

Single-dye multispectral PLIF (SDMS-PLIF) for quantitative thermographic visualisation of nucleate boiling

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Keywords: Nucleate boiling, Miniaturised square channel, Spatiotemporally-resolved two-colour PLIF, Spectral division

ABSTRACT

The boiling of dielectric fluids in miniaturised channels has emerged as one of the most promising solutions to high-density electronics cooling. Although significant breakthroughs have been made, a fundamental understanding of the hydrodynamic and thermal performance in relevant flows is still lacking, which calls for further development of state-of-the-art measurement techniques and their deployment for the provision of high-quality, detailed experimental information. To this end, we conducted an experimental investigation of flow boiling in a miniaturised vertical square channel with a hydraulic diameter of 5 mm, using HFE-7100 as the working fluid. A whole-field thermographic imaging approach referred to as single-dye multispectral planar laser-induced fluorescence (SDMS-PLIF) was developed and applied to measure spatiotemporally-resolved temperature fields. For its implementation, Nile Red, a thermosensitive lipophilic dye, was dissolved in HFE-7100 as a fluorophore. The measurements were taken at selected conditions to achieve a nucleate boiling regime in a laminar flow. Time-lapse temperature maps provided direct evidence for bubble-induced mixing observed as thermal plumes, where a portion of hot fluid is advected above the thermal boundary layer at the heated wall and penetrates the colder bulk phase in the flow core.

1. Introduction

The rapid growth in the demand for effective cooling of high-power-density electronics has appeared as one of the most pressing issues in the field of heat transfer. Among a few existing cooling approaches, flow boiling of low-boiling-point dielectric fluids in miniaturised channels has become one of the most promising solutions of highly-efficient heat removal for modern and next-generation high-power-density electronic components (Karayiannis & Mahmoud, 2017). Although significant contributions in this field have already been made through rigorous experimental (Thome, 2004) and numerical (Magnini et al., 2013) studies, the challenges associated

with the multiscale physics and transient phenomena of flow boiling still persist. Available results obtained with conventional intrusive measurement techniques provide a limited understanding of the hydrodynamic and thermal interactions between the continuous (liquid) and dispersed (vapour) phases in this type of two-phase flow due to the complex and non-equilibrium nature of local transient phenomena. Specifically for flow boiling of low-surface-tension fluids such as refrigerants (Moran et al., 2021), high variability of the interface results in faster alternations of various phenomena compared with water, which typically occur on a finer spatial and temporal scale and, therefore, are more susceptible to invasive measurements.

To overcome the limitations inherent in intrusive pointwise measurement techniques, advanced panoramic laser-based diagnostic methods including planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV) have recently been developed to allow non-invasive, whole-field and simultaneous spatiotemporally-resolved measurements of instantaneous temperature and velocity in various kinds of multiphase flow (Voulgaropoulos et al., 2022). In a conventional single-dye one-colour PLIF approach, the uniformity of stain concentration in a fluid is critical, which is however inconsistent in boiling flows due to the inhomogeneity caused by thermal diffusion. In more advanced two-colour PLIF that involves a ratiometric analysis of fluorescence emission intensities of two or more dyes distributed similarly in a fluid flow, excited by either a single (Sakakibara & Adrian, 1999) or twin (Soltys & Crimaldi, 2011) laser source, this issue is alleviated to some extent but still persists as the ratio of dye concentrations remains variable due to differences in the physicochemical properties of molecules of different chemical compounds.

Thus, recording fluorescence signals separately for two or more selected bands of the emission spectrum of a single stain can potentially make it possible to completely overcome the problem with non-uniform dye concentration for the PLIF thermography in boiling flow (Lavieille et al., 2001). In this paper, we propose and demonstrate the applicability of a new whole-field thermographic imaging technique - single-dye multispectral planar laser-induced fluorescence (SDMS-PLIF) - to investigate transient phenomena as applied to nucleate boiling of a low-surface-tension dielectric fluid (HFE-7100) in an upward laminar flow in a miniaturised vertical square channel, where spatiotemporally-resolved temperature fields were successfully measured.

2. Experimental methods: apparatus and flow conditions

The experimental facility was specifically designed to reproduce various flow boiling conditions in a miniaturised channel (Fig. 1a). The apparatus has a closed loop which consists of a storage

tank, a peristaltic pump with an in-line particulate filter, mass flow controller (MFC), test section, condenser, two preheaters and bypass circuit which contains a pressure controller.

The working liquid is 3M Novec 7100 (known as hydrofluoroether-7100 or HFE-7100) with a boiling point of 61 °C at atmospheric pressure, and is kept in the storage tank. The peristaltic pump capable of transporting liquids containing tracer particles drives the working fluid around the apparatus. The particulate filter has an average pore size of 90 μm and is connected to the pump intake to prevent large impurities from entering the main flow loop. The MFC unit adjusts and maintains the mass flow rate in the main circuit to/at a preset level by a PID valve control, with the pressure controller in the bypass loop stabilising the inlet pressure at an adapted value by diverting part of the fluid back to the pipeline before the pump. Preheater-1 is a plate heat exchanger coupled with a heated circulating bath filled with ethylene glycol, which heats the fluid to a relatively high temperature, well below its boiling point. Preheater-2, an in-line electrical heater connected to a variable AC power supply, heats the fluid further to a stable temperature, thus securing a desired subcooling degree as the inlet condition for the test section.

Flow boiling is initiated by an electrical heating plate inside the test channel through a DC power supply. The boiling fluid exiting the test section is then condensed and subcooled by the condenser, a plate heat exchanger coupled with a cooling water circuit, and finally moved back to the storage tank. Several temperature and pressure sensors are installed throughout the flow loop, including two 0.5-mm diameter sheathed T-type thermocouples and two Omega pressure transducers attached to the inlet and outlet of the test section. Their readings were recorded by a Keysight DAQ973A data acquisition system at a sampling rate of 1 s^{-1} .

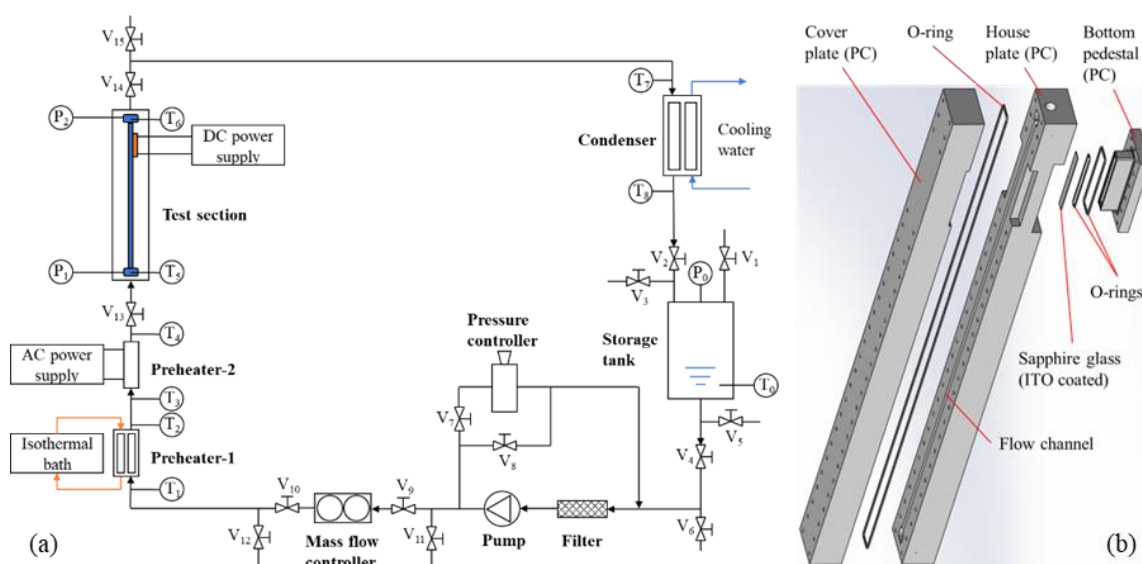


Figure 1 (a) Flow diagram of the experimental apparatus, and (b) breakdown of the test section into individual components.

The test section has two main parts (base and cover) both made of polycarbonate (PC) and vapour polished to be optically accessible (Fig. 1b). A groove of 5×5 mm cross-section with inlet and outlet chambers was milled in the base element to serve as the flow duct. At a downstream location of the test section, a thin heating plate comprised of an 80-mm long, 10-mm wide and 0.5-mm thick sapphire substrate coated with a thin ($0.2 \mu\text{m}$) transparent conductive indium tin oxide (ITO) film and supported by a hollow bottom pedestal is flush-mounted into the base (Fig. 1b). After assembling the test section, a square channel of 5-mm hydraulic diameter was created with a fully developed entrance length of 500 mm and the exit one equalling 50 mm. The resulting effective heated length is 60 mm, with one sheet wall heated uniformly and the three others being adiabatic.

In the experiment, the test section was oriented vertically, with the working fluid flowing upward (Fig. 2). The working conditions are as follows: the heat flux (q), mass flux (G) and inlet fluid subcooling degree (ΔT_{sub}) were respectively varied in the ranges of 0–15 kW/m^2 , 30–120 $\text{kg}/\text{m}^2\text{s}$ and 5–25 K at nearly ambient pressure to achieve nucleate boiling in a laminar flow. The working fluid was completely degassed beforehand through intense flow boiling in Preheater-2 for one hour and repeated release of air by opening a relief valve on the storage tank. After activating the bypass loop and setting up the inlet pressure for MFC, the main circuit was operated at a certain mass flow rate. Once the circulation of cooling water in the condenser was started, both preheaters were switched on to elevate the fluid temperature. After achieving a targeted subcooling condition, the heat flux imposed to the ITO-coated plate in the test section was increased in steps. Each experimental run lasted for about 10 min to reach thermal equilibrium, after which relevant measurements were taken simultaneously (see below).

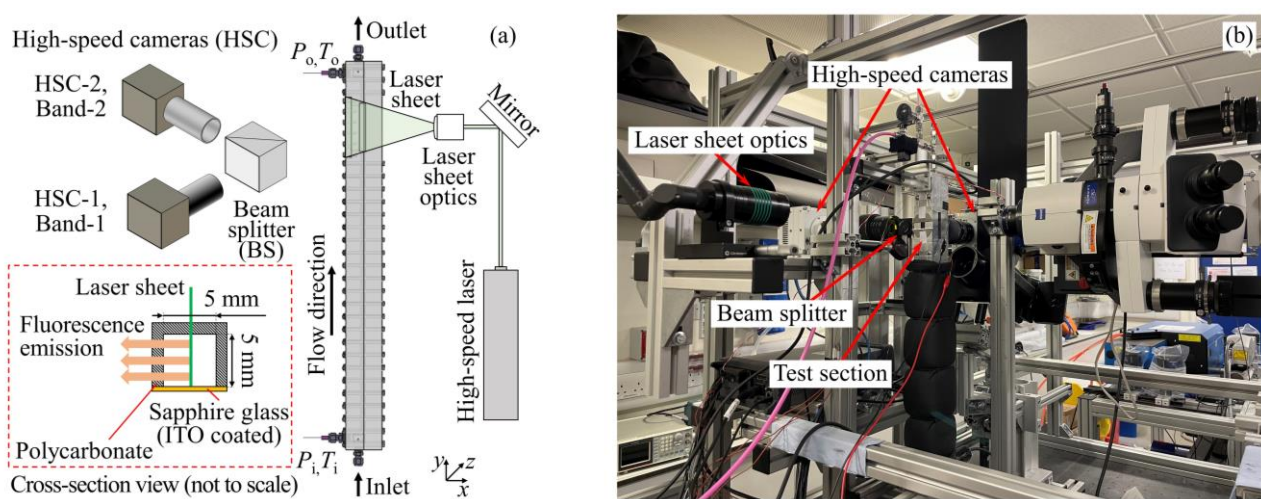


Figure. 2 (a) Schematic of the assembled test section displaying the optical arrangement of components of the measurement system, and (b) corresponding photograph.

3. SDMS-PLIF method

In order to measure temperature fields in the bulk liquid phase, a single-dye multispectral planar laser-induced fluorescence (SDMS-PLIF) method was suggested and elaborated to evade the problem of nonuniformly and inconsistently distributed dye concentrations encountered in flows with high temperature/velocity/pressure gradients and intense phase transitions, which is inherent in the conventional two-colour PLIF (2c-PLIF) approach (see Introduction). In contrast to 2c-PLIF, where two fluorescent stains with opposite temperature sensitivities and distinctive emission spectra are used, SDMS-PLIF harnesses different thermally-dependent spectral bands of the same fluorophore doped in the working fluid. Herein, for its implementation, Nile Red, a thermosensitive lipophilic dye, was premixed with the working liquid. As Nile Red is weakly soluble in HFE-7100, ethanol was utilised as an auxiliary solvent to facilitate mixing of the components.

The normalised absorbance and emission spectra of Nile Red at a concentration of 3 mg/L with 1 vol.-% of ethanol were measured using a HORIBA Scientific Duetta spectrometer provided with a built-in Peltier heating unit for different temperatures T ranging from 298 K to 333 K, as shown in Fig. 3. As the temperature of the mixture increases, the maximum of the emission spectrum shifts towards shorter wavelengths, resulting in an increase of the fluorescence intensity for $\lambda < 575$ nm and accordingly its decrease above this threshold. Thus, two distinctive wavelength bands with opposite temperature sensitivities can be selected to allow ratiometric temperature measurements. For Band-1 having a positive dependence on T (i.e., the signal intensity grows with the temperature), we selected a range of $550 \leq \lambda \leq 570$ nm, where the dye absorbance is insignificant. At the same time, $\lambda \geq 650$ nm appears to be one of the best options for Band-2 as a spectral domain with a negative temperature dependence.

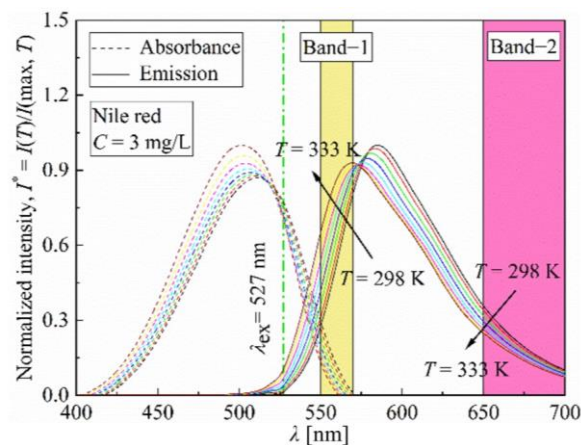


Figure. 3 Normalised absorbance and emission spectra of Nile Red in HFE-7100 at a concentration of 3 mg/L with admixture of 1 vol.-% of ethanol at different temperatures.

In the experiment, the boiling flow in the test channel was illuminated by a high-speed Nd:YLF laser (527 nm, 30 W, 20 kHz) fitted with a specific sheet optics to make a 0.4-mm thick laser sheet used as an excitation source. The laser radiation came from the side of the adiabatic wall and, passing through it, propagated further across the working fluid towards the heated surface (Fig. 2a). Two sCMOS Phantom VEO-E 310L high-speed cameras (1280 × 800 pixels @ 3200 fps; 12 bit; pixel pitch = 20 μm) each equipped with a Sigma 105 mm f/2.8 EX DG Macro lens and an extension ring were placed on the same side of the test section but perpendicular to each other to view the boiling flow through a beam splitter (Fig. 2a). In order to cut off the laser radiation and ensure that each camera captures the fluorescence emission within one of the two selected spectral bands, a notch filter was installed on the beam splitter, while two appropriate band-pass filters were attached to the camera lenses. The measurement system was synchronised and managed using a LaVision DaVis 10 software. Its sampling rate was set to 1000 Hz.

4. Data reduction and calibration procedure

Prior to temperature calibration of the SDMS-PLIF method, we performed a series of preliminary procedures necessary to reconstruct the temperature map. First, background intensity fields were captured, which are distributions of the emission intensity of the pure liquid (i.e., with no stain and ethanol added) irradiated by the laser sheet. A calibration target with a regular reflective dotted pattern on it was then placed in the test section within the field of view of the cameras, such that its working surface was positioned to be inside the laser sheet and to coincide with the camera focus planes. Snapshots of this target were afterwards used to correct any optical distortions, to quantify the spatial resolution of the measurement system and to spatially reconcile the fields of view of both cameras. Finally, flat-field SDMS-PLIF images of the working liquid moving at a high flow rate were recorded at room temperature, where a uniform temperature distribution across the camera field of view is expected to take place, to correct for the nonuniformity of intensity distribution in the laser sheet and the effect of dye emission self-absorption, especially for Band-1.

In order to perform in-situ SDMS-PLIF temperature calibration for the ethanol-dopped Nile Red/HFE-7100 mixture, we used reference temperature data measured independently by a 0.5-mm T-type TC Direct thermocouple (response time = 0.03 s, measurement uncertainty = ±0.1 °C) inserted into the test section through its outlet. Its tip was situated in the region of interest and was slightly offset from the axis of symmetry of the test channel not to obstruct the path of propagation of the laser sheet and the line of sight of the cameras. The data acquisition rate of the thermocouple was set to 1 Hz. The calibration procedure was started 10 min after stabilisation of

the bulk temperature of the working liquid. The SDMS-PLIF and thermocouple measurements were conducted together for the bulk temperature varied from 305 to 340 K with a step of 5 K. At each temperature step, 1000 images were recorded and spatiotemporally averaged over a 1×1 mm rectangular region around the tip of the thermocouple and across the entire ensemble separately for each camera. These datapoints were then used to fit a temperature calibration curve shown in Fig. 4. The temperature sensitivity of the SDMS-PLIF method was evaluated to be $2.6\%/^{\circ}\text{C}$.

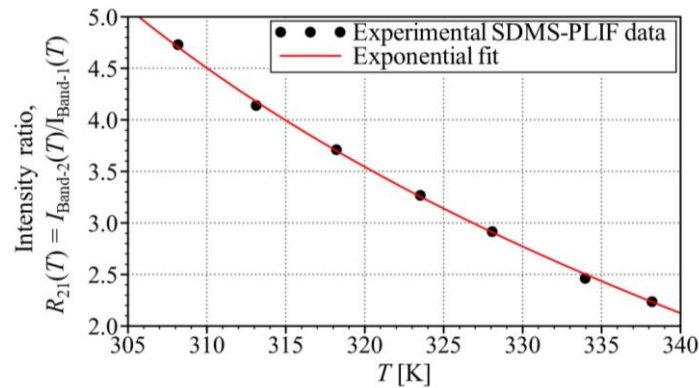


Figure. 4 Calibration curve of the intensity ratio of the two wavelength bands as a function of temperature.

With all these intermediate data at our disposal, we performed the following image-processing routine. A background intensity field with a maximum intensity of 40 counts out of a total of 4096 was initially subtracted from an ensemble of raw SDMS-PLIF images to eliminate the influence of laser light reflections, thermal noise of the camera matrix and any other light sources. Next, all the images in the series from both cameras were spatially transformed using a third-order polynomial function obtained from corresponding photographs of the calibration target to result in spatially-matched images. In order to minimise the influence of nonuniformity of energy distribution in the laser sheet, laser radiation absorption and overlapping of the emission and absorption fluorescence spectra within Band-1, the resulting images from each camera were individually multiplied with the corresponding flat-field images. Thermal maps were eventually reconstructed using the dependence of the logarithm of the ratio of fluorescence intensities from the two spectral bands on temperature obtained from the calibration procedure. Figure 5 shows the main steps of the image processing routine to convert two fluorescence signals from raw SDMS-PLIF images captured by different cameras into a thermal map.

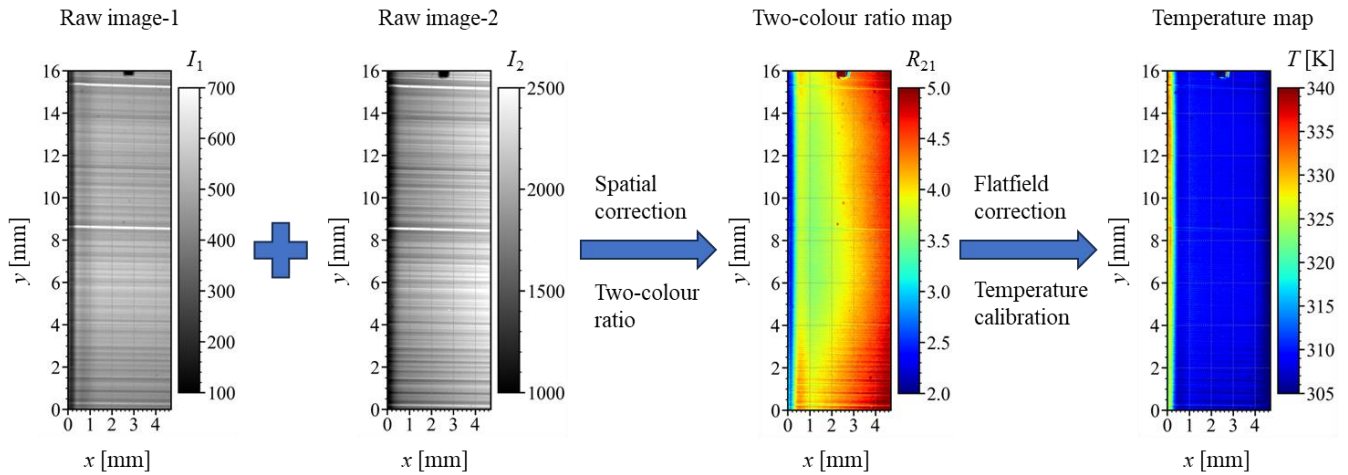


Figure. 5 Flowchart of the processing procedure of conversion of raw SDMS-PLIF images into temperature maps.

5. Results and discussion

Before vapour bubbles begin to nucleate ($t = 0$ ms in Fig. 6a), a uniform thermal boundary layer (TBL) is formed along the heated wall in the single-phase flow. Overall, Figure 6a shows the process of time evolution of vapour bubbles. As seen, they are initiated at single nucleation sites on the heated surface, which marks the early stage of boiling bubbly flow. Once arisen in the TBL, the bubbles expand and are advected downstream by the bulk liquid flow along the heated wall under the dual action of flow inertia and vapour buoyancy. The growth and sliding of the bubbles induce thermal and hydrodynamic disturbances around their interfaces and near the heated wall, which, in turn, rearranges the temperature distribution in their immediate vicinity and in the wakes ($t = 80$ ms in Fig. 6a). It is worth noting that, in Fig. 6, significant temperature variations are observable in the nearly circular domains next to the heated wall (the areas occupied by the bubbles), which is the result of their incorrect display but not genuine measurements.

A more developed regime of the boiling bubbly flow is presented in Fig. 6b showing a remote region downstream of the nucleation site location at a lower fluid subcooling condition. Although the bubbles noticeably disturb the TBL ($t = 0$ ms in Fig. 6b), it turns out to be relatively uniform upstream of them, where their number randomly decreased. Each of these bubbles displaces a portion of hot fluid out of the TBL forcing it to penetrate into the colder core of the bulk flow, causing the formation of thermal plumes. Occasionally, the bubbles also coalesce ($t = 20$ and 40 ms in Fig. 6b), with a thermal plume swelling around the newly formed bigger bubble. In general, this phenomenon can be described as bubble-induced thermal mixing. This mechanism is apparently responsible for the increased thermal transport which is one of the most important characteristics of nucleate boiling regime.

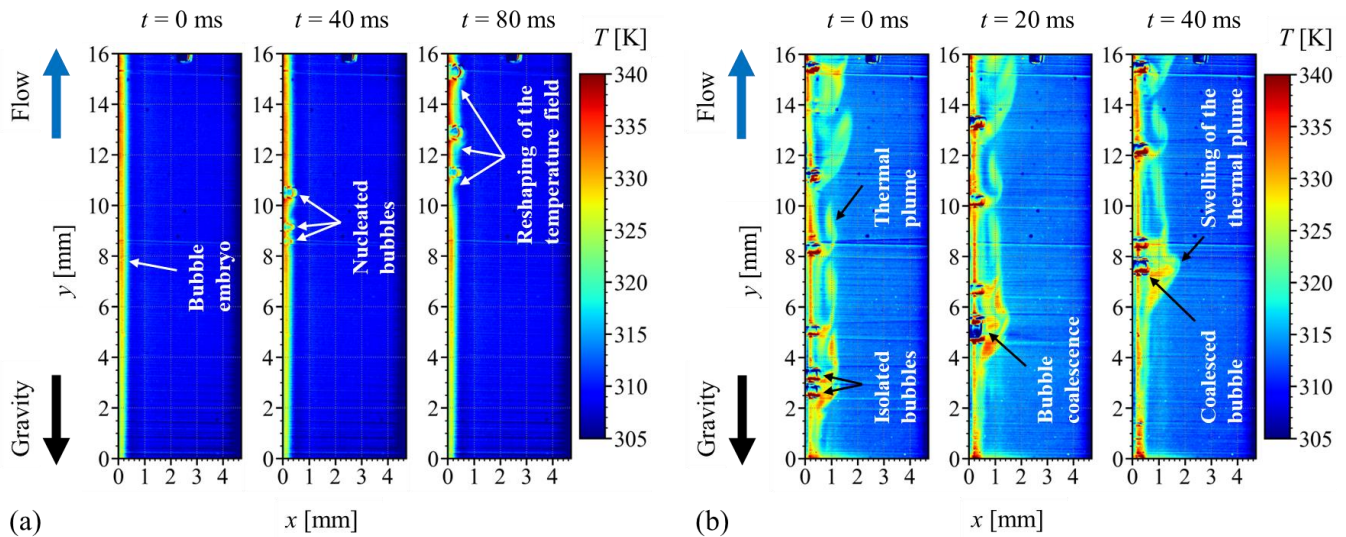


Figure 6 Instantaneous temperature fields of nucleate boiling flows at the following conditions: (a) $q = 8.7 \text{ kW/m}^2$, $G = 100 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 25 \text{ K}$, and (b) $q = 8.7 \text{ kW/m}^2$, $G = 100 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 20 \text{ K}$.

6. Conclusions

We proposed and developed a single-dye multispectral planar laser-induced fluorescence (SDMS-PLIF) technique for thermographic whole-field measurements in two-phase flows, which is robust to variations in the ratio of concentrations of different dyes inherent in classic two-colour PLIF approaches. Thermosensitive lipophilic dye Nile Red was dissolved in the working liquid (HFE-7100) and used as a fluorophore. Two distinctive spectral bands of the fluorescent emission of the dye with opposite temperature sensitivity were selected as part of a ratiometric fluorescence approach. This method was successfully applied for the study of nucleate boiling in an upward laminar flow through a miniaturised vertical square channel of 5-mm hydraulic diameter. Based on the spatiotemporally-resolved temperature maps obtained with SDMS-PLIF, it was possible to identify bubble-induced thermal mixing phenomena, which appeared as thermal plumes around vapour bubbles extending from the heated wall into the bulk of the fluid flow. This phenomenon may be a contributor to increased thermal transport in the nucleate flow boiling regime.

Acknowledgments

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/T03338X/1]. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk. For the purpose of Open Access, the authors have applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

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