

Laser-based diagnostics of slug flow boiling in a horizontal pipe

Hannah R. Moran¹, Konstantin S. Pervunin^{1,2}, Omar K. Matar¹, Christos N. Markides^{1,2,*}

¹ Department of Chemical Engineering, Imperial College London, London, United Kingdom

² Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, Russian Federation

* Corresponding author. E-mail: c.markides@imperial.ac.uk

N.B.: This is the accepted version of this article. The final, published version of the article can be found at: <https://doi.org/10.1615/InterfacPhenomHeatTransfer.2021040554>

ABSTRACT

We present results from an experimental investigation on flow boiling, in the slug flow regime, of refrigerant R245fa through a 12.6-mm inner diameter horizontal plain pipe using particle image velocimetry (PIV) and an interface detection method. The study is supplemented by an overview of the state-of-the-art in experimental research of two-phase dispersed pipe flows and the development of modern optical and laser-based full-field non-intrusive measurement techniques as applied to these flows. We consider different flow conditions, with heat fluxes over the range 5.3 to 7.9 kW/m² and mass fluxes from 300 to 460 kg/m²·s. Significant disturbances in the instantaneous velocity fields are revealed in both the noses and tails of slugs, with their values being two times higher behind vapour bubbles. The slug passage frequency is determined based on the results of the interface detection method. The vapour bubble velocity is found to increase linearly with the interfacial velocity of the two-phase mixture, while its gradient grows with the heat flux. Moreover, at increased heat fluxes the bubbles may move even faster than the mixture itself, which implies that they must significantly enhance local turbulence, thereby additionally intensifying heat transfer. This research demonstrates the applicability of laser-based diagnostic techniques to boiling slug flows, to which such experimental methods have not been widely applied in macro-scale geometries. In addition to the conclusions, we provide practical recommendations for possible future research in this particular field of fluid mechanics and the further development of sophisticated laser-based measurement techniques for boiling, and similar, flows.

Keywords: boiling, horizontal pipe, interface detection, particle image velocimetry, R245fa, slug flow, vapour bubble, velocity field

1. INTRODUCTION

1.1. Horizontal flow boiling

Many experimental studies have been undertaken to investigate flow boiling in horizontal macro-scale tubes, typically with pipe inner diameters $d_i > 3$ mm (Kandlikar and Grande, 2003), where gravity is significant. In many of these studies, heat transfer and pressure drop data have been collected to validate, modify and improve upon existing flow pattern maps and predictive correlations. The boiling heat transfer mechanism is also significantly affected by the tube size. For example, in a 7.49-mm pipe, Balachander et al. (2012) found nucleate boiling to be dominant, while Zhang et al. (2014) revealed that convective boiling prevails in a 38.5-mm tube and attributed this effect to its larger size. Passos et al. (2003) also showed that the dominant heat transfer mechanism is dependent on the pipe diameter, finding it to be nucleate and convective boiling for $d_i = 6.5$ mm and 10.7 mm, respectively.

The tube length has also been varied in an effort to understand its influence on flow boiling. Jung et al. (1989) stated that long test sections are necessary to eliminate entry-length effects and to make measurements over a range of vapour qualities. They did not give quantitative guidance on what constitutes 'long' but their test section had a length-to-inside-diameter ratio of 880. Cho and Tae (2001) reported that the effect of flow disturbances caused by the inlet conditions on heat transfer disappeared after a length of 48 diameters, although this study was performed with a microfin tube. The pressure drop along and flow rate through a test section were also measured in most of the studies, with inlet and outlet conditions also recorded.

1.2. Heating conditions and wall temperature measurements

In a number of studies, a preheater was used to partially evaporate the flow before a test section. This reduces the heated length of the test section necessary to achieve a given vapour quality at

the outlet but the two-phase flow at the inlet may require a longer development length. Test sections are typically heated electrically or by a heat exchanger. Electric heating supplies a constant heat flux to a pipe wall and, therefore, to a test liquid and is a convenient method for this goal. A counter-current double pipe, or tube-in-tube, heat exchanger was recommended by Kattan et al. (1998) as the preferred heating method for realistic study of the heat transfer coefficient for boiling of a refrigerant mixture, which is likely to be why a number of researchers have chosen this method. In addition, Shin et al. (1997) suggested that electrical heating is not appropriate for stratified flows or flows with partial dryout.

In order to measure the outside temperature of a pipe wall, multiple thermocouples or platinum resistance thermometers are commonly used in the literature. Often, they are arranged in a number of stations along the test section, with several thermocouples placed circumferentially at each station (as a rule, four thermocouples at 90° intervals around the pipe). Alternatively, infrared (IR) thermography can be employed, where an IR camera is used to measure a temperature field of a heated wall rather than a flow itself. This allows for calculation of local heat transfer coefficients with a high spatial and temporal resolution, though IR cameras are significantly more expensive than thermocouples (Hassan et al., 2014; Hardik et al., 2017). For instance, Kossolapov et al. (2019) and Su et al. (2020) applied infrared thermometry to subcooled boiling flows specifically to investigate the impact of surface roughness. The resulting temperature and heat flux distributions obtained using a high-speed IR camera could be correlated to bubble nucleation sites using corresponding images from backlit high-speed video of the wall.

1.3. Flow visualization and optical laser-based measurements

Tubular test sections are mostly provided with sight glasses at one or both ends to discern flow patterns. Nasr et al. (2015) used the flow pattern visualization method developed by Jassim et al. (2007) where a diffuse white film pigmented with evenly spaced black stripes is placed behind

the sight glass and illuminated with a stroboscope, while images are captured by a web camera. Wojtan et al. (2005a; 2005b) illuminated a flow cross-section with a laser sheet and recorded high-speed images, detecting the vapour-liquid interface and, thus, extracting information on the dry angle and void fraction using the method developed by Ursenbacher et al. (2004).

Estrada-Perez and Hassan (2010) employed particle tracking velocimetry (PTV) to investigate turbulent subcooled boiling in vertical rectangular channels with a hydraulic diameter of 10 mm and to ultimately evaluate flow properties such as the mean velocity, turbulence intensity and Reynolds stresses. In PTV, the flow is seeded with tracer particles and illuminated by a laser light sheet, with images of a region of interest captured by a CCD- or high-speed CMOS-camera. The motion of individual particles is then tracked from frame to frame, the time step between which is known, to provide a measurement of an irregular velocity field in a fluid provided that the tracer velocity has negligible variations during the time interval between two successive frames. Hassan et al. (2014), for example, combined IR thermography and PTV to assess the impact of heating on the Reynolds stresses.

Particle image velocimetry (PIV) is a laser-based measurement technique similar to PTV but the flow is seeded with particles at a much higher density and the mean displacement of groups of particles between frames is tracked using a cross-correlation function to provide an estimate of a regular velocity field. PIV has been used in pool boiling experiments alongside IR thermometry to provide detailed measurements of phase, temperature and velocity fields on and above the boiling surface, providing a useful benchmark for nucleate boiling simulations (Duan et al., 2013). Voulgaropoulos et al. (2021) combined PIV and PTV with IR thermometry and two-colour laser-induced fluorescence to investigate simultaneously velocity and temperature fields around a bubble during its nucleation. As a result, they were able to obtain detailed spatiotemporally resolved measurements of temperature and velocity fields and observe their coupling. In LIF techniques, a fluorescent dye is typically merged into to a fluid flow, which is

then excited using a laser sheet at an appropriate wavelength. A camera equipped with an optical filter, which is transparent for the fluorescent radiation but opaque to the laser light, is used to capture only the fluorescence signal. Resulting images can be processed to provide data on phase distribution (Schubring et al., 2010), temperature fields (Seitzman et al., 1985) or local component concentration (Crimaldi, 2008), depending on specific experimental aims.

While there is little evidence in the literature of the application of the laser-based diagnostic techniques described in this section to boiling flows in horizontal pipes, these methods have been employed successfully to investigate two-phase flows in similar geometries. Morgan et al. (2013) used simultaneously high-speed planar LIF (PLIF), PIV and PTV to take detailed spatiotemporally resolved measurements of characteristics of two-phase liquid-liquid flows in a horizontal transparent tube with $d_i = 27.6$ mm. Thus, the authors determined the local phase fraction, interface level and droplet size distribution in different regimes, including stratified and dispersed flow conditions. Zadrazil and Markides (2014) and Zadrazil et al. (2014) used a combination of PLIF and PIV/PTV techniques to study isothermal downwards co-current gas-liquid annular flows in a 32.4-mm pipe. As a result, velocity fields and turbulent kinetic energy profiles in a liquid film as well as data on the film thickness, interface and wave statistics and gas entrainment into the liquid were obtained. Cherdantsev et al. (2019) applied a brightness-based LIF approach to measure a film thickness in annular flow in the same facility, comparing its results to those of a conventional PLIF approach. Charogiannis et al. (2016) presented a thermographic particle velocimetry (TPV) technique capable of the simultaneous measurement of two-dimensional surface temperature and velocity at the interface of multiphase flows. For this, a fluid flow is seeded with highly reflective particles of a different emissivity and the particle patterns are captured using an IR camera. The technique is, for example, useful for studying gravity-driven liquid-film flows over inclined heated substrates but can be also applied to any flow with a sufficient density difference between the two phases.

1.4. Summary and article focus

Aside from the research discussed above, there has been no attempt made to measure detailed velocity profiles, turbulence characteristics, local temperatures, film thicknesses and other important detailed characteristics in boiling pipe flows. Optical and laser-based full-field measurement techniques present an excellent potential to conduct such experiments, although these methods have not been widely applied to boiling flows, particularly under saturated conditions. In this article, we aim at an experimental investigation of slug flow boiling in a horizontal pipe using modern laser-based methods for two-phase flow diagnostics.

It is widely acknowledged that slug flow occurs at low vapour qualities (i.e., small mass fractions of vapour) as the mass flux is increased above a critical value below which stratified flow is dominant (Wojtan et al., 2005a). It is characterized by alternating liquid slugs, in which the liquid phase occupies the entire cross-section of a pipe, and vapour bubbles around which a liquid film exists. This structure can result in effective heat transfer, but the intermittent nature of the flow pattern can cause large variations in pressure drop and momentum transfer along the pipe. It is thus useful to measure liquid velocity fields in slug flows and characteristic parameters such as passage frequency and velocity of vapour bubbles. Moran et al. (2021) showed how laser-based diagnostic techniques could be used to investigate horizontal flow boiling in the stratified flow regime. The present research presents an extension of these techniques to boiling slug flows, to which such experimental methods have not been widely applied in macro-scale geometries.

In the next section (Section 2), we give a brief description of the experimental facility with its main components and metering equipment, the flow conditions investigated, measurement techniques and data processing procedures used to generate the results presented herein. In Section 3 the main results of the article are presented and discussed. Findings and conclusions of the study are summarized in Section 4, along with some practical recommendations that have

emerged from this work for future research in this particular field of fluid mechanics, in particular on the further development of advanced laser-based measurement techniques for boiling flows.

2. EXPERIMENTAL METHODS

2.1. Test facility and flow conditions

The experiments have been performed in the flow boiling facility (FLOBOF) at Imperial College London, a simplified diagram of which is shown in Fig. 1a. This study utilises the same experimental facility and similar experimental techniques as those employed in Moran et al. (2021). The experimental facility consists of the following main components: a Crest AM50 TGARV centrifugal pump (speed 2900 rpm, maximum capacity 150 L/min, maximum head 11 m, best efficiency 70%) for moving an operating liquid over the circulating loop, an Omega CHF01863 circulation preheater (voltage 240V-1Ph, maximum power 6 kW) for warming-up the fluid to a certain temperature, a 90- μ m coarse filter for removing relatively large impurities from the flow, a Titan 1065-EOS-O pulse output turbine flowmeter (flow rate 0.25–6.5 L/min, linearity 1.5% FSD, typical frequency 230 Hz) for gauging the volumetric flow rate, a test section of changeable geometry and orientation, a SWEP B12H condenser (maximum flow rate 282 L/min, number of plates 140) for chilling the two-phase flow and a 20-l tank for receiving and keeping the liquid. The desired degree of subcooling of the fluid is achieved by a PID controller with a temperature transducer installed at the test section inlet. In order to regulate the flow rate, an AC-10 Parker inverter (output voltage 230 V, output current 2.5 A, maximum frequency 590 Hz, power 400 W) which uses an output of the flowmeter as its input to adjust the pump rotation speed is employed, so that a back coupling between them is implemented. The condenser is a water-cooled brazed-plate heat exchanger in which the vapour condenses and the liquid loses its extra heat before being returned to the receiver (Fig. 1a).

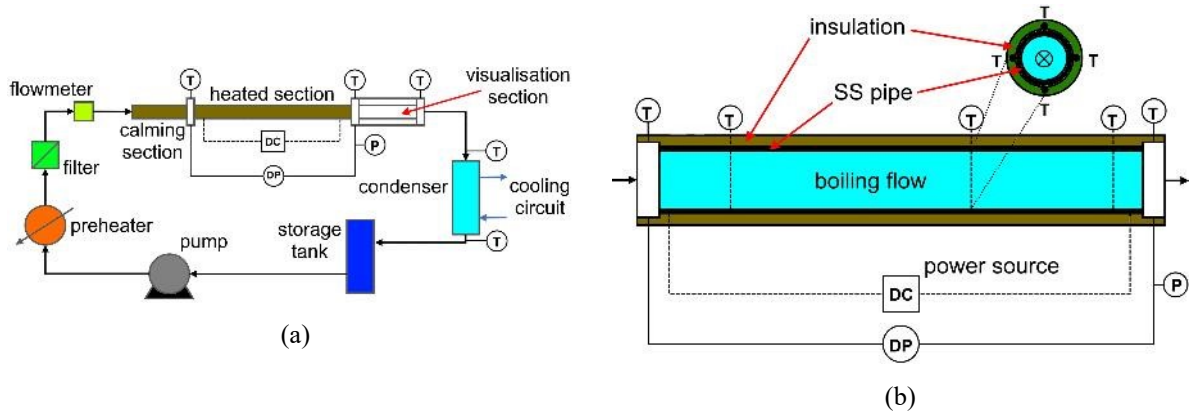


Figure 1. Schematic of: (a) FLOBOF flow loop, and (b) heated section with indication of locations of controlling units for temperature ‘T’, pressure ‘P’ and differential pressure ‘DP’.

A 2-m long stainless-steel (SS) pipe with an inner diameter of $d_i = 12.6$ mm oriented horizontally is utilized as the test section in the present study (Fig. 1b) which is preceded by a 0.6-m long straight flow-calming channel of the same cross-section and material to eliminate any entrance effects. This SS duct is thermally insulated with 19-mm thick black nitrile rubber and heated by applying voltage to both of its ends through copper rods and braids from a Glassman Europe BPI DC power supply (maximum output voltage 20 V, maximum output current 750 A) to spread heat over its surface uniformly. So, the liquid enters the heated duct as a subcooled one-phase substance, is warmed up to its saturation point, boils as it flows along the tube and exits as a two-phase vapour-liquid medium with vapour quality x . In order to determine the inlet and outlet flow conditions, the flow temperature and pressure are measured at the entrance and exit of the heated duct using respectively mineral insulated T-type Class 1 thermocouples (diameter 0.5 mm, uncertainty ± 0.5 °C) and Rosemount 2051C differential pressure transmitters (pressure range 0–2 bar, frequency 22 Hz, error $\pm 0.05\%$ of span) supplemented with an Omega PXM309-3.5G absolute pressure transducer (maximum pressure 3.5 bar, maximum frequency 1 kHz, uncertainty $\pm 1\%$) that is installed below the test section.

In order to guarantee optical access to the boiling flow, the tubular test channel is followed by a visualization section representing a fluorinated ethylene propylene (FEP) pipe with an inner

diameter equivalent to that of the heated duct. The FEP tube is encased in a Perspex correction box constructed from acrylic resin and filled with distilled water (Fig. 2). The refractive indices of the water and FEP closely match within the experimental temperature range, allowing this box to reduce optical distortions attributed to the pipe curvature and the relative position of a recording device. The optical distortions are further accounted for by placing and imaging a predefined graticule target of known dimensions in the measurement region (Morgan et al., 2013; 2017). When a laser light sheet is used for flow illumination which usually coincides in space with the central longitudinal section of a test channel, an image of the target can be spatially calibrated to compensate the camera inclination and other constant optical distortions.

The experiments are performed for slug flow conditions at mass fluxes $G = 4\tilde{V}\rho_l/\pi d_i^2$ varied in the range of 300 to 460 kg/m²·s and three heat fluxes $q = Q_{in}/\pi d_i L_{ht} = 5.3, 6.6$ and 7.9 kW/m², where $\tilde{V}$ is the measured volumetric flow rate, ρ_l the liquid density, d_i the inner diameter of the pipe, L_{ht} the heated length of the pipe and Q_{in} the heat input rate accounting for Ohmic losses due to the resistance of the copper rods and braids connecting the power supply to the test section. The test section was wholly insulated with black nitrile rubber with a thickness of 19 mm. The losses were found not to exceed 2% of the input power delivered to the pipe. Furthermore, the maximum thermal losses to the ambient were also estimated and found to be less than 1% of the input power across all flow regimes by evaluating the single-phase energy balance over the range of input powers and flowrates used in this work.

The operating liquid is R245fa since it is one of the newer, less environmentally damaging refrigerants which attracts increasing research interest due to its dominance in modern heat exchanging systems based on the organic Rankine cycle (Landelle et al., 2017). This cycle is typically employed in generation of electrical power from low-temperature thermal energy sources (Kang, 2012; Galloni et al., 2015), e.g., solar heating (Freeman et al., 2017; Ramos et al., 2018), or in waste heat recovery (Chatzopoulou et al., 2019; Pantaleo et al., 2019). However,

experimental data available in the literature is scarce for R245fa boiling in macro-scale pipes, with the overwhelming majority of R245fa studies focusing on mini- and micro-channels (Tibirić and Ribatski, 2011; Charnay et al., 2013; Huang and Thome, 2016; Kanizawa et al., 2016), vertical tubes (Pike-Wilson and Karayiannis, 2014), or condensation processes (Kedzierski et al., 2013; Liu et al., 2016).

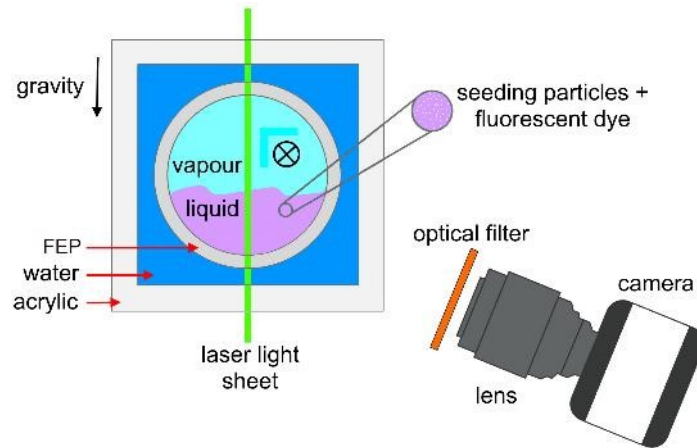


Figure 2. Outline of the relative arrangement of the camera and visualization section for both interface detection and PIV measurements. The flow direction is from the reader.

Output signals from the facility instrumentation are processed by three data acquisition devices connected to a computer and recorded through a LabView interface which is also used for monitoring and controlling the system. For given experimental conditions, a steady state of the flow is regarded as being achieved when measurement data remains within a 5% range for at least 300 s, after which the data is recorded during a period of 120 s. A LabView interface is developed to read instrument signals, display their data in real time and store them in a text file for further processing including calculation of integral thermophysical properties (temperature, pressure and flow velocity), reduction of measurement data to deduce non-dimensional quantities (similarity criteria) and evaluation of time-averaged flow characteristics and their fluctuations. Thus, for each flow regime investigated, control variables are set accordingly, and the system

allows reaching steady-state conditions before the data recording starts. All other specific details on various technical features and processing procedures can be found in full in Moran (2021).

2.2. Laser-based flow diagnostics

The experimental apparatus used for both the interface detection and velocity measurements by PLIF and PIV methods respectively is shown in Fig. 2. Rhodamine 6G dye at a concentration of 1 ppm was mixed into the operating liquid to allow PLIF visualisation. The slug flow is illuminated by a light sheet generated by a copper-vapour laser of Oxford lasers production which emits two narrow-band laser beams at 510.6 nm (green light) and 578.2 nm (yellow light) at a nominal output power of 20 W, frequency of 2 kHz, pulse duration of 2 ns, and pulse energy of 2 mJ. Both beams are directed to a sheet generator via a fiberoptic cable, with the sheet expanded in the streamwise direction and passing through the central longitudinal section of the pipe from the bottom of the correction box. However, in the experiment, one beam is sufficient for PIV implementation, so the green light is only utilized. To capture instantaneous images of the flow, an Olympus i-Speed 3 camera (matrix size 1280×1024 pixels, sampling rate 2 kHz) equipped with a Sigma 105 mm f/2.8 EX DG Macro lens is employed. In this application, the camera is mounted at an angle of approximately 20° from the horizontal (Fig. 2), with the camera plane of focus corrected using the Scheimpflug principle.

Images are captured at a frame rate of 1500–2000 fps, depending on the flow velocity. The shutter exposure is set to 100 μ s to allow sufficient light to reach the sensor while avoiding image blurring due to the vapour-liquid mixture movement when the shutter is open. In images, the liquid film above vapour bubbles appears in a region hidden by a glow from the top of the FEP pipe and, therefore, is not discernible at the camera magnification (frame size 12.6×25 mm, scale factor 20 μ m/pixel). In order to measure the thickness of the liquid layer underneath bubbles and estimate their integral characteristics (length, frequency and velocity), we apply

the same interface detection algorithm used previously in Moran et al. (2021) for stratified and stratified-wavy flows. The presence of tiny vapour bubbles, particularly within the fronts and tails of liquid slugs, causes unphysical peaks in the detected interface, so these data are also smoothed along the time scale on a pixel-by-pixel basis.

To enable PIV measurements, the liquid is seeded with 10- μm silver-coated reflective tracer particles. Their density is comparable to that of the liquid and they are sufficiently small to follow the flow streamlines with minimal interference, as determined by considering the Stokes number:

$$\text{Stk} = \frac{\rho_p d_p^2}{18\mu_l} \frac{u_l}{d_{\text{pipe}}} \quad (1)$$

where ρ_p and d_p are the density and characteristic size of the particles, μ_l and u_l are the dynamic viscosity and velocity of the liquid and d_{pipe} is the pipe diameter. Tropea et al. (2007) reported that, for $\text{Stk} \ll 0.1$, any tracing errors associated with the particle displacements are below 1%. Evaluating Eq. (1) for the given experimental conditions gives $\text{Stk} \sim 10^{-4}$, which meets the above criterion. In this article, we use the identical PIV data processing procedures applied in the same sequence as discussed in detail in Moran (2021) and Moran et al. (2021).

The main limitation of PIV application in this arrangement to boiling flows is that it is only possible to measure velocity fields in the liquid phase. Because of the evaporation, the particle concentration can also vary between measurements at different vapour qualities. In reality, some particles are lost around the facility, so we had to regularly redose the refrigerant with particles. Typically, we took sets of measurements at similar vapour qualities and, thus, were able to maintain a fairly constant concentration of the tracers. Another potential issue with PIV in boiling flows is the concentration of particles at the interface during evaporation which can affect the interfacial characteristics and, in turn, the flow pattern along with the flow boiling behaviour. We have performed analysis of the effect of particles on surface tension and have not revealed a significant change at the levels used, even accounting for the concentration due to evaporation. The bubble

departure diameter is typically of the order of 1 mm, which is much larger than the particle size of 10 μm , so the tracers should not evidently affect the bubble dynamics.

2.3. Measurement uncertainties

The mean absolute uncertainty in the interface locations detected using the PLIF method was evaluated based on the standard deviation of the measured interface height for flat liquid interfaces and found to be ± 0.16 mm, which is equal to approximately ± 8 pixels. Uncertainties in velocity profiles of bubble interfaces are reported as the standard deviation along the axial direction of the velocity at a given vertical (y) coordinate. This results in an average error of approximately $\pm 30\%$, although this is typically larger towards the interface and pipe wall.

The PIV method was validated by comparing velocity profiles of the single-phase flow rate for a range of conditions with the parabolic and power-law velocity profile in case of laminar and turbulent (with $n = 7$) flow, respectively (Fig. 3a and 3b). The resulting profiles match the theoretical predictions of Eqs. (2) and (3) very closely, particularly in the centre of the pipe. Towards the pipe walls the glow of the translucent FEP pipe as it is illuminated by the laser sheet can distort the light scattered by the PIV particles, causing large uncertainties in the measurements and poor agreement with theory.

$$\text{Laminar: } \frac{u}{u_{\max}} = 1 - \left(\frac{r}{r_{\text{pipe}}} \right)^2, \quad (2)$$

$$\text{Turbulent: } \frac{u}{u_{\max}} = \left(1 - \frac{r}{r_{\text{pipe}}} \right)^{1/n}, \quad (3)$$

where r_{pipe} is the pipe radius and r the transversal coordinate measured from the pipe centre.

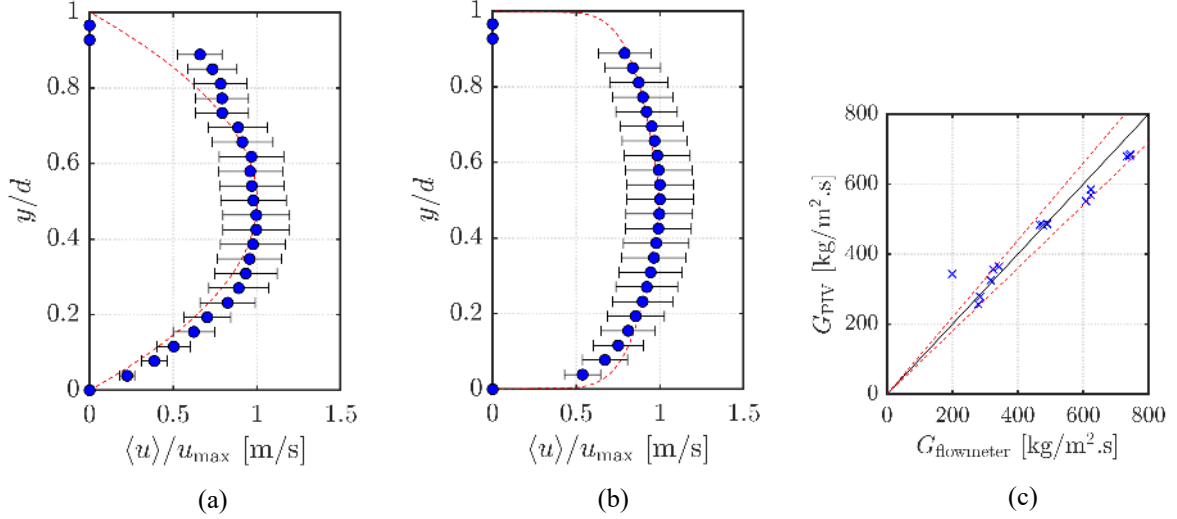


Figure 3. (a, b) Time-averaged streamwise velocity profiles of the single-phase liquid flow from PIV measurements normalised by the maximum velocity $u_{\max}$ (blue circles) together with the theoretical prediction (red dashed line) when the flow is: (a) laminar, and (b) turbulent. The vertical (y) coordinate is divided by the pipe diameter d . (c) Mass flux G calculated based on the PIV measurements versus the flowmeter measurements for single-phase liquid flow. The solid black line represents $G_{\text{PIV}} = G_{\text{fm}}$, and the red dashed line represents $G_{\text{PIV}} = G_{\text{fm}} \pm 10\%$.

In order to validate the absolute values of the streamwise velocity obtained with PIV, a flowrate and subsequently mass flux were calculated based on these measurements and compared to that measured using the flowmeter. For each validation case, the velocity profile was integrated across the pipe assuming a parabolic decay of the velocity towards the pipe wall from its maximum value at the centreline. The resulting mass flux values are plotted against the corresponding mass flux based on the flowmeter measurement in Fig. 3c. The majority of points are within 10% of the flowmeter value, with an average absolute deviation of 6%. There is one outlier at the mass flux $G_{\text{fm}} \approx 200 \text{ kg/m}^2\text{s}$, where some vapour may have been present in the flow, impacting the flowmeter reading.

3. RESULTS

In this section, we present a selection of results obtained for different conditions in terms of the heat and mass fluxes. The section is divided into three subsections, focusing on: the instantaneous liquid velocity fields around vapour bubbles, the frequency of liquid slug passages and, finally, the effect of the heat flux on the velocity of vapour bubbles.

3.1. Velocity fields

Figure 4 shows snapshots of the vapour bubble interface and instantaneous flow velocity distributions around it gathered simultaneously. The colourmap represents its magnitude, while the arrows also indicate its direction. Figure 4b shows a middle part of the bubble and is extracted at a time stamp halfway between Figs. 4a and 4c. As it enters the frame, the bubble disturbs the flow in the tail of a liquid slug ahead (Fig. 4a). The velocity magnitude decreases in this region becoming smaller than that of the bulk flow, with close-to-zero values at some points as the flow direction changes. The radial (vertical) velocity component is predominantly negative (downward movement), exhibiting that the liquid is pushed away by the advancing vapour phase. The velocity field below the main body of the bubble, which is around 7 mm in height, does not however seem to be very sensitive to its presence (Fig. 4a). The flow is mainly directed streamwise, with its velocity taking the maximum value at the axis of the pipe and declining towards the wall.

The flow behind the bubble (Fig. 4c), i.e., in a liquid slug located in its wake, is similarly disturbed, although the radial liquid movement is mainly upwards (positive vertical velocities) as the liquid fills up the space previously occupied by the vapour bubble. However, it is worth noting that the velocity magnitude in the liquid slug nose is up to two times higher than in its tail (cf. Figs. 4a and 5c). This effect was previously observed by other authors both experimentally (Czapp et al., 2013; Xu et al., 2020) and numerically (Frank, 2005; Czapp et al., 2013; Pineda-Pérez et al., 2018). The liquid flow under the back of the main body of the vapour

bubble also demonstrates a more significant upwards movement further towards the interface in Fig. 4c as compared to the downwards movement under the front of its main body in Fig. 4a (see arrows for $z < 5$ mm). Strong velocity variations in the liquid slug nose in Fig. 4c are indicative of the formation of a mixing eddy proposed by Dukler and Hubbard (1975), and it would be interesting to consider how they relate to local changes in the heat transfer coefficient. Such measurements could be performed by, for example, IR imaging of the pipe wall.

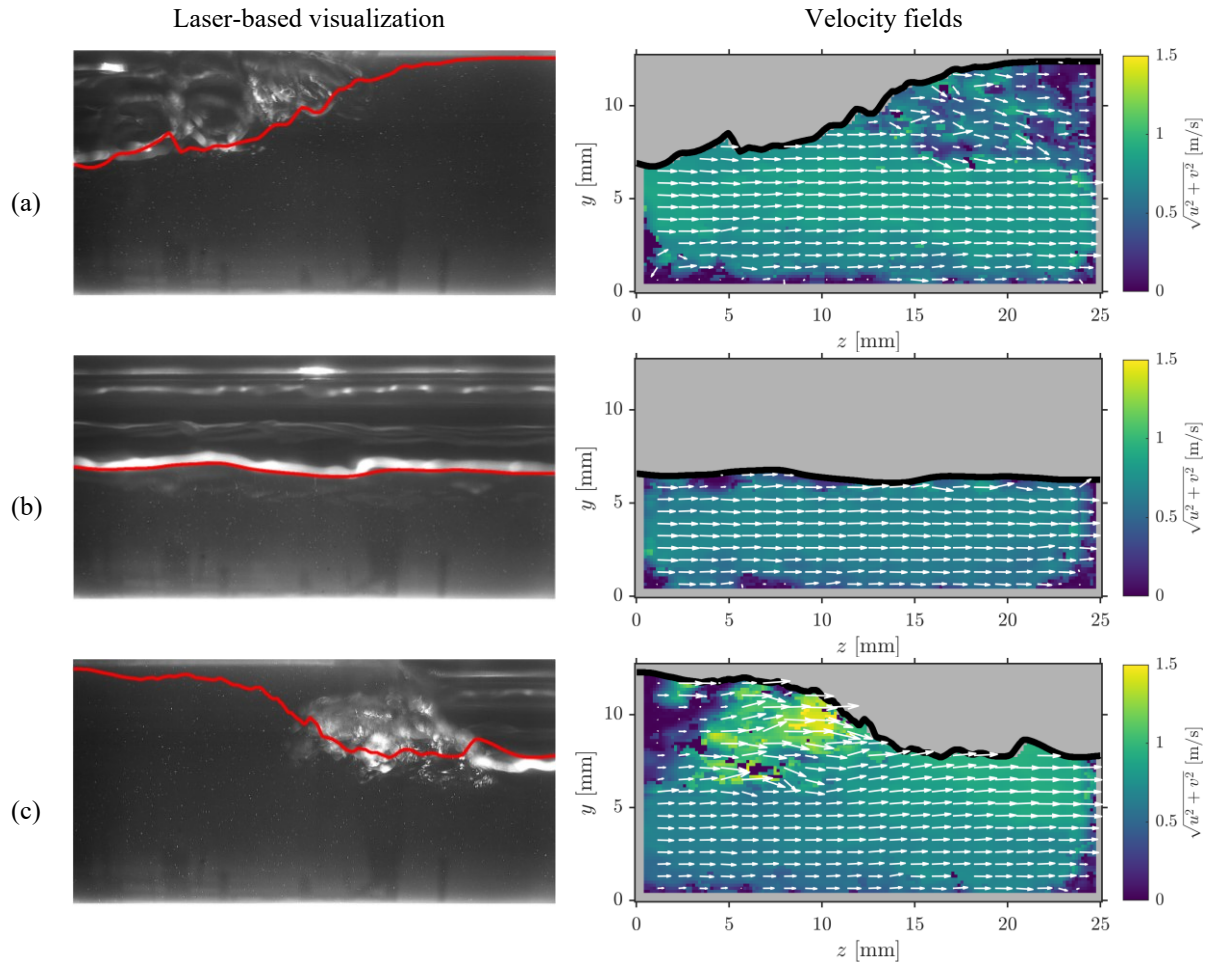


Figure 4. Representative high-speed images (left column) with indication of the detected interface marked by the red curve and corresponding masked instantaneous velocity fields (right column) measured along the central plane of the pipe for $G = 460 \text{ kg/m}^2\cdot\text{s}$ and $q = 7.9 \text{ kW/m}^2$ at different streamwise positions corresponding to the: (a) tail, (b) middle, and (c) front of a vapour bubble.

Although the streamwise velocity across the pipe is almost constant underneath the central region of the vapour bubble (Fig. 4b), with its magnitude decreasing only in a near-wall region (approximately $0 \text{ mm} < y < 2.5 \text{ mm}$), there are some variations close to the interface caused by its waviness. Similarly-shaped velocity profiles under a vapour bubble were also observed by Xu et al. (2020) in an air-water slug flow in a 51-mm pipe. Across the three regions in Fig. 4, the magnitude of the liquid velocity in the near-wall region is very similar, which is compatible with the behaviour noted in Xu et al. (2020), and shows how the impact of the vapour bubble on the liquid phase movement decays with increasing the distance from the interface. It might then be expected that the local heat transfer coefficient at the bottom of the pipe would not vary in time as much as that at the top of the pipe.

3.2. Slug passage frequency

The slug frequency is calculated through analysis of time-dependent traces of the interface height y_{int} . An example of such a trace is shown in Fig. 5a. In this figure, periods where y_{int} is equal to 12.6 mm, i.e., coincides with the pipe inner diameter, correspond to liquid slugs since no vapour-liquid interface is detected and, therefore, no vapour is present within them (Fig. 5a). After each of these periods, the trace undergoes a sudden decrease in the interface level, so that $y_{\text{int}} \approx 5.5 \text{ mm}$, thereby indicating the appearance of a vapour bubble. Then the vertical position lifts stepwise up to $y_{\text{int}} = 7\text{--}7.5 \text{ mm}$ as the bubble goes downstream through the sampling cross-section before jumping back to 12.6 mm when the back of the bubble has passed. The shape of the peaks is somewhat different just before and immediately after 2 s, where a few small vapour bubbles remained at the top of the pipe in the liquid slug between consecutive long vapour bubbles.

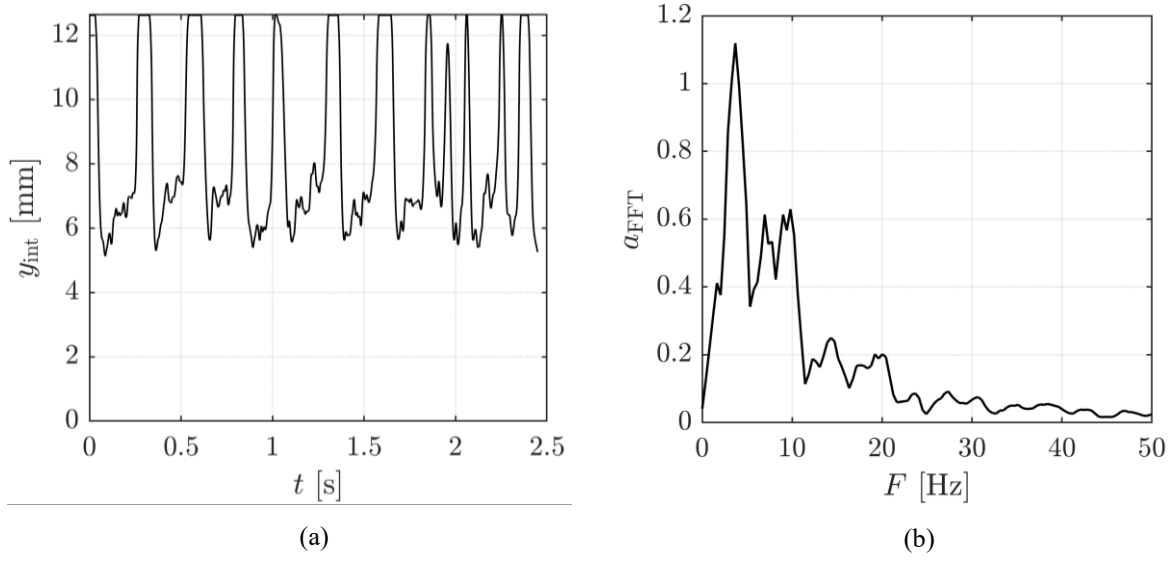


Figure 5. (a) Time trace of changes of the interface vertical position, and (b) corresponding FFT signal extracted from the visual data in cross-section $z = 12.5$ mm (Fig. 4) for mass flux $G = 460 \text{ kg/m}^2\cdot\text{s}$ and heat flux $q = 7.9 \text{ kW/m}^2$.

From Fig. 5a we observe the existence of a characteristic slug passage frequency F_{slug} . To this end, a fast Fourier transform (FFT) is applied to the interface level trace to express the data in the frequency domain. As visible in Fig. 5b, the resulting frequency signal has a dominant peak at a frequency of 3.7 Hz, which corresponds to F_{slug} and is in accordance with Fig. 5a, where the interface vertical position reaches the level of 12.6 mm around four times in each second. In order to assess the effect of F_{slug} on heat transfer in the horizontal pipe, the latter is plotted in Fig. 6 in a nondimensional form of the Stanton number $St = h/Gc_{p,l}$, where h is the heat transfer coefficient, G is the mass flux and $c_{p,l}$ the liquid heat capacity, to account for varied mass fluxes. Considering all of the points together, it might be concluded that St increases with F_{slug} . A higher slug passage frequency would result in more frequent appearances of slug noses and tails which disturb the flow as seen in Fig. 4 and induce mixing eddies. These secondary flows enhance the heat transfer. However, the picture in general remains unclear when the data points in Fig. 6 are considered separately for different heat fluxes. For example, St seems to be practically independent of F_{slug} for $q = 5.3$ and 6.6 kW/m^2 but it grows by up to 50% over a very short range of frequencies for

$q = 7.9 \text{ kW/m}^2$. So, more data points are required across the present range of heat flux conditions to draw any significant conclusion and could be the focus of further research.

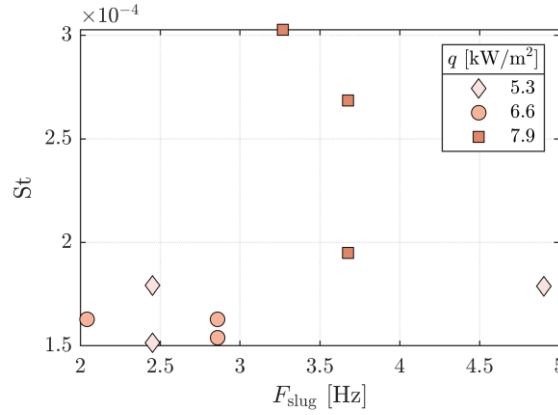


Figure 6. Dependence of heat transfer expressed in form of the Stanton number St on the slug passage frequency F_{slug} for three selected heat fluxes $q = 5.3, 6.6$ and 7.9 kW/m^2 .

3.3. Vapour bubble velocity

Another flow characteristic of note that can be extracted from the interface level data is the vapour bubble velocity. It is obvious that there must exist a time shift from one trace to another in different cross-sections as identical flow features pass the two points separated in space at different times. For example, Fig. 7 shows such time-dependent traces for two cross-sections $z = 0$ and 25 mm (see Fig. 4). The shift between the two traces at the points, where the interface level starts to decrease from 12.6 mm (Fig. 7), is equal to the time taken for the front of a vapour bubble to travel from the left-hand side of the frame ($z = 0 \text{ mm}$ in Fig. 4) to its right-hand side ($z = 25 \text{ mm}$ in Fig. 4). Based on this time shift and the known distance travelled, the average velocity of vapour bubbles u_b is determined for each set of slug flow conditions (Fig. 8).

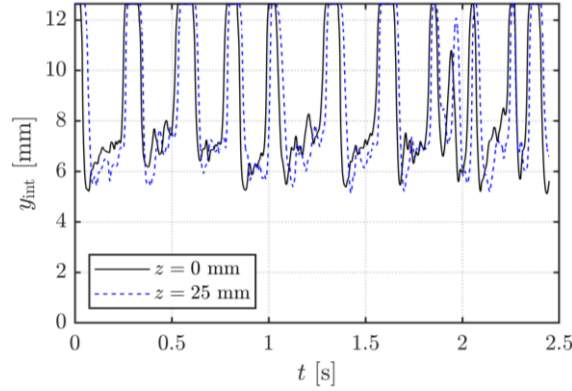


Figure 7. Temporal variations of the vertical interface position y_{int} extracted from the visual data in two cross-sections z for mass flux $G = 460 \text{ kg/m}^2\cdot\text{s}$ and heat flux $q = 7.9 \text{ kW/m}^2$.

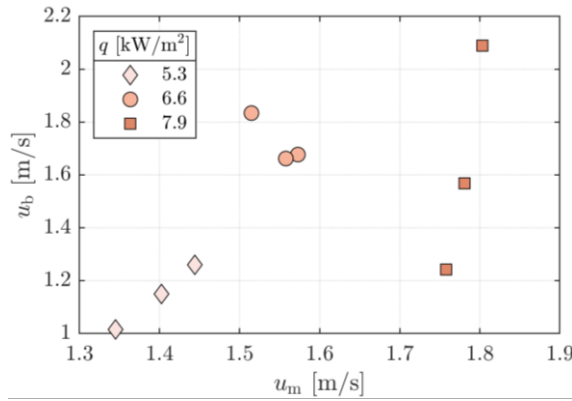


Figure 8. Dependence of the average velocity of vapour bubbles u_b on the superficial mixture velocity u_m for three selected mass fluxes $G = 320, 370, 450 \text{ kg/m}^2\cdot\text{s}$ and heat fluxes $q = 5.3, 6.6$ and 7.9 kW/m^2 , respectively.

Overall, as could be expected, the bubble velocity increases with the superficial mixture velocity u_m (Fig. 8). For $q = 5.3$ and 7.9 kW/m^2 , u_b increases linearly with u_m , albeit with a larger gradient for the higher q . This linear behaviour is in accordance with the relationship proposed by Nicklin et al. (1962): $u_b = C_0 u_m + C_1$, where C_0 and C_1 are constants, with the latter interpreted as the drift velocity (Picchi et al., 2015). From Fig. 8, there is evidence to suggest that C_0 might depend on the heat flux in boiling flows. Because of this pronounced heat flux effect on the

bubble-mixture velocity relationship, a direct comparison of our results with those from Nicklin et al. (1962) is not straightforward. It is evident that additional data are required for the further exploration of these constants in boiling flows, and forms an interesting and important area of future work. It is also worth noting that, at increased heat fluxes, the average velocity of vapour bubbles exceeds the superficial mixture velocity ($u_b > u_m$) (Fig. 8). This is an important observation which implicitly confirms that the bubble passage frequency must increase with the heat flux (see Fig. 6). Moreover, this also implies that these high-speed vapour bubbles must significantly enhance flow turbulence, thereby additionally intensifying heat transfer.

4. CONCLUSIONS AND RECOMMENDATIONS

Data from the application of laser-based diagnostic techniques have been presented, generated during flow boiling of refrigerant R245fa in a 12.6-mm inner diameter horizontal plain pipe in the slug flow regime and different conditions in terms of the imposed heat and mass fluxes. We used a single laser-camera arrangement to identify the vapour bubble interface and to perform PIV measurements in these flows. Inspection of the instantaneous velocity fields revealed significant disturbances at both the noses and tails of liquid slugs, with a value two times higher behind vapour bubbles. The flow velocity in the near-wall region (close to the bottom of the pipe) did not change significantly in direction or magnitude as vapour bubbles passed. The slug passage frequency was determined based on interface detection in the collected data. The vapour bubble velocity was calculated in a similar way and found to increase linearly with the interfacial velocity of the two-phase mixture, while its gradient grew with the heat flux. Moreover, at increased heat fluxes the bubbles moved faster than the mixture itself, which implies that they might significantly enhance local turbulence, thereby intensifying heat transfer.

These detailed spatiotemporally resolved measurements of boiling in horizontal slug flow conditions represent an important contribution to the experimental data available in the literature.

They can provide insight into the physics of interference of turbulence and heat transfer phenomena in heat-exchange systems, as well as improve our understanding of boiling in many important practical applications, including solar collectors, refrigeration and heat pumps, waste-heat recovery and conversion and concentrating solar power technology. The data is also useful for the development and validation of advanced multiphase models and can be translated to a more effective design and operation of modern devices based on flow boiling heat transfer.

The database generated in the experimental campaign reported in this paper can be further extended by changing the heat and mass flux conditions over a wider range to form a more complete picture of the phenomena observed in this research. Tests with other liquids would add a further dimension to the database and aid in the identification of suitable predictive methods for boiling in this geometry. The measurement of temperature fields using IR imaging and thermal PLIF techniques can provide further insight into the thermohydraulic flow behaviour. Ensemble averaging techniques can be utilised to examine velocity variations in liquid slugs, particularly at the slug noses and tails where intense mixing and secondary flows occur.

In closing, it is our view that there is significant scope for further development of advanced laser-based measurement techniques specifically aimed at the inspection of boiling flows. Capturing velocity fields simultaneously in both phases would give further insight into the interaction of the phases, particularly across the interface. Examination of the flow in the pipe cross-section would allow a more accurate determination of the phase distribution and aid further improvement of predictive methods for heat transfer, pressure drop and flow patterns. Another useful next step would be the corresponding evaluation of spatiotemporally resolved wall and liquid temperatures, rather than integral point measurements, for direct comparison with the information on interface profiles and velocity distributions.

ACKNOWLEDGEMENTS

The research was funded by the Ministry of Science and Higher Education of the Russian Federation (Megagrant Project No. 075-15-2019-1888), the UK Department for International Development (DFID) through the Royal Society-DFID Africa Capacity Building Initiative, and the UK Engineering and Physical Sciences Research Council (EPSRC) [grant numbers EP/P004709/1, and EP/L020564/1]. The authors gratefully acknowledge this support. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

REFERENCES

- Balachander, P., Raja, B., and Lal, D.M., Evaporative Heat Transfer Characteristics of R404a and R134a under Varied Heat Flux Conditions, *Exp. Heat Transf.*, vol. **25**, no. 3, pp. 254–265, 2012. DOI: 10.1080/08916152.2011.623820
- Charnay, R., Revellin, R., and Bonjour, J., Flow Pattern Characterization for R-245fa in Minichannels: Optical Measurement Technique and Experimental Results, *Int. J. Multiph. Flow*, vol. **57**, pp. 169–181, 2013. DOI: 10.1016/j.ijmultiphaseflow.2013.05.015
- Charogiannis, A., Zadrazil, I., and Markides, C.N., Thermographic Particle Velocimetry (TPV) for Simultaneous Interfacial Temperature and Velocity Measurements, *Int. J. Heat Mass Transf.*, vol. **97**, pp. 589–595, 2016. DOI: 10.1016/j.ijheatmasstransfer.2016.02.050
- Chatzopoulou, M.A., Lecompte, S., De Paepe, M., and Markides, C.N., Off-design Optimisation of Organic Rankine Cycle (ORC) Engines with Different Heat Exchangers and Volumetric Expanders in Waste Heat Recovery Applications, *Appl. Energy*, vol. **253**, pp. (113442)–26, 2019. DOI: 10.1016/j.apenergy.2019.113442
- Cherdantsev, A.V., An, J.S., Charogiannis, A., and Markides, C.N., Simultaneous Application of Two Laser-Induced Fluorescence Approaches for Film Thickness Measurements in

- Annular Gas–Liquid Flows, *Int. J. Multiph. Flow*, vol. **119**, pp. 237–258, 2019. DOI: 10.1016/j.ijmultiphaseflow.2019.07.013
- Cho, K., and Tae, S.–J., Condensation Heat Transfer for R-22 and R-407C Refrigerant–Oil Mixtures in a Microfin Tube with a U-bend, *Int. J. Heat Mass Transf.*, vol. **44**, no. 11, pp. 2043–2051, 2001. DOI: 10.1016/S0017-9310(00)00253-2
- Crimaldi, J.P., Planar Laser Induced Fluorescence in Aqueous Flows, *Exp. Fluids*, vol. **44**, no. 6, pp. 851–863, 2008. DOI: 10.1007/s00348-008-0496-2
- Czapp, M., Utschick, M., Rutzmoser, J., and Sattelmayer, T., Investigations on Slug Flow in a Horizontal Pipe Using Stereoscopic Particle Image Velocimetry and CFD Simulation with Volume of Fluid Method, *ICONE 2012, Proc. of 20th Int. Conf. Nucl. Eng. & ASME 2012 Power Conf.*, Anaheim, California, USA, vol. **3**, pp. 477–486, 2013. DOI: 10.1115/ICONE20-POWER2012-54591
- Duan, X., Phillips, B., McKrell, T., and Buongiorno, J., Synchronized High–Speed Video, Infrared Thermometry, and Particle Image Velocimetry Data for Validation of Interface–Tracking Simulations of Nucleate Boiling Phenomena, *Exp. Heat Transf.*, vol. **26**, nos. 2–3, pp. 169–197, 2013. DOI: 10.1080/08916152.2012.736837
- Dukler, A.E., and Hubbard, M.G., A Model for Gas–Liquid Slug Flow in Horizontal and Near Horizontal Tubes, *Ind. Eng. Chem. Fund.*, vol. **14**, no. 4, pp. 337–347, 1975. DOI: 10.1021/i160056a011
- Estrada–Perez, C.E., and Hassan, Y.A., PTV Experiments of Subcooled Boiling Flow through a Vertical Rectangular Channel, *Int. J. Multiph. Flow*, vol. **36**, no. 9, pp. 691–706, 2010. DOI: 10.1016/j.ijmultiphaseflow.2010.05.005
- Frank, T., Numerical Simulation of Slug Flow Regime for an Air–Water Two–Phase Flow in Horizontal Pipes, *NURETH–11, Proc. of 11th Int. Top. Meeting Nucl. Reactor Therm. Hydraul.*, Avignon, France, pp. (038)–13, 2005.

- Freeman, J., Guarracino, I., Kalogirou, S.A., and Markides, C.N., A Small-Scale Solar Organic Rankine Cycle Combined Heat and Power System with Integrated Thermal Energy Storage, *Appl. Therm. Eng.*, vol. **127**, pp. 1543–1554, 2017. DOI: 10.1016/j.applthermaleng.2017.07.163
- Galloni, E., Fontana, G., and Staccone, S., Design and Experimental Analysis of a Mini ORC (Organic Rankine Cycle) Power Plant Based on R245fa Working Fluid, *Energy*, vol. **90**, **Part 1**, pp. 768–775, 2015. DOI: 10.1016/j.energy.2015.07.104
- Hardik, B.K., Kumar, G., and Prabhu, S.V., Boiling Pressure Drop, Local Heat Transfer Distribution and Critical Heat Flux in Horizontal Straight Tubes, *Int. J. Heat Mass Transf.*, vol. **113**, pp. 466–481, 2017. DOI: 10.1016/j.ijheatmasstransfer.2017.05.073
- Hassan, Y.A., Estrada-Perez, C.E., and Yoo, J.S., Measurement of Subcooled Flow Boiling Using Particle Tracking Velocimetry and Infrared Thermographic Technique, *Nucl. Eng. Design*, vol. **268**, pp. 185–190, 2014. DOI: 10.1016/j.nucengdes.2013.04.044
- Huang, H., and Thome, J.R., Local Measurements and a New Flow Pattern Based Model for Subcooled and Saturated Flow Boiling Heat Transfer in Multi-microchannel Evaporators, *Int. J. Heat Mass Transf.*, vol. **103**, pp. 701–714, 2016. DOI: 10.1016/j.ijheatmasstransfer.2016.07.074
- Jassim, E.W., Newell, T.A., and Chato, J.C., Probabilistic Determination of Two-Phase Flow Regimes in Horizontal Tubes Utilizing an Automated Image Recognition Technique, *Exp. Fluids*, vol. **42**, no. 4, pp. 563–573, 2007. DOI: 10.1007/s00348-007-0264-8
- Jung, D.S., McLinden, M., and Radermacher, R., Measurement Techniques for Horizontal Flow Boiling Heat Transfer with Pure and Mixed Refrigerants, *Exp. Heat Transf.*, vol. **2**, no. 3, pp. 237–255, 1989. DOI: 10.1080/08916158908946367

- Kandlikar, S.G., and Grande, W.J., Evolution of Microchannel Flow Passages – Thermohydraulic Performance and Fabrication Technology, *Heat Transf. Eng.*, vol. **24**, no. 1, pp. 3–17, 2003. DOI: 10.1080/01457630304040
- Kang, S.H., Design and Experimental Study of ORC (Organic Rankine Cycle) and Radial Turbine Using R245fa Working Fluid, *Energy*, vol. **41**, no. 1, pp. 514–524, 2012. DOI: 10.1016/j.energy.2012.02.035
- Kanizawa, F.T., Tibiriçá, C.B., and Ribatski, G., Heat Transfer during Convective Boiling inside Microchannels, *Int. J. Heat Mass Transf.*, vol. **93**, pp. 566–583, 2016. DOI: 10.1016/j.ijheatmasstransfer.2015.09.083
- Kattan, N., Thome, J.R., and Favrat, D., Flow Boiling in Horizontal Tubes: Part 3 – Development of a New Heat Transfer Model Based on Flow Pattern, *J. Heat Transf.*, vol. **120**, no. 1, pp. 156–165, 1998. DOI: 10.1115/1.2830039
- Kedzierski, M.A., Carr, M.A., and Brown, J.S., Measurement and Prediction of Vapor–Space Condensation of Refrigerants on Trapezoidal–Finned and Turbo-C Geometries, *J. Enhanc. Heat Transf.*, vol. **20**, no. 1, pp. 59–71, 2013.
- Kossolapov, A., Phillips, B., and Bucci, M., Experimental Investigation of Subcooled Flow Boiling and CHF at High Pressure Using High–Resolution Diagnostics, *NURETH–18, Proc. of 18th Int. Top. Meeting Nucl. Reactor Therm. Hydraul.*, Portland, Oregon, USA, pp. 307–318, 2019.
- Landelle, A., Tauveron, N., Haberschill, P., Revellin, R., and Colasson, S., Organic Rankine Cycle Design and Performance Comparison Based on Experimental Database, *Appl. Energy*, vol. **204**, pp. 1172–1187, 2017. DOI: 10.1016/j.apenergy.2017.04.012
- Liu, S., Dai, B., Zhang, W., and Li, X., Experimental Study on R245fa Condensation Heat Transfer Properties in Horizontal Tube, *Energy Procedia*, vol. **104**, pp. 419–424, 2016. DOI: 10.1016/j.egypro.2016.12.071

- Moran, H.R., Flow Boiling in Horizontal Pipes: Integral Measurements, Optical Diagnostics, and Numerical Simulations, PhD, Imperial College London, 2021.
- Moran, H.R., Zogg, D., Voulgaropoulos, V., Van den Bergh, W.J., Dirker, J., Meyer, J.P., Matar, O.K., and Markides, C.N., An Experimental Study of the Thermohydraulic Characteristics of Flow Boiling in Horizontal Pipes: Linking Spatiotemporally Resolved and Integral Measurements, *Appl. Therm. Eng.*, vol. **194**, pp. (117085)–17, 2021, DOI: 10.1016/j.applthermaleng.2021.117085
- Morgan, R.G., Ibarra, R., Zadrazil, I., Matar, O.K., Hewitt, G.F., and Markides, C.N., On the Role of Buoyancy–Driven Instabilities in Horizontal Liquid–Liquid Flow, *Int. J. Multiph. Flow*, vol. **89**, pp. 123–135, 2017. DOI: 10.1016/j.ijmultiphaseflow.2016.07.009
- Morgan, R.G., Markides, C.N., Zadrazil, I., and Hewitt, G.F., Characteristics of Horizontal Liquid–Liquid Flows in a Circular Pipe Using Simultaneous High–Speed Laser–Induced Fluorescence and Particle Velocimetry, *Int. J. Multiph. Flow*, vol. **49**, pp. 99–118, 2013. DOI: 10.1016/j.ijmultiphaseflow.2012.09.004
- Nasr, M., Akhavan–Behabadi, M.A., Momenifar, M.R., and Hanafizadeh, P., Heat Transfer Characteristic of R-600a during Flow Boiling inside Horizontal Plain Tube, *Int. Commun. Heat Mass Transf.*, vol. **66**, pp. 93–99, 2015. DOI: 10.1016/j.icheatmasstransfer.2015.05.024
- Nicklin, D.J., Wilkes, J.O., and Davidson, J.F., Two–Phase Flow in Vertical Tubes, *Trans. Inst. Chem. Eng.*, vol. **40**, no. 1, pp. 61–68, 1962.
- Pantaleo, A.M., Simpson, M., Rotolo, G., Distaso, E., Oyewunmi, O.A., Sapin, P., De Palma, P., and Markides, C.N., Thermoeconomic Optimisation of Small–Scale Organic Rankine Cycle Systems Based on Screw vs. Piston Expander Maps in Waste Heat Recovery Applications, *Energy Convers. Manage.*, vol. **200**, pp. (112053)–18, 2019. DOI: 10.1016/j.enconman.2019.112053

- Passos, J.C., Kuser, V.F., Haberschill, P., and Lallemand, M., Convective Boiling of R-407c inside Horizontal Microfin and Plain Tubes, *Exp. Therm. Fluid Sci.*, vol. **27**, no. 6, pp. 705–713, 2003. DOI: 10.1016/S0894-1777(02)00308-4
- Picchi, D., Manerba, Y., Correr, S., Margarone, M., and Poesio, P., Gas/Shear-Thinning Liquid Flows through Pipes: Modeling and Experiments, *Int. J. Multiph. Flow*, vol. **73**, pp. 217–226, 2015. DOI: 10.1016/j.ijmultiphaseflow.2015.03.005
- Pike-Wilson, E.A., and Karayiannis, T.G., Flow Boiling of R245fa in 1.1 mm Diameter Stainless Steel, Brass and Copper Tubes, *Exp. Therm. Fluid Sci.*, vol. **59**, pp. 166–183, 2014. DOI: 10.1016/j.expthermflusci.2014.02.024
- Pineda-Pérez, H., Kim, T., Pereyra, E., and Ratkovich, N., CFD Modeling of Air and Highly Viscous Liquid Two-Phase Slug Flow in Horizontal Pipes, *Chem. Eng. Res. Design*, vol. **136**, pp. 638–653, 2018. DOI: 10.1016/j.cherd.2018.06.023
- Ramos, A., Chatzopoulou, M.A., Freeman, J., and Markides, C.N., Optimisation of a High-Efficiency Solar-Driven Organic Rankine Cycle for Applications in the Built Environment, *Appl. Energy*, vol. **228**, pp. 755–765, 2018. DOI: 10.1016/j.apenergy.2018.06.059
- Schubring, D., Ashwood, A.C., Shedd, T.A., and Hurlburt, E.T., Planar Laser-Induced Fluorescence (PLIF) Measurements of Liquid Film Thickness in Annular Flow. Part I: Methods and Data, *Int. J. Multiph. Flow*, vol. **36**, no. 10, pp. 815–824, 2010. DOI: 10.1016/j.ijmultiphaseflow.2010.05.007
- Seitzman, J.M., Kychakoff, G., and Hanson, R.K., Instantaneous Temperature Field Measurements Using Planar Laser-Induced Fluorescence, *Opt. Lett.*, vol. **10**, no. 9, pp. 439–441, 1985. DOI: 10.1364/OL.10.000439
- Shin, J.Y., Kim, M.S., and Ro, S.T., Experimental Study on Forced Convective Boiling Heat Transfer of Pure Refrigerants and Refrigerant Mixtures in a Horizontal Tube, *Int. J. Refrig.*, vol. **20**, no. 4, pp. 267–275, 1997. DOI: 10.1016/S0140-7007(97)00004-2

- Su, G.Y., Wang, C., Zhang, L., Seong, J.H., Kommajosyula, R., Phillips, B., and Bucci, M., Investigation of Flow Boiling Heat Transfer and Boiling Crisis on a Rough Surface Using Infrared Thermometry, *Int. J. Heat Mass Transf.*, vol. **160**, pp. (120134)–14, 2020. DOI: 10.1016/j.ijheatmasstransfer.2020.120134
- Tibirićá, C.B., and Ribatski, G., Two-Phase Frictional Pressure Drop and Flow Boiling Heat Transfer for R245fa in a 2.32-mm Tube, *Heat Transf. Eng.*, vol. **32**, nos. 13–14, pp. 1139–1149, 2011. DOI: 10.1080/01457632.2011.562725
- Tropea, C., Yarin, A.L., and Foss, J.F., Eds., *Springer Handbook of Experimental Fluid Mechanics*, Springer-Verlag Berlin Heidelberg, 2007. DOI: 10.1007/978-3-540-30299-5
- Ursenbacher, T., Wojtan, L., and Thome, J.R., Interfacial Measurements in Stratified Types of Flow. Part I: New Optical Measurement Technique and Dry Angle Measurements, *Int. J. Multiph. Flow*, vol. **30**, no. 2, pp. 107–124, 2004. DOI: 10.1016/j.ijmultiphaseflow.2003.11.010
- Voulgaropoulos, V., Aguiar, G.M., Bucci, M., and Markides, C.N., Simultaneous Laser- and Infrared-Based Measurements of the Life Cycle of a Vapour Bubble during Pool Boiling, in *Advances in Heat Transfer and Thermal Engineering*, C. Wen and Y. Yan, Eds., Singapore: Springer Nature Singapore, pp. 169–173, 2021. DOI: 10.1007/978-981-33-4765-6_31
- Wojtan, L., Ursenbacher, T., and Thome, J.R., Investigation of Flow Boiling in Horizontal Tubes: Part I – A New Diabatic Two-Phase Flow Pattern Map, *Int. J. Heat Mass Transf.*, vol. **48**, no. 14, pp. 2955–2969, 2005a. DOI: 10.1016/j.ijheatmasstransfer.2004.12.012
- Wojtan, L., Ursenbacher, T., and Thome, J.R., Investigation of Flow Boiling in Horizontal Tubes: Part II – Development of a New Heat Transfer Model for Stratified-Wavy, Dryout and Mist Flow Regimes, *Int. J. Heat Mass Transf.*, vol. **48**, no. 14, pp. 2970–2985, 2005b. DOI: 10.1016/j.ijheatmasstransfer.2004.12.013

- Xu, K.-W., Zhang, Y., Liu, D., Azman, A.N., and Kim, H.-B., Slug Flow Development Study in a Horizontal Pipe Using Particle Image Velocimetry, *Int. J. Heat Mass Transf.*, vol. **162**, pp. (120267)–15, 2020. DOI: 10.1016/j.ijheatmasstransfer.2020.120267
- Zadrazil, I., and Markides, C.N., An Experimental Characterization of Liquid Films in Downwards Co-current Gas–Liquid Annular Flow by Particle Image and Tracking Velocimetry, *Int. J. Multiph. Flow*, vol. **67, Supplement**, pp. 42–53, 2014. DOI: 10.1016/j.ijmultiphaseflow.2014.08.007
- Zadrazil, I., Matar, O.K., and Markides, C.N., An Experimental Characterization of Downwards Gas–Liquid Annular Flow by Laser–Induced Fluorescence: Flow Regimes and Film Statistics, *Int. J. Multiph. Flow*, vol. **60**, pp. 87–102, 2014. DOI: 10.1016/j.ijmultiphaseflow.2013.11.008
- Zhang, L., Fan, L., Hua, M., Zhu, Z., Wu, Y., Yu, Z., Hu, Y., Fan, J., and Cen, K., An Indoor Experimental Investigation of the Thermal Performance of a TPLT–Based Natural Circulation Steam Generator as Applied to PTC Systems, *Appl. Therm. Eng.*, vol. **62**, no. 2, pp. 330–340, 2014. DOI: 10.1016/j.applthermaleng.2013.09.045