temperature of the nucleation site surroundings promptly reduces as the bubble is generated. Peak local heat fluxes up to 500 kW m^{-2} are recorded for the nominal heat flux of 30 kW m^{-2} . During the initial stages of bubble growth, the vapour-liquid interface rapidly moves outwards and a thin layer of liquid of few microns thick is trapped underneath the bubble. This liquid layer is known as the mi-

cro-layer and it exhibits low thermal resistance owing to the transient heat conduction through the thin liquid film. The high heat transfer efficiency of this mechanism explains the observed difference between peak and nominal heat flux.

The bubble grows due to the microlayer evaporation and the heat transferred from the superheated liquid layer adjacent to the heater. A critical bubble size is reached, when the buoyancy forces overcome the adhesion forces, and the bubble departs from the heater surface. After its departure, the superheated liquid from the surroundings rewets the surface and the wall temperature keeps increasing up to the mean T_w , until a new bubble forms and the cycle repeats.

3.5 Velocity field

The velocity and vorticity fields calculated with PIV are shown in Fig. 11 for the same nucleating bubble as Figs. 7, 9 and 10, where $\dot{q}'' = 30 \text{ kW m}^{-2}$ and $T = T_{\text{sat}}$. An upwards motion of high velocity magnitude appears during the initial steps of the bubble nucleation, which justifies the aforementioned findings of superheated liquid above the thermal boundary layer over the heater. It appears that the upwards motion decreases with time, as the bubble growth

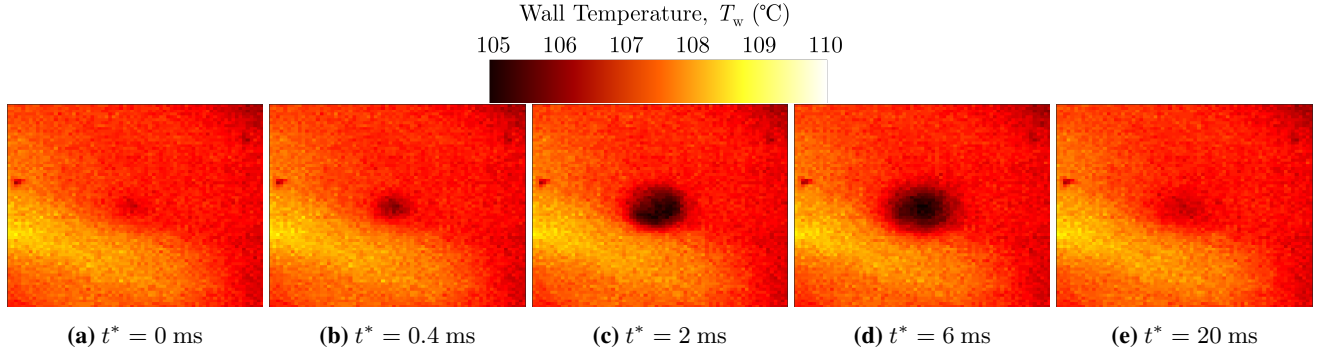


Figure 10: Wall temperature fields over the heater surface measured with IR at different time-steps for $\dot{q}'' = 30 \text{ kW m}^{-2}$ and at $T = T_{\text{sat}}$. The images are portraying the whole heater area of 10 mm^2 .

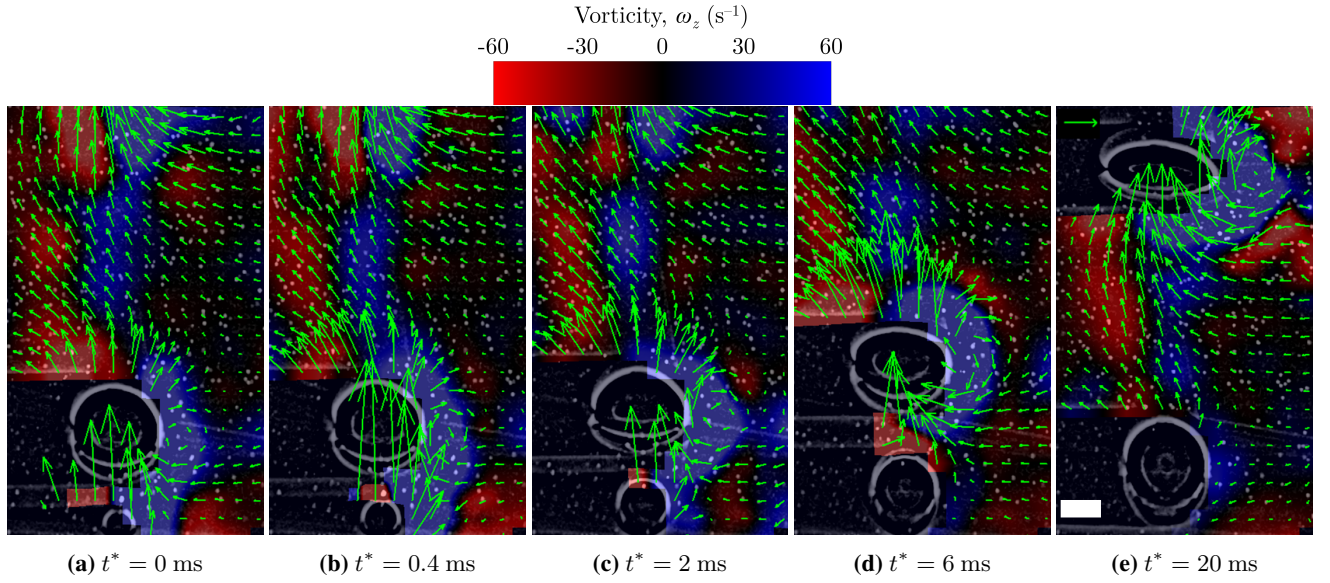


Figure 11: Vector and vorticity fields of the water measured with PIV at different time-steps for $\dot{q}'' = 30 \text{ kW m}^{-2}$ and at $T = T_{\text{sat}}$. The scale bar is 1 mm long and the reference vector corresponds to a velocity magnitude of 0.1 m s^{-1} . The velocity fields are superimposed over the sliding average images of CAM_{SR} .

slows down. It is our future aim to explore the links between the two rates and define the contributions of the natural convection and bubble growth in the resulting velocity field.

Two counteracting vortices are forming on each side of the bubble after its departure, as shown in Fig. 9. These two vortices exhibit high levels of vorticity, with the maxima of the vorticity magnitude located close to their centres. These vortices induce an upwards mixing motion, which contributes to the presence of superheated liquid away from the heater. These vortices can also help reform the thermal boundary layer after the bubble departs. Similar observations have been previously explored in Refs. (9; 24). From the velocity vectors located away from the nucleating bubble we can observe a distinct left-hand side motion, which can be attributed to the natural circulation caused by temperature gradients between the top and bottom of the cell.

4 Concluding remarks

We developed a combined high-speed infrared and laser-based diagnostic technique that enabled the simultaneous

acquisition of spatiotemporally-resolved information on the water velocity as well as the water and wall temperature during nucleate pool boiling. The technique is based on the simultaneous application of two-colour laser-induced fluorescence and particle image velocimetry and was applied to a pool boiling cell of transparent side windows. The technique was combined with infrared measurements performed from the bottom of the cell, which was equipped with a sapphire glass/ITO heater. The set of measurements allowed us to find links between the heat transfer and fluid flow mechanisms taking place during the boiling process at saturated conditions and low heater heat fluxes.

This study focused on the technical challenges encountered during the experiments of single-bubble nucleate boiling and presented a measure of steps to define and overcome them. From the resulting temperature fields around the bubble we found the presence of superheated liquid being transferred from the growing and rising bubble to the bulk. Vortices were formed on each side of the rising bubble, which contributed to mixing close to the heater. The infrared measurements supported these findings showing low

temperatures at the nucleation site during the bubble formation, which were accompanied by high local heat fluxes.

Generally, the results show the intrinsic coupled nature of the flow and thermal fields during this important phenomenon. For this reason, we plan to investigate a wide range of heat fluxes and bulk water temperatures (subcooled conditions) to obtain a holistic view of the phenomena. Finally, an on-going effort is being made to extract information close to the thermal boundary layer from these flows, enabling a detailed analysis of the heat flux partitioning.

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