An experimental characterization of liquid films in downwards co-current gas–liquid annular flow by particle image and tracking velocimetry

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ABSTRACT

The hydrodynamics of downwards gas–liquid annular flows and falling films in a pipe were studied experimentally using simultaneous planar laser-induced fluorescence and a combination of particle image and particle tracking velocimetry techniques. The investigated conditions covered the range of liquid and gas Reynolds numbers: ReL = 306—1532 and ReG = 0—84600. The results presented in this paper concern: (i) information on the local and instantaneous velocity fields underneath the interfacial waves and the appearance of recirculation zones within the liquid films under certain conditions, and (ii) mean velocity, velocity fluctuation rms and kinetic energy profiles within the liquid films. The results indicate that large waves contain multiple recirculation zones, which may play an important role in the gas and liquid phase entrainment mechanisms as well as in the mass and momentum transfer from the near-wall region towards the gas–liquid interface.

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Introduction

Gas–liquid annular flow refers to an important multiphase flow regime where a liquid occupies the area around the circumference of a pipe and the gas is present in the pipe core. This flow regime can deliver high rates of heat and mass transport per unit volume, and therefore finds practical application in a broad range of industrial processes, such as in condensers, evaporators and reactors. Yet, these flows are highly complex, nonlinear and multiscale, which presents a major challenge to scientists and engineers who have been working to address fundamental questions that arise in these flows, while also remaining difficult to harness at a practical level and to predict effectively and reliably. A detailed understanding of the underlying phenomena that occur in annular flows is therefore important not only from a fundamental, but also from a practical point of view. In particular, downwards co-current annular flow, or simply, downwards annular flow, is an annular flow in which both the liquid film and the gas core are travelling in a vertical pipe in the direction of gravity. A special case of downwards annular flow is that of a liquid film falling under the forcing of gravity only, i.e. in the absence of gas shear. This case is referred as to a falling film. In this paper we present an experimental investigation of downwards annular flows, both with and without a gas flow in the pipe core region.

In general, liquid film flows of practical relevance are turbulent and, hence, are associated with the presence of broadband interfacial waves on the film surface. A thorough understanding of the characteristic profiles, scales and dynamics of these interfacial waves is of essential importance in making accurate and reliable predictions of heat and mass transfer rates (Mathie and Markides, 2013a; Mathie et al., 2013). Previous efforts in downwards annular flow have focused on the spatio/temporal measurement of liquid film thickness, followed by in-depth statistical analyses of this film thickness (Webb and Hewitt, 1975; Belt et al., 2010; Alekseenko et al., 2012; Zhao et al., 2013). These efforts have contributed to a much improved understanding of the interfacial topology observed in downwards annular flows and also to the subsequent proposal of a series of correlations for the quantification of the mean film thickness, wave amplitudes and liquid entrainment rates into the gas phase (Ambrosini et al., 1991; Karapantsios and Karabelas, 1995; Azzopardi, 1997). On the other hand, less has been published on the velocity distribution and the flow structure within the liquid films, underneath the film surface. This can be related to the relative difficulty of these measurements caused by: (i) the extremely restricted measurement space, due to
the small thickness of the liquid films (in the order of and often sub-mm), (ii) the highly disturbed and intermittent nature of the gas–liquid interface, (iii) the entrainment of gas inside the liquid film and of liquid into the gas core, and (iv) the relatively high velocities of both the gas and liquid phases.

Nevertheless, a few investigators have performed measurements and provided information on the instantaneous and mean velocity distributions within liquid films. Ho and Hummel (1970) used a photochromic dye tracing (PDT) technique to measure the velocity distributions within falling films \( \text{Re}_L = 0 \) at liquid Reynolds numbers \(^1\) of \( \text{Re}_L = 31–700 \). They found that the fully-developed mean velocity profiles inside the films were independent of the distance from the liquid inlet, and were a function of \( \text{Re}_L \) alone. The velocity profiles were found to be parabolic for all investigated conditions.

Ueda and Tanaka (1975) used hot-wire anemometry (HWA) to measure velocity and velocity fluctuation distributions within falling spindle oil films in an inclined rectangular channel. They observed some turbulence activity close to the gas–liquid interface, however, no eddy motions were detected in the vicinity of the wall. HWA allows high-temporal resolution, local information to be obtained, however, some questions arise concerning the use of this technique in multiphase flow measurements, due to the intermittent exposure of the hot-wire probe to the moving gas–liquid interface.

Mudawwar and Houpt (1993) investigated the effect of the large waves on the mass and momentum transfer in wavy-laminar falling films over the range \( \text{Re}_L = 52–104 \) using laser Doppler velocimetry (LDV). The large waves were observed to be sliding at high velocities over a continuous low-speed substrate, while carrying 40–70% of the total liquid flow-rate. An increase in the thickness of the film substrate (or, base film) led to a smaller discrepancy between the substrate and wave velocity profiles, resulting in a more uniform distribution of the liquid mass transfer between the waves and the substrate. The authors also reported that the axial velocity component was dominant and the radial velocities were smaller than 0.01 m/s.

More recently, Dietze et al. (2008) used a similar approach, featuring LDV, coupled with confocal chromatic imaging (CCI), in order to obtain simultaneous information on film thickness and velocity at selected locations underneath the waves in low-Re falling films \( \text{Re}_L = 15.6 \). The data was used to validate a numerical code, which was then used to demonstrate the existence of ‘backflow’ (flow in the opposite direction to gravity, in an absolute frame of reference) in the capillary-wave flow regions.

Karimi and Kawaji (2000) used a PDT technique to visualize with some detail the hydrodynamic structures of falling films and counter-current annular flows. Interestingly, this work indicated, based on the measurements of the instantaneous velocity profiles inside wavy falling films, that the local laminar or turbulent character of the liquid film depends on the local root mean square (rms) of the film thickness fluctuations (i.e. waviness or film roughness) and not the local \( \text{Re}_L \).

Dietze et al. (2009) and Dietze and Kneer (2011) also considered closely the velocity field underneath waves in annular flows with a combination of CCI, LDV and particle image velocimetry (PIV), providing unique insight into these flows and focusing specifically, and with high spatiotemporal detail, on the so-called ‘capillary separation eddy’ that arises in the capillary-wave region of the falling liquid flows. However, these efforts where limited to low-Re falling film flows, in the range \( \text{Re}_L = 8.6–15.0 \), with the absence of gas flow. The work also included complementary numerical simulations and brief extensions to a consideration of heat transfer in these flows. Strong variations in the heat transfer coefficient (HTC) and thus also the Nusselt number Nu were suggested, in alignment with the findings of previous investigators. The flow was observed to exhibit significant HTC enhancement at the localities of capillary film thickness minima. An experimental validation of these results, mainly suggested by numerical simulations and modelling efforts, has been provided in planar falling films by Schagen et al. (2006), who employed single-point luminescence-based measurements in very shallow (inclination angle of \( 2^\circ \)) film flows in the presence of gaseous (N\(_2\)) counterflow at a single heat flux setting with \( \text{Re}_L = 126 \) and \( \text{Re}_G = 200 \), and more recently by Mathie et al. (2013) and Mathie and Markides (2013b) in an open falling-film flow (with \( \text{Re}_L = 0 \)) over a heated foil inclined at an angle of 40° over a broader range of heat flux settings 0.1–4.2 W/cm\(^2\) and \( \text{Re}_G = 20–660 \), with two-dimensional measurements featuring the simultaneous use of planar laser-induced fluorescence (PLIF) and IR-thermography.

One of the most complex features of annular flow concerns the existence of so-called ‘disturbance waves’ that are observed at relatively high \( \text{Re}_L \). Brauner et al. (1987) predicted that interfacial stagnation points (in a coordinate system moving with the waves) that are accompanied by a circulating eddies within the waves, are formed above a certain ratio of wave height to substrate thickness. These large-scale circulating eddies or recirculation zones may play a crucial role in the governing mechanism for wall-to-interface mass and momentum transfer in wavy liquid films. Such a recirculating motion within large waves with significant velocities normal to the wall have been locally observed by Karimi and Kawaji (1999), by using a laser-induced PDT technique. Some attempts have also been made to predict these recirculation zones numerically, e.g. by Jayanti and Hewitt (1997).

In early work, local velocities in multiphase flows were characterized and measured by intrusive techniques, i.e. hot wire or film anemometry (Ueda and Tanaka, 1975). It was, however, noted that the local velocity measurements are sensitive to the disturbances caused by the presence of the probes, and their intermittent alternating exposure to the gas and liquid at the interface (Karimi and Kawaji, 1998; Karimi and Kawaji, 2000). Therefore, there has been a recent desire to move towards advanced, non-intrusive optical measurement methods, including PIV (Karimi and Kawaji, 2000), LDV (Yu et al., 2006), PLIF (Schubring et al., 2009) and particle tracking velocimetry (PTV) (Morgan et al., 2013). In addition, the laser-based techniques (LDV, PIV and PTV) can provide detailed spatial and/or temporal measurements of velocity fields in multiphase flows.

The present paper is a continuation of the experimental investigation of co-current gas–liquid downwards annular flow reported in Zadrazil et al. (2014). Contrary to this previous publication, where the topology of the gas–liquid interface was studied using a PLIF technique, the focus here is on the detailed velocity characterization of the flow within the liquid films. The results presented herein comprise spatially resolved (down to 22.4 μm) quantitative observations of liquid velocity in downwards annular flow and a subsequent analysis, based on a combination of PLIF, PIV and PTV techniques. To the best knowledge of the authors, this is the first instance of the application of this approach for the generation of simultaneous interfacial and velocity field information in downwards annular flows, with the presence of a gaseous core flow.

The paper is structured as follows. Firstly, the flow facility, which features a specifically designed test section, is briefly introduced, along with the laser measurement system (details can be found in Zadrazil et al., 2014). Following this, the data analysis methodology is described and the experimental results are then

\(^1\) Here, \( \text{Re}_L = \frac{\dot{U}_h \delta_{\text{th}}}{\nu_L} \) is based on the mean liquid film thickness and the bulk-mean film velocity, which in the absence of entrainment is also equal to that defined based on the Nusselt thickness \( \delta_{\text{th}} = (3q_L/\dot{G})^{1/3} \) and the Nusselt velocity \( \dot{U}_h = \frac{\dot{G} \delta_{\text{th}}}{3\nu_L} \), where subscript ‘L’ denotes the liquid phase and \( \dot{q} \) is the flow-rate per unit width.
presented and discussed. Specifically, the results contain our observations of recirculation zones, instantaneous and local velocity profiles within waves, as well as a statistical analysis that contains information on the profiles of the mean velocity and of the velocity fluctuations. The paper closes with the main conclusions that are derived from the present study.

**Experimental methods**

**Flow facility**

The experiments presented in the present paper were performed in the Downwards Annular Flow Laser Observation Facility (DAFLOF); see Fig. 1. This facility, along with the selected ranges of the investigated flow conditions, were described in detail in a previous publication (Zadrazil et al., 2014), but we repeat the main features here for completeness. The facility consists, essentially, of a 3 m long and 32.4 ± 0.4 mm ID vertically oriented fluorinated ethylene propylene (FEP) pipe. Prior to the experiments, the test section was aligned to the vertical position by using a line laser with a magnetically dumped pendulum (Stanley FatMax SLP5 5-Section) equiipped with a dedicated optical arrangement for producing light sheets with a divergence of 20° was used for flow illumination in a two-dimensional (2-D) plane. The thickness of the laser sheet at the measurement point was approximately 0.1 mm.

The flow was seeded with 10 μm mean-diameter, monodisperse (< 3%) and highly uniform in shape melamine resin particles doped with Rhodamine-B, or 2-[6-(diethylamino)-3-(diethylimino)-3H-xanthene-)yl] benzolic acid (LaVision GmbH, Göttingen, Germany), at a concentration of 0.06 g/L. The particles occupied no)-3H-xanthen-)-yl benzolic acid (LaVision GmbH, Göttingen, Germany), resulting in a pixel resolution of 22.4 pixel/m. During each measurement a set of 500 image pairs was taken at a frequency of 100 Hz. The time interval dt between successive individual images in each PIV image-pair was adjusted in order to achieve a maximum particle displacement of approximately 8–12 pixels from one image to the next (see Table 1). The laser measurement configuration was identical to that used in Zadrazil et al. (2014).

**Data processing**

The raw images were first processed in order to obtain liquid-phase information from the PLIF measurement (of the Rhodamine-B dye in the water). The procedure by which this was done is described in detail in Zadrazil et al. (2014), which explains how the raw images were first binarized based on a thresholding experimental arrangement and the data processing approach employed in our investigation. The laser-based measurements were performed at a location 2.35 m downstream of the liquid injector (i.e. 72D), by using a specially constructed visualization section. The visualization section comprised a short section (~ 0.5 m) of the vertical FEP pipe, enclosed in a Perspex box, which was filled with DI water in order to minimize distortions that arise in the line-of-sight of the measurement due to the curvature of the round tube test section. A double-pulsed frequency-doubled 532 nm Nd:YAG laser (Nano-L-50-100PV; Litron Lasers Ltd., Rugby, UK) equipped with a dedicated optical arrangement for producing light sheets with a divergence of 20° was used for flow illumination in a two-dimensional (2-D) plane. The thickness of the laser sheet at the measurement point was approximately 0.1 mm.

The investigated Re ranges for the liquid (i.e. water) and the gas (i.e. air) phases were: $Re_L = 306–1532$ and $Re_G = 0–84600$, respectively. It is noted that $Re_L = U_L / \langle \delta \rangle / \nu_L$ is defined in the present work based upon the bulk-mean film velocity $U_L$ and corresponding mean film thickness $\langle \delta \rangle$, such that it is four times smaller than that based on the superficial liquid conditions (velocity $U_{SL}$ and pipe diameter $D$). The investigated ranges of experimental conditions are shown in Table 1. Our minimum $Re_L$ flow conditions were selected specifically in order to prevent the possibility of occurrence of dry-out in the test section.

**Measurement technique**

In the present work, PIV and PTV measurements were employed for the velocity characterization of the downwards annular flows. The principles of these measurement techniques are well established in the literature (Willert and Gharib, 1991; Keane and Adrian, 1992) and the focus here will be merely to state the specific

![Fig. 1. Experimental apparatus employed in the present study; taken from Zadrazil et al. (2014).](image-url)
approach and then converted into black and white equivalents, and following this, how the liquid–gas interface was identified in each image with the use of a custom code, written in MATLAB. In addition, consecutive raw image-pairs were then evaluated using the PIV and PTV algorithms contained within the DaVis 7.2 software suite (LaVision GmbH). A typical example of: (i) a raw instantaneous image, (ii) the corresponding pre-processed image, (iii) the resulting instantaneous PIV velocity vector-map, and (iv) the corresponding instantaneous PTV velocity vector-map, is shown in Fig. 2. The raw image-pairs were first pre-processed by subtracting a moving threshold value that eliminated reflections at the solid surfaces and the low-intensity fluorescent light emitted by the liquid phase by the Rhodamine-B dye, and thus increased the signal-to-noise ratio of individual particles in the resulting image-pairs (i.e. the contrast between the particles and the background).

The pre-processed image-pairs (an example pre-processed image is shown in Fig. 2(b)) were then processed using a cross-correlation function that was applied to the images based on a multi-pass approach. During the first pass (i.e. the initial estimation of the velocity vectors) the PIV interrogation window was set to 64 × 64 pixels with 50% overlap of adjacent areas. Based on this window size, each interrogation window contained 7 particles on average. Keane and Adrian (1990), Keane and Adrian (1992) showed that the probability of valid displacement detection exceeds 95% for double-frame PIV when 5 particles are present within an interrogation window.

Furthermore, concerning the measurement of the lower velocities near the wall it is generally accepted that PIV has a dynamic range of 100—200, such that the lowest uncertainty and resolvable velocity amounts to about 0.5% of the maximum velocity (Adrian and Westerweel, 2010). In more detail, our uncertainty in the calculated pixel displacement is estimated at 0.04 pixels (8%) for a particle image shift of 0.5 pixels (corresponding to 280 ± 2 mm/s and 75 ± 6 mm/s for a dt of 40 and 150 μs, respectively). This uncertainty increases to approximately 0.01 pixels (10%) for a particle image shift of 0.1 pixels (corresponding to 56.0 ± 5.6 mm/s and 14.9 ± 1.5 mm/s for a dt of 40 and 150 μs, respectively). These estimates fall within the expected range of the uncertainty in the

| Q_L (×10^{-3} m^3/s) | Q_G (×10^{-3} m^3/s) | U_SL (×10^{-2} m/s) | U_SC (m/s) | Re_L (-) | Re_C (-) | Re_G (-) | dt (μs) |
|----------------------|----------------------|----------------------|------------|----------|----------|----------|---------|
| 2.8                  | 0.0                  | 3.4                  | 0.0        | 306      | 1224     | 0        | 100–150 |
| 5.6                  | 0.0                  | 6.7                  | 0.0        | 613      | 2452     | 0        | 100–150 |
| 8.4                  | 0.0                  | 10.1                 | 0.0        | 919      | 3676     | 0        | 100–150 |
| 11.1                 | 0.0                  | 13.5                 | 0.0        | 1226     | 4904     | 0        | 75–150  |
| 13.9                 | 0.0                  | 16.8                 | 0.0        | 1532     | 6128     | 0        | 75–100  |
| 2.8                  | 8.3                  | 3.4                  | 8.5        | 306      | 1224     | 21100    | 75–150  |
| 5.6                  | 8.3                  | 6.7                  | 8.5        | 613      | 2452     | 21100    | 75–150  |
| 8.4                  | 8.3                  | 10.1                 | 8.5        | 919      | 3676     | 21100    | 75–150  |
| 11.1                 | 8.3                  | 13.5                 | 8.5        | 1226     | 4904     | 21100    | 75–150  |
| 13.9                 | 8.3                  | 16.8                 | 8.5        | 1532     | 6128     | 21100    | 75–150  |
| 2.8                  | 16.7                 | 3.4                  | 17.0       | 306      | 1224     | 42300    | 75–100  |
| 8.4                  | 16.7                 | 10.1                 | 17.0       | 919      | 3676     | 42300    | 40–75   |
| 11.1                 | 16.7                 | 13.5                 | 17.0       | 1226     | 4904     | 42300    | 40–75   |
| 5.6                  | 33.3                 | 6.7                  | 34.0       | 613      | 2452     | 84600    | 40–75   |

Fig. 2. Examples of: (a) raw instantaneous image, (b) pre-processed image with indicated gas–liquid interface from the PLIF processing procedure (Zadrazil et al., 2014) and the wall position, (c) PIV velocity vector-map obtained from an image pair such as the one in (b), and (d) PTV velocity vector-map obtained from an image pair such as the one in (b).
particle displacement, which is typically less than 5–10% of the particle diameter (Prasad et al., 1992). For the second and third passes the PIV interrogation window was reduced to 16 x 16 pixels with 50% overlap, while employing the information from the PIV window displacement from the first pass that was retained.

The intermediate PIV velocity vector-maps, obtained from the initial two passes, were post-processed by: (i) a cross-correlation peak intensity filter whereby a vector was deleted if the ratio of the first to the second cross-correlation peak was < 1.4, (ii) a median filter where a vector was removed if the difference was > 1.4 x the average of the rms of the neighboring vectors; a vector was reinserted if the difference was < 1.9 x the average of the rms of the same vectors, (iii) groups containing less than 10 vectors were removed, (iv) empty spaces (i.e. regions containing no velocity information) were filled using an interpolation or extrapolation from the existing vectors, and (v) the velocity vector-map was subjected to 3 x 3 smoothing filter. The final PIV velocity vector-maps (i.e. the results of the final pass) were post-processed by: (i) an allowable vector range restriction (0 < u_x < 6 m/s and −0.4 < u_y < 0.4 m/s), (ii) a cross-correlation peak intensity filter where a vector was deleted if the ratio of first and second cross-correlation peak was < 1.1, (iii) a median filter where a vector was removed if a difference was > 1.4 x to the average of the rms of the neighboring vectors; a vector was reinserted if a difference was < 1.9 x to the average of the rms of the same vectors, and (iv) groups containing less than 10 vectors were removed.

An example of a resulting PIV velocity vector-map can be seen in Fig. 2(c), where the PIV vector-to-vector spatial resolution is 179 μm. Finally, based on the PIV results, a PTV algorithm was also employed in which individual particles were tracked within 8 x 8 pixels PTV interrogation windows. A particle size in the range 1–3 pixels was applied, allowed vector range of 0–6 m/s and −0.4 < u_y < 0.4 m/s, (ii) a cross-correlation peak intensity filter where a vector was deleted if the ratio of first and second cross-correlation peak was < 1.1., (iii) a median filter where a vector was removed if a difference was > 1.4 x to the average of the rms of the neighboring vectors; a vector was reinserted if a difference was < 1.9 x to the average of the rms of the same vectors, and (iv) groups containing less than 10 vectors were removed.

An example of a resulting PIV velocity vector-map can be seen in Fig. 2(c), where the PIV vector-to-vector spatial resolution is 179 μm. Finally, based on the PIV results, a PTV algorithm was also employed in which individual particles were tracked within 8 x 8 pixels PTV interrogation windows. A particle size in the range 1–3 pixels was applied, allowed vector range of ±2 pixels relative to the reference vector from PIV, as well as a minimum particle scattering intensity during the PTV calculation. Fig. 2(d) shows an example of the instantaneous PTV velocity vector-map that was generated from a single PIV image-pair.

The instantaneous velocity profiles within the waves (see Fig. 3(c)) were constructed from the instantaneous PIV velocity vector-maps described in the previous paragraphs (see Fig. 3(a)). The profiles were obtained by spatial averaging over ≤ 100 pixels (< 2.6 mm, or 7.8% of the image width) in the streamwise direction, which corresponds to a maximum of 12 vectors. The averaging was only performed in manually selected areas with a flat gas–liquid interface. The topology of the gas–liquid interface was obtained from the PLIF measurement as described previously and shown in Fig. 3(b).

Finally, for each given experimental run (i.e. set of independent flow conditions; see Table 1), the set of 500 instantaneous PTV velocity vector-maps were time-averaged. Spurious vectors (e.g. vectors having an amplitude significantly larger or those pointing in the opposite direction to their adjacent vectors) present in the time-averaged PTV velocity vector-maps were removed by: (i) an allowable vector range restriction and (ii) a median filter. The resulting processed time-averaged PTV velocity vector-maps were spatially averaged in the streamwise direction, yielding velocity profiles such as those shown in Fig. 6.

The downwards annular flows investigated in this experimental campaign were characterized in terms of the mean velocity profiles in the liquid films, the rms of the velocity fluctuations, the Reynolds stresses and the fluctuating velocity kinetic energy. The instantaneous 2-D local liquid flow speed is defined as:

\[ U(x, y, t) = \sqrt{u_x^2(x, y, t) + u_y^2(x, y, t)}, \]  

where \( u_x \) and \( u_y \) are the instantaneous axial and radial velocity components, respectively. The instantaneous temporal fluctuations of velocity \( u_x \) and \( u_y \) are defined from Reynolds decompositions:

\[ u_x(x, y, t) = \langle u_x \rangle (x, y) + u_x'(x, y, t), \]  
\[ u_y(x, y, t) = \langle u_y \rangle (x, y) + u_y'(x, y, t), \]

where \( \langle u_x \rangle \) and \( \langle u_y \rangle \) are the time-mean axial and radial velocities, respectively. The axial and radial velocity fluctuation rms are defined as:

\[ u_{x,\text{rms}} = \langle u_x'^2 \rangle^{1/2} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (u_{x,i} - \langle u_x \rangle)^2}, \]  
\[ u_{y,\text{rms}} = \langle u_y'^2 \rangle^{1/2} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (u_{y,i} - \langle u_y \rangle)^2}, \]

where \( n \) is the number of instantaneous velocity field images and \( u_{x,i} \) and \( u_{y,i} \) are the instantaneous axial and radial velocity components, respectively. In addition, the x–y Reynolds stress (RS) component is given by:

\[ \text{RS} = \langle u_x'u_y' \rangle = \frac{1}{n} \sum_{i=1}^{n} (u_{x,i} - \langle u_x \rangle)(u_{y,i} - \langle u_y \rangle). \]

Finally, the 2-D kinetic energy (KE) associated with temporal axial and radial velocity fluctuations in the liquid film flows is defined as:

\[ \text{KE} = \langle k_{xy} \rangle = \frac{1}{2} \left( u_{x,\text{rms}}^2 + u_{y,\text{rms}}^2 \right). \]

In this work all reported statistical velocity measures, including the mean and rms velocities, the Reynolds stresses and kinetic energies, were evaluated from at least 75000 velocity vectors.

Fig. 3. A series of images depicting the process of construction of instantaneous velocity profiles such as those shown in Fig. 5: (a) PIV velocity vector-map, (b) instantaneous velocity profiles superimposed on an instantaneous raw image with highlighted gas–liquid interface and the wall position, and (c) resulting instantaneous velocity profiles.
Results and discussion

Recirculation zones

Fig. 4 shows a series of instantaneous streamline patterns in a 2-D planar section through three liquid film flows for the conditions corresponding to falling films (with $Re_c = 0$) at $Re_c$ of: (a) 919, (b) 1226, and (c) 1532. In this figure, streamlines are shown in a reference frame moving with the translational interfacial velocity of the wave observed in each image $U_{wave}$, which are: (a) 1.61 m/s, (b) 1.51 m/s, and (c) 1.52 m/s, respectively. The gas-liquid interface, which was obtained from the low-intensity fluorescent light emitted by the Rhodamine-B dye as part of the PLIF part of our measurement, and the wall position are also shown.

The three cases shown depict the conditions of various local and instantaneous ratios of the wave peak to the substrate thickness $\delta_p/\delta_s$, specifically: (a) 2.0, (b) 3.2, and (c) 6.6. The total uncertainty in the measurements of local and instantaneous film thickness $\delta_i$ was $\pm 33.4 \mu m$ (see Zadrazil et al., 2014), and the worst-case uncertainty in the aforementioned $\delta_p/\delta_s$ ratios is 5.5%. Brauner et al. (1987) discussed the existence of interfacial stagnation points (in a moving coordinate system) that are accompanied by a circulating eddy within the wave (i.e. a recirculation zone). This occurs when the wave velocity is exceeded by the interfacial velocity at $\delta_p/\delta_s$ values higher than 2.5–3.0 (Brauner et al., 1987). Close inspection of a number of waves in the data generated in the present experimental work, such as those depicted in Fig. 4, validate this prediction. Indeed, the indicative results in Fig. 4 suggest that with increasing $\delta_p/\delta_s$ values the waves become more complex and begin to feature multiple recirculation zones and hence stagnation points.

The presence of multiple recirculation zones within a wave is not surprising, since as pointed out by Karimi and Kawaji (1999), the length scales of a given wave (i.e. wavelength $\lambda_w$) and the recirculation zones present within the wave, which are in the order of the local film thickness $\lambda_s$, are not equal $\lambda_{sw} \gg \lambda_s$. These multiple circulating eddies or recirculation zones may be crucial in the governing mechanism for wall-to-interface mass and momentum transfer in wavy liquid films. This would be in agreement with Alekseenko et al. (2009), who predicted that the presence of stagnation points is essential for the generation of ripples at the wake of the disturbance wave, and the liquid and gas entrainment at the wave crest. The present results could not, however, verify this assumption due to the low temporal resolution.

Instantaneous liquid velocity profiles

Even though downwards annular flows have been widely studied in the past, little has been done, and is known, concerning a possible correlation between the instantaneous velocity and the interfacial topology of the liquid films (i.e. between the instantaneous velocity profiles of the substrate and the interfacial waves features). Knowledge of the instantaneous liquid film velocity distribution based on information of the local liquid topology is important for the successful modelling and predictions of these flows. Karimi and Kawaji (2000) visualised the instantaneous local velocity profiles in a counter-current annular flow and found that the character of the film (laminar or turbulent) depends on the rms of the film thickness fluctuations (i.e. waviness or film roughness), rather than on the local $Re_c$ as commonly expected.

Fig. 5 shows instantaneous local velocity profiles within a sequence of waves for falling film flows (i.e. with $Re_c = 0$) at $Re_c = 306–1532$. The following observations can be made from Fig. 5: (i) the wave velocity is significantly larger than the velocity of the substrate (base) film, (ii) the velocity of a substrate film region located downstream of a wave is smaller when compared to the substrate upstream of the same wave, and (iii) some smaller-amplitude ripple waves that appear at the crests of disturbance waves have higher velocities than the disturbance waves themselves. This observation is important and has serious implications, since it is considered highly likely that these high-speed ripples are partially responsible for the phenomenon of liquid entrainment into the gas core (Azzopardi, 1997). Finally, (iv) the ripples at the back of the disturbance waves have a lower velocity than the substrate film located underneath the corresponding ripple.

Although a few representative combined film thickness and velocity field cases are shown in Fig. 5, it is important to note that the observations that arise from such figures, and any conclusions that emerge from these observations, are based on multiple film thickness and velocity profiles at varying distances from what can be considered a disturbance wave and over a large number of waves. Therefore, they are not sensitive, for instance, to how one defines the precise demarcation the wave and the substrate. The same applies to our stated observations and related conclusions from the typical waves and streamlines shown in Fig. 4, which form only a small selection of instances from which our conclusions concerning the appearance of recirculation zones and their possible link to the height of the disturbance waves relative to the substrate thickness are drawn.

Alekseenko et al. (2009) observed and described two types of ripple waves based on the point of their origin/generation. The authors reported that all ripples were generated on the backward slope of a disturbance wave, however, those that originated downstream (i.e. ahead) of a certain point were found to accelerate sharply and to travel faster than the velocity of the disturbance wave itself. It was assumed by Alekseenko et al. (2009) that these ripples are subsequently disrupted and entrained into the gas core. On the other hand, the authors suggested that ripples generated upstream (i.e. behind) of the point of separation decelerate gradually until they detach from the disturbance wave and become part of the substrate. The observations made here based on Fig. 5 are in

\[ \text{Fig. 4. Instantaneous streamlines for identified waves in falling films (Re}_c = 0) \text{ showing the recirculation zones within the waves. The stated wave peak-to-substrate film thickness ratios (}\delta_p/\delta_s\text{) are local and instantaneous values corresponding to the shown wave case. The flow conditions are: (a) Re}_c = 919, (b) Re}_c = 1226, \text{ and (c) Re}_c = 1532. \]
agreement with those made by Alekseenko et al. (2009). It is noted also that the point of separation is most probably identical to an upstream stagnation point of a corresponding recirculation zone of a given disturbance wave (see Fig. 4).

**Time-averaged liquid-phase velocity profiles**

Fig. 6 presents the main results obtained in the present experimental campaign: that of the mean (i.e., time-averaged) axial velocity profiles in the liquid films \((u_x)\) as a function of normalized distance from the wall \((y/R)\) over a range of both liquid and gas flow-rate (and thus, also, Reynolds number) conditions, and specifically \(Re_L = 306–1532\) and \(Re_G = 0–84,600\). In addition, we also indicate in this figure the corresponding mean film thickness \((\delta)\) and the thickness of the substrate or base film \((\delta_b)\) for each flow case, as reported previously in Zadrazil et al. (2014). The data here focuses on the axial velocity component since this is the dominant flow direction. This was confirmed by Yu et al. (2006), who reported that the axial velocity was dominant and the radial and wall-normal velocity components were more than an order of magnitude smaller.

In general, the time-averaged liquid-phase velocity inside the films increases with increasing flow rates in either phase, and hence both \(Re_L\) and \(Re_G\). The role of \(Re_G\) is as expected at zero (falling flows) or low \(Re_G\) whose simplified representation is Nusselt flow, while the effect of \(Re_L\) can be understood by considering that in these co-current flows the gas phase acts to impose a driving shear force on the liquid films in the flow direction.

Furthermore, the time-averaged liquid-phase velocity profiles are smooth and continuous; no abrupt change in the shapes of the velocity profiles can be observed at the threshold depth of the film substrate and the waves above it. Due to the viscosity of the liquid, the speed in the liquid flow at the vicinity of the wall approaches zero and gradually increases with increasing distance from the wall. Moreover, it is interesting to observe that the point of mean thickness \((\delta)\) appears to shift towards the steeper sloped part of the velocity profiles (with a higher gradient \(d(u_x)/dy\)) as \(Re_L\) increases.

Mudawwar and Houpt (1993) presented their velocity profile results differently. They multiplied the axial velocity by the residence time function and showed that the velocity increases from the wall to the approximate substrate thickness. Further away from the wall the velocity decreased, despite the presence of intermittent high velocity waves. In our case the velocity was considered as non-existent if no liquid was present at the interrogation window of interest, so in fact the profiles in Fig. 6 show the mean of local velocities conditional on the presence of liquid phase at that location.

In Fig. 7(a) and (b) the mean axial velocity profiles \((u_x)(y/R)\) in Fig. 6(a) and (b) are normalized by a bulk-mean film velocity defined as \(U_L = Q_L/A_F\), and in Fig. 7(c) and (d) the same profiles are normalized by a mean liquid film velocity \(U_{LF} = Q_{LF}/A_F\), respectively. Here, \(Q_L\) corresponds to the measured (by the flow meter) inlet liquid flow-rate introduced by the injector into the pipe, whereas \(Q_{LF}\) is a local measure of the mean liquid film flow-rate given by \(Q_{LF} = 2\pi \int_{0}^{\delta}(u_x(r)r)dr = \pi D \int_{0}^{\delta}(u_x(r))r dr\), where \(\delta\) is the mean film thickness as measured by PLIF (Zadrazil et al., 2014). It is important to note that in the absence of entrainment (but not otherwise) \(Q_L\) is the true mean flow-rate in the liquid films, while \(Q_{LF}\) is only an approximate measure of this flow-rate although it is, nevertheless, more robust to the occurrence of entrainment. Numerical experimentation with synthesized sinusoidal waves in the absence of any entrainment and a self-similar Nusselt profile in the liquid films readily shows that our measure of \(U_{LF}\) leads to a gradually increasing underestimation of the true \(U_L\) with increasing film roughness, i.e. wave amplitude over the mean film thickness. For steady films with no wave activity the two measures \((U_{LF} and U_L)\) coincide. With wave activity, a largest discrepancy of ~20% is found at the highest tested relative film roughness of 0.8 (Zadrazil et al., 2014). In both mean liquid velocity definitions, \(A_F\) is the liquid film mean area \(A_F = \pi (D(\delta) - (\delta)^2) \approx \pi D(\delta)\). The uncertainty of \(U_L\) and \(U_{LF}\) is in the range of 1.9–7.3% (with a mean, i.e. from all experimental conditions, uncertainty of 3.6%) and 0.6–4.7% (with a mean uncertainty of 2.0%), respectively.

Returning to Fig. 7, an inspection of each one of the two sets of dimensionless and normalized mean velocity profiles over a range of \(Re_L\) in either Fig. 7(a) for \(Re_G = 0\) or Fig. 7(b) for \(Re_G = 21,100\), and comparison with the corresponding dimensional profiles in Fig. 6(a) or (b), reveals that the normalization of the velocity profiles by \(U_L\) does not lead toward a collapse and actually results in a divergence of the profiles in both of the considered \(Re_G\) cases. This may be an indication of either of the following:

1. That a certain but different in each flow case fraction of the liquid phase has been entrained in the gas, such that the inlet flow-rate of liquid \(Q_L\) and the associated bulk velocity \(U_L\) are
not representative of the flow-rate and bulk flow speed in the liquid film at the location of the measurement of the mean profile which is shown in the figure.

2. That there is also a finite rate of entrainment of gas into the liquid film in the form of bubbles.

3. That the mean film thickness \( h_d \) on which the film area \( A_F \) is based is not a representative scaling length, for example due to the spatiotemporally varying character of the wave activity and the coupling between the local/instantaneous velocity field and film depth.

4. That transition from laminar to turbulent flow in the liquid films gives rise to different velocity profile shapes.

The presence of entrained liquid in the gas core in the form of droplets, often a significant amount thereof, or of gas in the liquid film in the form of bubbles (Webb and Hewitt, 1975; Zadrazil et al., 2014), are particularly important characteristics of annular flow. The fraction of the entrained liquid in the gas core is usually measured by various intrusive means (e.g., probes, etc.), either by direct sampling measurements in the gas or indirectly by measuring the liquid film flow-rate, at some point downstream the injector. This approach is a spatially averaged measurement of entrainment between the injector and the measurement location, and will yield different results compared to local measurements of entrainment. In the present work an approximate attempt can be made to infer indirectly the presence of liquid entrainment from the normalized mean velocity profiles in Fig. 7.

Specifically, whilst it is difficult to draw conclusions from the direct comparison of the results in Fig. 6(a) and (b) with those in Fig. 7(a) and (b), it is possible to compare results in Fig. 7(a) and (b) with ones in Fig. 7(c) and (d) since any one profile in these two figures will effectively differ only due to the difference between \( U_L \) and \( U_{LF} \), and thus \( Q_L \) and \( Q_{LF} \). One must bear in mind that differences between these two quantities may arise due to one or any possible combination of the four factors listed above. It is clearly the case from Fig. 7 that at low \( Re_L \) : \( U_L < U_{LF} \), whereas at high \( Re_L \) : \( U_L > U_{LF} \). Now, it is possible to suggest from Fig. 6(a) and (b) that even if there is a laminar to turbulent transition inside the range of investigated \( Re_L \), this does not appear to affect strongly the shape of the mean velocity profiles. Furthermore, if one neglects the effect of gas entrainment, which is known from Zadrazil et al. (2014) only to occur with any regularity in the disturbance wave regime flows that are associated with the very highest values of \( Re_L \) in both \( Re_G \) cases, the two remaining factors that can be used to explain any difference between a normalized profile as this appears in Fig. 7(a) and (b) with the same profile as it appears in Fig. 7(c) and (d) are: (i) liquid entrainment leading to a discrepancy between \( U_L \) and \( U_{LF} \) that is greater as the degree of entrainment increases; and (ii) the spatiotemporally varying nature of the film thickness leading to a discrepancy between \( U_L \) and \( U_{LF} \) due to the approximate nature of the latter, which is also expected to increase at progressively higher levels of wave roughness and intermittency. The effect of the appearance of entrainment would therefore be to shift a profile upwards in Fig. 7(c).
and (d) relative to Fig. 7(a) and (b), since the inlet $Q_L$ is an incorrect overestimate of the local $Q_{LF}$. This is indeed observed at the higher $Re_L$ flows in Fig. 7. Conversely, assuming an absence of entrainment and at higher wave roughnesses, one would expect an increase in any overestimation of the true flow-rate ($Q_L$) by the local estimate $Q_{LF}$, in turn shifting a profile downwards in Fig. 7(c) and (d) relative to Fig. 7(a) and (b). Again, this is observed at the lower $Re_L$ flows in Fig. 7 (and in particular for the dual-wave regime flows: black data in Fig. 7(a), black and blue^2 data in Fig. 7(b); see Zadrazil et al. (2014)).

Although it is possible to use the two flow-rate/velocity measures ($U_L$ and $U_{LF}$), with caution, in an attempt to explain to some extent the trends in Fig. 7 with respect to important flow processes and, in particular, to discuss the qualitative effect of entrainment on the collapse or lack thereof in these figures, it is not possible to use these velocity measures and the data in the figures to quantify entrainment. Hence, our inferences at this stage concerning entrainment be acting in the higher $Re_L$ flows, and specifically for $Re_L > 600$ in our investigated conditions ($Re_G < 21,100$).

In summary, it is found that a partial collapse of the mean axial velocity profiles ($U_L$) can be achieved after normalizing by the mean liquid film velocity $U_{LF}$, as is done in Fig. 7(c) and (d). The dimensionless profiles that are formed after normalizing by $U_{LF}$ are within ±10% of each other for the falling films and ±20% for the low gas-shear cases, respectively. Although this velocity parameter is an imperfect measure of the true local mean flow-rate at the measurement location where the profiles were generated, it does to a certain extent account for liquid entrainment, since it only considers the flow inside the liquid film at the location of the velocity profile measurement, as well as the intermittently varying nature of the film thickness, at least in as much as this determines the local mean velocity profile. Therefore, one would expect that the resulting normalized velocity profiles in Fig. 7(c) and (d) would be somewhat less sensitive to varying degrees of liquid entrainment and variations in film thickness. Still, the normalized mean axial velocity profiles retain some degree of scatter and do not collapse entirely onto a unique profile. This indicates that not all relevant processes are correctly and/or entirely accounted for by $U_{LF}$.

Given that these processes, which include liquid and gas entrainment, spatiotemporal film thickness variations and their coupling to the underlying velocity field in the liquid phase, and the laminar/turbulent character of the flow, are expected to play a role in affecting the liquid film flow profiles, our results indicate that further considerations are necessary before a more representative liquid-phase velocity profile can be proposed. This observation, which has been made possible by the generation of the velocity data presented in this paper, suggests that further measurements and/simulations and subsequent analysis are necessary of the liquid-phase velocity in such flows if we are to reach a point where we are confident in prescribing a shape for the velocity profile and

Fig. 7. Mean axial velocity ($U_L$) profiles for gas Reynolds numbers: (a) and (c) $Re_G = 0$ (falling films), (b) and (d) $Re_G = 21,100$, normalized by the bulk-mean film velocity (a and b), and the mean liquid film velocity (c and d).

^2 For interpretation of color in 'Fig. 7', the reader is referred to the web version of this article.
are aware of the uncertainties and deviations related with this approach, for example in reduced models for such multiphase flows. At the same time, it may be that such a reduction is not possible within a reasonable certainty.

**Liquid-phase velocity fluctuations**

The rms of the velocity fluctuations in the axial and radial directions, $u_{x,\text{rms}}$ and $u_{y,\text{rms}}$, are shown in Fig. 8(a, b) and (c, d), respectively, as a function of the normalized distance from the wall $y/R$, for various $Re_L$ and at two values of $Re_G$ ($=0$ and 21 100). The rms profiles of the axial velocity fluctuations $u_{x,\text{rms}}$ increase sharply in the immediate vicinity of the wall, reach a peak ($\approx 0.25-0.35 \text{ m/s}$ for $Re_G = 0$ and $\approx 0.3-0.4 \text{ m/s}$ for $Re_G = 21100$) and then decrease again further away from the wall. In the highly intermittent wave region $y/R \gtrsim 0.1$ where mainly high-amplitude, infrequent disturbance waves are found (not evident here), the axial velocity fluctuations show a gradual increase in intensity, however, the data are noisy and large scatter is observed. The equivalent rms profiles of the radial velocity fluctuations $u_{y,\text{rms}}$ also exhibit high values in the near-wall region. At progressively larger distances away from the wall, the radial velocity fluctuations first drop over a short distance and reach a minimum value ($\approx 0.03-0.5 \text{ m/s}$ at $y/R = 0.005-0.01$), after which they increase again monotonically. Similarly to the axial velocity fluctuations, the profiles show significant scatter near the free-surface, however, at this point they attain their largest values.

The corresponding Reynolds stresses (RS), as is defined in Eq. (6), were also considered as a function of the same normalized distance from the wall ($y/R$) for various $Re_L$ at constant $Re_G = 0$ and $Re_G = 21100$ (though not shown here). Generally, it was found that the RS values in the liquid films were small; being zero at the wall, decreasing to slightly negative values (reaching values of $\approx -0.002 \text{ m}^2/\text{s}^2$ at $Re_G = 0$ and $\approx -0.003 \text{ m}^2/\text{s}^2$ at $Re_G = 21100$ at the film heights associated with the mean film thicknesses) and then increasing very gradually towards zero again at increasingly larger distances where large scatter was observed, as with the axial and radial velocity rms $u_{x,\text{rms}}$ and $u_{y,\text{rms}}$. Unlike with the rms measures, however, the scatter was of the order of the average measured RS values.

Finally, Fig. 9(a) and (b) shows the kinetic energy (KE) associated with the unsteadiness (i.e. temporal fluctuations around the time-mean) of the liquid flow, evaluated based on the two known velocity components from the 2-D measurement, as a function of normalized distance from the wall, $y/R$. The KE is defined in Eq. (7) and, as such, is the sum of the squares of the corresponding axial and radial rms results shown in Fig. 8. In addition, and along the lines of what was attempted for the mean velocity profiles in Section ‘Time-averaged liquid-phase velocity profiles’, Fig. 9(c, d) and (e, f) depict dimensionless measures of the KE, normalized by $U_{LF}$ and the local $(u_x(y/R))$, respectively.

Similarly to the axial and radial velocity rms $u_{x,\text{rms}}$ and $u_{y,\text{rms}}$ in Fig. 8, the KE increases in the vicinity of the wall and reaches a maximum. The KE value at the peak, amounting to about...
0.1—0.15 $m^2/s^2$, increases and approaches the wall with increasing $Re_L$. Farther away from the wall the KE deceases and reaches a plateau of about half of its maximum value. The KE profiles, especially further away from the wall, are not strongly dependent on $Re_L$. On the other hand, the KE is clearly higher in the higher $Re_G$ flow.

Importantly, when normalized by the local (axial) flow speed $u_x$ (see Fig. 9)) and not the bulk flow speed $U_{LF}$ (see Fig. 9(c) and (d)), the profiles collapse approximately onto a common shape, although they retain some distinction; at increasingly higher values of $Re_L$, the profiles appear to shift to shorter distances $y/R$, which may scale with the film thickness $h_f$. At longer distances from the wall, $y/R \geq 1$ the KE amounts to approximately 2–3% of the square of the local flow speed, such that the intensity in the fluctuations (square root of the KE) amounts to $\approx 15\%$.

Fig. 9. Kinetic energy in the liquid velocity fluctuations $KE$ for gas Reynolds numbers: (a) $Re_G = 0$ (falling films) and (b) $Re_G = 21100$. (c and d) KE results in (a) and (b) normalized by the mean liquid film velocity $U_{LF} = Q_{LF}/A_F$. (e and f) KE results in (a) and (b) normalized by the local (axial) flow speed $u_x$. The mean film thickness $h_f$ and the mean substrate thickness $h_s$ are also indicated (taken from Zadrazil et al. (2014)) on the mean axial velocity profiles as hollow and full large corresponding symbols, respectively.
Conclusions

Non-intrusive optical diagnostic techniques, namely PLIF and PIV/PTV, were used simultaneously for both the qualitative and quantitative characterization of downwards co-current gas–liquid annular flows. The measurements revealed the presence of recirculation zones within a wave front of disturbance waves. These recirculation zones were observed for local and instantaneous wave peak to substrate thickness ratios greater than 3. Together with the fast moving ripples on the crest of disturbance waves, identified from instantaneous velocity profiles, the zones might be crucial for the mechanism of liquid entrainment into the gas phase. Information is also made available on the mean axial velocity profiles, axial and radial velocity rms profiles, Reynolds stress and kinetic energy profiles in the liquid films over a range of liquid Reynolds number conditions, at zero (falling films) and low gas Reynolds numbers. Dimensionless profiles that were formed after normalizing by a measure of mean velocity based on an approximate estimate of the local time-mean liquid flow-rate and the local mean film thickness were within ±10% of each other for the falling films and ±20% for the low gas-shear flow case, respectively. Such experimental data are crucial for the successful modelling of these gas–liquid flows and reliable predictions thereof. The exploitation of the instantaneous and local velocity profiles, together with the gas–liquid topology, will be part of a follow-up publication that will focus on the measurement of liquid entrainment using the described experimental techniques in the present paper and in Zadrazil et al. (2014).

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References

Alekseenko, S., Cherdantsev, A., Cherdantsev, M., Isaenko, S., Kharlamov, S., Markovich, D., 2012. Application of a high-speed laser-induced fluorescence technique for studying the three-dimensional structure of annular gas–liquid flow. Exp. Fluids 53, 77–89.
Alekseenko, S., Antipin, V., Cherdantsev, A., Kharlamov, S., Markovich, D., 2009. Two-wave structure of liquid film and wave-interrelation in annular gas–liquid flow with and without entrainment. Phys. Fluids 21, 061701/1–061701/4.
Ambrosini, W., Andreussi, P., Azzopardi, B.J., 1991. A physical based correlation for drop size in annular flow. Int. J. Multiph. Flow 17, 497–507.
Azzopardi, B.J., 1997. Drops in annular two-phase flow. Int. J. Multiph. Flow 23, 1–53.
Belt, R.J., Van’t Westende, J.M.C., Prasser, H.M., Portela, L.M., 2010. Time and spatially resolved measurements of interfacial waves in vertical annular flow. Int. J. Multiph. Flow 36, 570–587.
Brauner, N., Maron, D.M., Toovey, I., 1987. Characterization of the interfacial velocity wavy thin film flow. Int. Comm. Heat Mass Transf. 14, 293–302.
Schagen, A., Modigliani, M., Dietze, G., Kneer, R., 2006. Simultaneous measurement of local film thickness and temperature distribution in wavy liquid films using a luminescence technique. Int. J. Heat Mass Transf. 49, 5049–5051.
Dietze, G.F., Lefkken, A., Kneer, R., 2008. Investigation of the backflow phenomenon in falling liquid films. J. Fluid Mech. 595, 435–459.
Dietze, G.F., Al-Sibai, F., Kneer, R., 2009. Experimental study of flow separation in laminar falling liquid films. J. Fluid Mech. 637, 73–104.
Dietze, G.F., Kneer, R., 2011. Flow separation in falling liquid films. Front. Heat Mass Transf. 2, 033001–033014.
Ho, F.C.K., Hummel, R.L., 1970. Average velocity distributions within falling liquid films. Chem. Eng. Sci. 25, 1225–1237.
Jayanti, S., Hewitt, G.F., 1997. Hydrodynamics and heat transfer of wavy thin film flow. Int. J. Heat Mass Transf. 40, 179–190.
Karapantzos, T.D., Karabelas, A.J., 1995. Longitudinal characteristics of wavy falling films. Int. J. Multiph. Flow 21, 119–127.
Karimi, G., Kawaji, M., 1998. An experimental study of freely falling film in a vertical tube. Chem. Eng. Sci. 53, 3501–3512.
Karimi, G., Kawaji, M., 1999. Flow characteristics and circulatory motion in wavy falling films with and without counter-current gas flow. Int. J. Multiph. Flow 25, 1305–1319.
Karimi, G., Kawaji, M., 2000. Flooding in vertical counter-current annular flow. Nucl. Eng. Des. 200, 95–105.
Keane, R.D., Adrian, R.J., 1990. Optimization of particle image velocimeters. Part I: Double pulsed systems. Meas. Sci. Technol. 1, 1202–1215.
Keane, R.D., Adrian, R.J., 1992. Theory of cross-correlation analysis of PIV images. Appl. Sci. Res. 45, 191–215.
Adrian, R.J., Westerweel, J., 2010. Particle Image Velocimetry. Cambridge Univ. Press, p. 724.
Prasad, A.K., Adrian, R.J., Landreth, C.C., Oliff, P.W., 1992. Effect of resolution on the speed and accuracy of particle image velocimetry interrogation. Exp. Fluids 13, 105–116.
Mathie, R., Markides, C.N., 2013a. Heat transfer augmentation in unsteady conjugate thermal systems – Part I: Semi-analytical 1–D framework. Int. J. Heat Mass Transf. 56, 802–818.
Mathie, R., Markides, C.N., 2013b. Part II: An experimental study of conjugate heat transfer in thin liquid–film flows over an inclined heated foil. In: Proceedings of the 8th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Lisboa, Portugal.
Mathie, R., Nakamura, H., Markides, C.N., 2013. Heat transfer augmentation in unsteady conjugate thermal systems – Part II: Applications. Int. J. Heat Mass Transf. 56, 819–833.
Morgan, R.G., Markides, C.N., Zadrazil, I., Hewitt, G.F., 2013. Characteristics of horizontal liquid–liquid flows in a circular pipe using simultaneous high-speed laser-induced fluorescence and particle velocimetry. Int. J. Multiph. Flow 49, 99–118.
Mudawar, I., Houpf, R.A., 1993. Measurement of mass and momentum transport in wavy-laminar falling liquid films. Int. J. Heat Mass Transf. 36, 4151–4162.
Schubring, D., Foster, R.E., Rodriguez, D.J., Shedd, T.A., 2009. Two-zone analysis of wavy two-phase flow using micro-particle image velocimetry (micro-PIV). Meas. Sci. Technol. 20, 1–11.
Ueda, T., Tanaka, H., 1975. Measurements of temperature, velocity and velocity fluctuation distributions in falling liquid films. Int. J. Multiph. Flow 2, 261–272.
Webb, D.R., Hewitt, G.F., 1975. Downwards co-current annular flow. Int. J. Multiph. Flow 2, 35–49.
Willert, C.E., Gharib, M., 1991. Digital particle image velocimetry. Exp. Fluids 10, 181–193.
Yu, L.M., Zeng, A.W., Yu, K.T., 2006. Effect of interfacial velocity fluctuations on the enhancement of the mass-transfer process in falling film flow. Ind. Eng. Chem. Res. 45, 1201–1210.
Zadrazil, I., Matar, O.K., Markides, C.N., 2014. An experimental characterization of downwards gas–liquid annular flow by laser-induced fluorescence: flow regimes and film statistics. Int. J. Multiph. Flow 60, 87–102.
Zhao, Y., Markides, C.N., Matar, O.K., Hewitt, G.F., 2013. Disturbance wave development in two-phase gas–liquid upwards vertical annular flow. Int. J. Multiph. Flow 53, 111–129.