NRC Publications Archive Archives des publications du CNRC

Curvature induced flow pattern transitions in serpentine mini-channels Donaldson, A. A.; Kirpalani, D. M.; Macchi, A.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.ijmultiphaseflow.2010.10.003>

International Journal of Multiphase Flow, 37, pp. 429-439, 2010-10-11

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=e29e0d21-ca0f-4809-b052-fcba45c8cb38>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=e29e0d21-ca0f-4809-b052-fcba45c8cb38>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Curvature induced flow pattern transitions in serpentine mini-channels

A.A. Donaldson^{a,b}, D.M. Kirpalani^{b,*}, A. Macchi^a

^aDept. of Chemical and Biological Engineering, University of Ottawa, 161 Louis Pasteur Street, Ottawa, Ontario, Canada K1N 6N5

^bInstitute for Chemical Process and Environmental Technology, National Research Council Canada, M-12, 1200 Montreal Road, Ottawa, Ontario, Canada K1A 0R6

ARTICLE INFO

Article history:

Received 30 April 2010

Received in revised form 8 October 2010

Accepted 11 October 2010

Keywords:

Serpentine channel

Two-phase flow

Curvature effects

ABSTRACT

Experimental investigation of the phase interactions in two-phase mini-channel serpentine systems is performed with a focus on determining the effect of radius of curvature of the serpentine on two-phase flow pattern transitions. The initial formation of two-phase flow patterns in T-junction contactors and the resulting effect on the flow through serpentine geometries are studied to predict the initiation of bubble breakup and/or coalescence in planar serpentine arrangements. Bubble breakup maps are developed for each of the serpentine geometries, identifying curvature-induced shifts in the transitions between flow patterns.

Single-phase dimensionless analysis for curved geometries is extended to two-phase flow to identify the geometric dependence of critical bubble breakup. Further analysis performed shows that the characteristic length for curved geometries encountered in the Dean number for single-phase flow is suitable for capturing the effects of curvature on the initiation of bubble breakup. The dependence of Weber number on the characteristic length is reported and a critical $We_{CDL} = 10$ is identified for predicting bubble breakup inception in the serpentine system.

© 2011 Published by Elsevier Ltd.

1. Introduction

The flow patterns generated by gas–liquid distributors for mini-scale contactors and reactor systems (diameter, $d \sim 1$ mm) have been investigated extensively in the past for a variety of cross-sectional geometrical shapes and lengths (Suo and Griffith, 1964; Barnea et al., 1983; Damianides and Westwater, 1988; Barajas and Panton, 1993; Fukano and Kariyasaki, 1993; Mishima et al., 1995; Mishima and Hibiki, 1996; Triplett et al., 1999a; Coleman and Garimella, 1999; Shekariz, 2000; Yang and Shieh, 2001; Zhao and Bi, 2001; Akbar et al., 2003). While conducted with model fluids, air and water, these studies are often extended to process fluids for engineering applications. Fundamental studies of this nature usually produce two-phase flow regime maps and semi-analytically determined regime transitions, providing insight into the hydraulic behaviour and heat and mass transfer properties of two-phase mixtures flowing through a straight channel (Triplett et al., 1999b; Kawahara et al., 2002; Angeli and Gavrilidis, 2008; Niu et al., 2009). Limited information is available in literature regarding the impact of complex downstream flow configurations on the flow patterns formed initially. With the continued development of new applications for process flow systems at this scale, the

incorporation of downstream phase contactors that enhance heat and mass transfer is inevitable.

Planar serpentine mixing arrangements are found in many industrial applications involving mini-channels; including compact heat exchangers, turbines, mini/micro reactors and fuel cells (Martin et al., 2005; Xiong and Chung, 2007; Huh et al., 2007). Noted for their ability to enhance heat transfer and radial mixing in single-phase flow through the formation Dean vortices, serpentine geometries are frequently used to increase the reaction time within a given geometric footprint by connecting long mini-channels with alternating U-shaped return bends. While previous studies have characterized the variation in flow patterns resulting from a single return bend (Wang et al., 2003, 2004, 2005; Kirpalani et al., 2008), a detailed analysis of the two-phase flow patterns developed in multiple mini-channel serpentine unit cells in series has yet to be reported in published literature.

In this work, air–water flow was examined in a serpentine system. Bubbly, plug, unstable plug and slug flow patterns were generated by a cross-flow T-junction and introduced into planar serpentine arrangements to study the impact of radius of curvature on flow pattern transitions and the initiation of bubble interactions such as inception, growth, breakup and coalescence. The objectives of this study were to: (a) determine the effects of the serpentine geometry on the two-phase flow pattern generated by a cross-flow T-junction, with a focus on the shift in flow pattern transitions between bubbly, plug, unstable plug and slug flow; (b) identify the mechanisms leading to bubble breakup, grouping and coales-

* Corresponding author. Tel.: +1 613 991 6958; fax: +1 613 991 2384.

E-mail address: Deepak.kirpalani@nrc-cnrc.gc.ca (D.M. Kirpalani).

¹ NRCC No: 5284.

cence before and within the serpentine geometry; and (c) extend single-phase dimensionless analysis for curved geometries to multi-phase flow for the purpose of identifying the geometric dependence of critical conditions necessary for bubble breakup to occur.

2. Experimental configuration

Two geometries were manufactured from cast acrylic to allow for visual observation of the flow patterns before, within, and after a series of serpentine unit cells. Semi-circular grooves were CNC-machined into two 9.5 mm. thick acrylic plates to create mirror patterns that formed the serpentine geometry when bonded together using dichloromethane (solvent). The flow path of the serpentine system consists of a cross-flow T-junction contactor for blending the two phases followed by a 47.5 mm straight channel where the gas–liquid flow pattern is further developed. The straight channel leads to a series of serpentine unit cells with a radius of curvature, r_c , of 3 mm or 6 mm. Exit flow effects from the geometry were reduced by adding a 47.5 mm straight channel after the last semi-circular curve of the serpentine. At the exit, an additional T-junction was fabricated for monitoring the outlet pressure. CNC-machining of the acrylic plates introduced the optimum groove depth variation expected. A dimensioned schematic of the $r_c = 3$ mm serpentine geometry is provided in Fig. 1.

The experimental setup, shown in Fig. 2, illustrates the operation of the serpentine mini-channel for air–water mixtures. The gas (dry air) was supplied from a cylinder through a pressure reducing valve (PRV) and a needle valve used to regulate flow. The gas flow rate at STP was measured using an electronic mass flow meter (Omega FMA-1812). Pressure was measured at the gas inlet and channel outlet using a water manometer at low flow rates (0–11 kPa, 0–1.6 psig), and a pressure transducer at high flow rates (PSI-Tronix 68920–30, 0–30 psig). Deionized water was introduced using a magnetically driven low flow rate gear pump (Micropump Series 200 P35, 1.17 mL/rev, 4.2 bar max ∇P) regulated using an electronic mass flow controller (Omega FLV-4619A). The liquid temperature was

also monitored at the mass flow controller to determine the liquid viscosity at each operating condition.

The two-phase flow patterns were photographed at the inlet and within the serpentine region of each geometry using a high-speed CMOS camera (Nanosense MKIII) and custom-built pulsed-LED backlighting module synchronized with the frame rate of the camera for visualization without raising the temperature of the process fluids. The system allowed for full-resolution image recording (1280×1024 pixels) at frame rates up to 2000 Hz, with higher frame rates achieved at reduced resolutions. A constant exposure of 20 μ s was used for all captured images. The equivalent pixel size was determined prior to each experiment with typical values on the order of 18 μ m/pixel.

3. Inlet bubble size distribution and flow pattern map

An analysis of the effects of the serpentine passive mixing arrangement on two-phase air–water flow patterns was necessarily precluded by the characterization of flow patterns and bubble size distributions generated by the upstream T-junction contactor. Visual identification of these flow patterns can be highly subjective, leading to multiple classifications for similar flow regimes and the definition of flow pattern transitions as a range of operating conditions (as opposed to well defined sharp boundaries). Of significant interest in this study was the bubbly to plug flow transition, which can be difficult to determine visually due to the capillary-number dependence of the thickness of the liquid film surrounding a fully developed plug. The inlet bubble size distribution was thus used as a measurable parameter for defining a sharp boundary between these two flow patterns.

The bubble length and velocity and trailing slug length were measured in both geometries for liquid and gas flow rates ranging from 10 to 100 cm^3/min and 10 to 180 cm^3/min at standard conditions, respectively. Ten thousand images were collected at each operating condition, at a frame rate sufficient to capture a minimum of 10 instances of the same bubble as it traveled along the region 25–47 diameters downstream of the T-Junction. The

Fig. 1. Schematic of geometry with $r_c = 3$ mm and 3.5 repeating serpentine unit cells.

Fig. 2. Experimental configuration.

location, projected area and length of each bubble within an image were measured using ImageJ® software, from which number-based distributions and arithmetic averages of the bubble length, velocity and trailing liquid slug length were determined. Typical results are provided in Fig. 3 for a liquid and gas flow rate of 63 cm³/min and 40 cm³/min STP, respectively.

3.1. Inlet bubble size distribution

Scaling laws for droplet and bubble formation in T-junctions are reported in existing literature for a range of operating conditions and channel dimensions (Laborie et al., 1999; Thorsen et al., 2001; Nisisako et al., 2002; Tice et al., 2003; Cristini and Tan, 2004; Garstecki et al., 2006; Xu et al., 2006a,b,c; Qian and Lawal, 2006; Menech et al., 2008; Xu et al., 2008). In a recent review by Xu et al. (2008), three regimes of bubble and plug formation were identified for square micro-channels (200 μm), where the transition between the mechanism responsible for breakup was

dependent on the capillary number for the continuous phase, $Ca_C = \mu_C U_C / \sigma$ (Garstecki et al., 2006; Menech et al., 2008).

$$\frac{L_b}{d} \approx A / Ca_C \quad \text{for } Ca_C > 0.01 \quad (1)$$

$$\frac{L_b}{d} \approx k Ca_{D,\mu_C}^\alpha Ca_C^{\beta-\alpha} \quad \text{for } 0.002 < Ca_C < 0.01 \quad (2)$$

$$\frac{L_b}{d} \approx \varepsilon + \omega (Ca_{D,\mu_C} / Ca_C) \quad \text{for } 10^{-4} < Ca_C < 0.002 \quad (3)$$

In these expressions, the bubble length, L_b , channel width, d , and modified dispersed phase capillary number determined using the continuous phase viscosity, $Ca_{D,\mu_C} = \mu_C U_D / \sigma$, are critical in the determination of the bubble lengths. When shear forces are dominant ($Ca_C > 0.01$), Xu et al. (2008) proposed a value of $A = dh / (dh - 0.785 L_b^2)$ for a rectangular channel, where h is the channel height. An equivalent expression can be derived for a circular channel, wherein $A = d^2 / (d^2 - L_b^2)$. When interfacial forces

Fig. 3. Image analysis results for $U_L = 63$ cm³/min and $U_G = 40$ cm³/min STP. Background correction was applied to raw images (top), and the results (middle) analyzed for individual particle identification (bottom). The population distributions for bubble length (left), bubble velocity (middle) and liquid slug length (right) were then obtained via particle tracking analysis.

are dominant ($Ca_C < 0.002$), ε and ω have ranged in magnitude from 1 and $\omega = 1$ for Garstecki et al. (2006), $\varepsilon = 1.38$ and $\omega = 2.52$ for Xu et al. (2006a), and $\varepsilon = 1.9$ and $\omega = 1.46$ for Tice et al. (2003). In the transient regime, Xu et al. (2008) proposed values of $k = 0.75$, $\alpha = 1/3$ and $\beta = -1/5$ for a T-junction contactor.

Since the aforementioned correlations were developed for 200 μm channels with square cross sections, the findings cannot be directly applied to circular 1 mm capillaries. Nonetheless, the force balances used to derive these scaling laws are still applicable to mini-scale geometries, and provide a basis for analyzing the empirical data for developing flow transition maps. Alternatively, a scaling law has been proposed for circular T-junctions by Qian and Lawal (2006) for gas and liquid superficial velocities from 0.01 to 0.25 m/s, gas holdups of $0.09 < \varepsilon_D \approx U_D/(U_C + U_D) < 0.91$, bubble-based Reynolds numbers of $15 < Re_b = \rho_C U_b d / \mu_C < 1500$, and bubble-based capillary numbers of $0.000278 < Ca_b = \mu_C U_b / \sigma < 0.01$.

$$\frac{L_b}{d} = 1.637 \varepsilon_D^{0.107} (1 - \varepsilon_D)^{-1.05} Re_b^{-0.075} Ca_b^{-0.0687} \quad (4)$$

The bubble velocity, U_b , was predicted using the correlation of Liu et al. (2005), valid for $2 \times 10^{-4} < Ca_{CD} = \mu_C (U_C + U_D) / \sigma < 0.39$.

$$\frac{U_b}{(U_C + U_D)} = \frac{1}{1 - 0.61 Ca_{CD}^{0.33}} \quad (5)$$

For the current range of operating conditions, the predicted U_b was within 5% of the experimentally measured values, validating the image analysis algorithm used to determine the bubble sizes, velocities, and slug lengths.

For the operating conditions encountered in the current cross-flow T-junction, $0.0058 < Ca_{CD} < 0.041$ and $545 < Re_{CD} = \rho_C (U_C + U_D) d / \mu_C < 4675$, Eq. (4) consistently overestimated L_b due to the limited number of experimental conditions falling within the operating range for which Eq. (4) was developed. It was noted that for $\varepsilon = 0.9$ and $\omega = 1.28$, Eqs. (3) and (4) yield comparable predictions for L_b ; thus confirming the similarity between the two scaling laws for bubble formation dominated by interfacial forces.

In an attempt to correlate the inlet bubble size distribution, the scaling law proposed by Xu et al. (2008) for the transient regime was employed with the expectation that $\beta - \alpha$ would approach -1 at higher capillary numbers. Two distinct regimes were observed when the measured bubble lengths were fitted to Eq. (2): one applying to bubbly flow, and the other to plug/unstable-plug flow.

$$\frac{L_b}{d} = \max \begin{cases} 0.844 Ca_{D,\mu_C}^{0.285} Ca_C^{-0.384} & (\text{Bubbly}) \\ 9.721 Ca_{D,\mu_C}^{1.232} Ca_C^{-1} & (\text{Plug/Unstable plug}) \end{cases} \quad (6)$$

The maximum operator was proposed to simplify the prediction of the bubble length when the flow pattern is not known. Based on experimental observations, the bubbly and plug/unstable plug expressions were consistently dominant in their respective flow regimes, only overlapping as $L_b/d \rightarrow 1 - 2\delta/d$. Under these transitional conditions, the larger of the predicted bubble lengths was closer to those observed experimentally.

The boundary between these regimes was assumed to occur when $L_b/d = 1 - 2\delta/d$, where δ is the width of the liquid film that would surround a fully developed plug at equivalent conditions. Based on the work of Aussilous and Qur (2000) for $10^{-3} < Ca_b < 1.4$, δ can be approximated as:

$$\frac{2\delta}{d} = \frac{1.34 Ca_b^{2/3}}{1 + 3.34 Ca_b^{2/3}} \quad (7)$$

Incorporating Eq. (5), this can be further expanded to provide the transition point for bubbly to plug flow, where the bubble length predicted by Eq. (6) must be less than the following critical value:

$$\left(\frac{L_b}{d}\right)_{\text{Transition}} = \frac{(1 - 0.61 Ca_{CD}^{0.33})^{2/3} + 2 Ca_{CD}^{2/3}}{(1 - 0.61 Ca_{CD}^{0.33})^{2/3} + 3.33 Ca_{CD}^{2/3}} \quad (8)$$

The bubble lengths predicted by Eq. (6) are compared to experimental values in Fig. 4, where reasonable agreement is observed for air–water flow in 1 mm circular T-junctions operated at $545 < Re_{CD} = \rho_C (U_C + U_D) d / \mu_C < 4675$, $0.0035 < Ca_C < 0.025$ and $0.0015 < Ca_{D,\mu_C} < 0.03$.

3.2. Inlet flow pattern

The flow patterns generated by different inlet distributor designs (T-junctions, Y-junctions, flow-focusing devices) have been extensively studied in previous literature, with multiple published works describing the criteria for transitions between bubbly, plug, slug and annular flow for different channel shapes, process fluids and channel orientations. However, a universal flow map has yet to be developed due to the strong dependency of the pattern obtained on a multitude of parameters including: viscosity, density and surface tension; channel shape, orientation and length scale; upstream and downstream configurations and pressure fluctuations; and even the interpretation of the flow patterns in transition regions. Nonetheless, a number of correlations have been developed to describe the transitions between flow patterns. A detailed review of all potential flow maps for a circular 1 mm T-junction with air–water flow is beyond the scope of this work, but can be found in reviews and articles by Triplett et al. (1999a), Kawahara et al. (2002), Akbar et al. (2003), and Hassan et al. (2005).

For comparison purposes, the flow patterns observed at a distance 25–47 diameters downstream of the T-junction were compared in Fig. 5 to existing flow patterns transitions for air–water flow in circular channels, along with the proposed bubbly–plug transition relationship given by Eqs. (6) and (8). Example images of the four different flow patterns observed are provided in Fig. 6 for the indicated gas and liquid velocities. Note that the transition from plug to unstable plug flow was characterized by a grouping of the gas plugs, while the transition to slug flow required the formation and entrainment of numerous small bubbles within the trailing liquid slug.

The discrepancy between the proposed bubbly/plug transition line and previous literature was primarily attributed to differences in wetting properties and gas densities within the T-junction, and potential variances in the method by which the transition was identified. Visual determination of the transition between bubbly and plug flow is extremely subjective, especially when the film thickness surrounding a developing plug is difficult to quantify. An approach using Eqs. (6) and (8) is considered more consistent, as it inherently accounts for the variation in film thickness and uses a measureable quantity (bubble length) to define the bubbly to plug transition. For the two geometries in this work, the flow pattern transitions occurred under similar conditions, enabling the subsequent analysis of the effects of radius of curvature on flow patterns and bubble size distributions.

In Section 4, breakup maps are constructed using the Weber numbers for each phase to account for the presence of pseudo-turbulent flow in the serpentine arrangement. The proposed correlation for the bubbly to plug flow transition was dependent only on the capillary number, necessitating an approximation of the gas density at each point along the transition line to determine the value of the dispersed phase Weber number, $We_D = \rho_D U_D^2 d / \sigma$. This was achieved through the interpolation of the gas density at inlet conditions from the experimental data. As a result of this conversion, the bubbly to plug transition line for the two serpentine geometries no longer overlap, as the $r_c = 6$ mm and $r_c = 3$ mm geometries have different diameters and inlet pressures. The Weber-based

Fig. 4. Comparison of the average bubble size predicted by the proposed correlations and experimentally obtained values. Error bars represent one standard deviation, obtained from number frequency distributions of the measured bubble length.

Fig. 5. Comparison of current flow conditions and the proposed bubbly to plug transition to flow pattern transitions from previous literature.

Fig. 6. Flow patterns observed for the given gas and liquid velocity, (U_D , U_C), at a location 27–45 channel diameters downstream of the T-junction.

equivalent of Fig. 5 is provided in Fig. 7, along with the boundary proposed by Akbar et al. (2003) for the shift from surface tension dominated flow (bubbly, plug, slug) to transitional flow (wavy annular, froth, churn), given in Eq. (9). Note that the continuous phase (water) is plotted on the horizontal axis for consistency with previously published We-based flow pattern maps.

$$We_D \leq \begin{cases} 0.11We_c^{0.315} & \text{for } We_c \leq 3 \\ 1 & \text{for } We_c > 3 \end{cases} \quad (9)$$

4. Flow pattern transitions within the serpentine geometry

The serpentine geometry is commonly employed to enhance heat transfer and radial mixing in single-phase applications through the formation of Dean vortices, and to maximize the flow path length within a given geometric footprint. In multi-phase applications, the serpentine geometry alters the centerline of the circulation patterns within the liquid slug (Fries and von Rohr, 2009), and is known to cause discrepancies between the entering and exiting flow patterns at larger diameters (Kirpalani et al., 2008). The presence of curvature has two distinct effects on the flow pattern and bubble size distribution: coalescence due to draining of the liquid slug between adjacent bubbles; and breakup due to increased shear resulting from secondary flow formation within the liquid slug. As the liquid phase flows between two alternating curves in the serpentine arrangement, it must cross over to the opposite side of the channel, creating higher shear rates on preceding bubble and intense secondary flows. The effect of the radius of curvature on coalescence and breakup, and the critical conditions necessary to induce bubble breakup have yet to be characterized.

High frame rate videos of the dynamic behaviour of gas bubbles traveling through serpentine channels were collected over a wide range of operating conditions and two radii of curvature ($r_c = 6$ mm and $r_c = 3$ mm). An assessment of flow patterns formed, nature of the bubble movement, extent of interfacial deformation, and presence or absence of breakup/coalescence within the serpentine unit cells was made from the video images. From this information, breakup maps were constructed for each radius of curvature and are presented in Figs. 8 and 9 for $r_c = 3$ mm, and $r_c = 6$ mm,

respectively. The breakup boundaries formed, shown in Figs. 8 and 9, represent the conditions above which notable bubble breakup was observed. Sequential images of a bubble traveling through the 3 mm serpentine geometry are provided in Fig. 10a–l for each of the regions identified.

The images in Fig. 10a–l are grouped by flow pattern and the extent of deformation and breakup observed. Fig. 10a–c illustrates the two-phase flow at the onset of deformations, where small deformations or wave instabilities (seen as striations) are observed at the trailing edge of the bubble. Larger deformations and the wavy-annular flow regime are described in Fig. 10d–f, followed by the various individual breakup mechanisms in Fig. 10g–i. A distinction was made between “bag type bubble breakup” and “shear induced bubble breakup” for unstable plug flow, shown in Fig. 10g–i: “bag type bubble breakup” is characterized by the fracture of an extruded interface as it rapidly snaps back to the bubble bulk upon the removal of shear; whereas “shear induced bubble breakup” occurs when a smooth pinching motion is observed throughout the breakup process. Subsequent increases in gas and liquid flow rates led to multiple degrees of breakup, Fig. 10j–l, where the transition from unstable plug to slug flow was distinguished by the presence of small bubbles entrained throughout the length of the liquid slug and multiple instances of breakup at the trailing edge of the bubble.

The Weber numbers in Figs. 8 and 9 for air, $We_D = \rho_D U_D^2 d / \sigma$, and water, $We_c = \rho_c U_c^2 d / \sigma$, were determined using the densities and superficial gas and liquid velocities at the point in the serpentine geometry where the images were collected (Fig. 1). In order to provide a comparison to the inlet flow patterns (Fig. 7), the expected bubbly to plug transition line was calculated by estimating the ideal-gas expansion that would be expected for the measured pressure drop, $\rho_{D,s} / \rho_{D,i} = P_s / P_i$, and determining the maximum bubble size at the inlet which would result in $L_b/d = (1 - 2\delta/d)(\rho_{D,s} / \rho_{D,i})^{1/3}$. Note that $\rho_{D,s}$, $\rho_{D,i}$, P_s , and P_i are the air densities and absolute pressures within the serpentine (s) and inlet (i). Fig. 11 provides an overlay of each of these breakup maps and the expected bubble-plug transition point.

The inlet flow pattern and those observed in the $r_c = 6$ mm and $r_c = 3$ mm serpentine unit cells were similar for $We_c < 8$. At higher liquid flow rates, the bubbly flow regime was extended to

Fig. 7. Flow pattern observed 27–45 channel diameters downstream of the T-junction. Qualitatively determined transitions between flow patterns are shown as shaded regions.

Fig. 8. Breakup map, flow pattern transitions and proposed breakup boundary ($We_{CDL_C} = 10$) within a serpentine geometry with $r_c = 3$ mm. Conditions where breakup was observed are indicated by open markers.

Fig. 9. Breakup map, flow pattern transitions and proposed breakup boundary ($We_{CDL_C} = 10$) within a serpentine geometry with $r_c = 6$ mm. Conditions where breakup was observed are indicated by open markers.

increasing values of We_D , while a combination of bubble grouping, coalescence and breakup shifted the transitions between plug and unstable plug flow. In single-phase flow, a smaller radius of curvature leads to the development of stronger Dean vortices and increased shear rates. As a result, it can be deduced that the earlier onset of breakup and the greater extension of the bubbly flow pattern observed for $r_c = 3$ mm may also be a result of similar vortices formed. As the two-phase mixture travels through each serpentine unit cell, the gas phase decelerates and the liquid phase migrates to the outside of each curve due to centrifugal forces. At the point where the direction of curvature alternates, the liquid must flow across the center of the channel to reach the opposing wall, exerting shear on the bubbles and completely separating the bubble from the channel wall at higher liquid flow rates. This

corresponded to an apparent increase in We_C and a decrease in We_D within the serpentine geometry, resulting in an upward shift of the transition boundary between bubbly and plug flow. Under these conditions, it would be possible to modify the bubble size distribution and significantly increase inter-phase mass transfer.

The discrepancies between the plug to unstable plug flow transitions observed at the inlet and within the two serpentine geometries has significant implications to reactor design and flow pattern management. Almost all bubble grouping and coalescence observed in these experiments occurred within the first 180° return bend of the serpentine geometry, suggesting that similar behaviour would be observed when U-bends are used to increase the length of a flow path. The deceleration of the gas phase as it travels through the curved geometry led to two initially separated

Fig. 10. Sequential images of air–water flow through the $r_c = 3$ mm geometry for different flow patterns, deformations, and breakup extents at (Q_c, Q_d) flow rates (cm^3/min).

bubbles coming into contact as the liquid between them was drained by centrifugal force. The higher intensity of centrifugal forces present at the lower radius of curvature would imply that

the liquid slug between bubbles would drain away quicker, resulting in an earlier onset of bubble grouping and unstable plug flow. As can be seen in Fig. 11, it is actually the larger radius of curvature

Fig. 11. Overlay of flow pattern transitions observed following the T-junction, and within the $r_c = 6$ mm and $r_c = 3$ mm geometries. Breakup was observed above the indicated boundary for breakup for each r_c .

which first transitions to unstable plug flow. The longer curvature length of the $r_c = 6$ mm geometry extended the time for the liquid slug between two bubbles to drain, eventually leading to an increased rate of bubble grouping and coalescence over that observed for the $r_c = 3$ mm geometry. Based on this observation, the engineering design of a serpentine must take into account the curvature for a mini-scale reactor/contact system, especially when a change in the flow pattern is undesirable. A smaller radius of curvature appears to deter bubble grouping and coalescence,

and should be considered when U-bend arrangements are used to increase the reactor volume within a given geometric footprint.

5. Critical conditions for bubble breakup

The extent of secondary flow formation in single-phase flow through curved channels is frequently characterized by the Dean number, $D = (\rho U d / \mu)(d / 2r_c)^{1/2}$, derived from an approximate solution to the Navier–Stokes equations for steady, axially uniform

Fig. 12. Flow pattern within the serpentine vs. $We_{CD} L_c$ for $r_c = 6$ mm and $r_c = 3$ mm. Breakup was observed for all points above the horizontal dotted line.

flow in a helical coil. While the Dean number is not directly applicable to multi-phase flow, the scaling used in its derivation may be useful in quantifying the effects of secondary flows in the serpentine channel. In formulating the Dean number, the cross-flow velocities are scaled by the root of a characteristic length parameter for curved geometries, $L_c = d/2r_c$. A similar scaling approach was applied for the combined gas and liquid velocities to account for the formation of secondary flows within the liquid slugs traveling through the curved channel. The following dimensionless number for curved flow is proposed for characterizing the onset of bubble breakup at elevated liquid flow rates:

$$We_{CDLc} = \frac{\rho_c(U_c + U_D)^2 d}{\sigma} (d/2r_c) \quad (10)$$

The near horizontal boundaries for breakup observed in Fig. 8 for $We_c < 16$ ($r_c = 3$ mm) and Fig. 9 for $We_c < 8$ ($r_c = 6$ mm) led to the assumption that breakup under these conditions was part of the natural transition from unstable plug to slug flow, with minimal dependence on the presence of a curved flow path. Determination of the onset of breakup due to the serpentine configuration thus focused on the transition between deformation and breakup at higher values of We_c , where a marked difference was observed for the location of the breakup boundary for $r_c = 6$ mm and $r_c = 3$ mm. The flow regime and deformation/breakup extent at each operating condition was plotted against We_{CDLc} for both geometries, and is given in Fig. 12. With the exception of a few data points, the transition between deformation and breakup occurs at a critical value of $We_{CDLc} \approx 10$.

The breakup boundary predicted by $We_{CDLc} = 10$ was reconstructed for each of the two radii of curvatures, and presented in Figs. 8 and 9. Based on the agreement of the resulting breakup boundary with experimentally observed flow patterns, We_{CDLc} was considered an effective parameter for characterizing the intensity of secondary flows induced in the liquid slug by curvature, relative to the surface forces maintaining the shapes of the leading and trailing bubble interfaces. Due to the limited variation of channel diameter and fluid physical properties used in this work, additional experimentation would be required to confirm the generalization of the $We_{CDLc} = 10$ condition for the onset of bubble breakup in mini-scale curved geometries. Nonetheless, this work has demonstrated that the single-phase dimensionless analysis for curved flow can be extended to the continuous phase to quantify the intensity of secondary flow formation and its effects on bubble deformation and breakup.

6. Conclusions

In this work, the effects of radius of curvature on two-phase flow pattern transitions and the initiation of bubble breakup/coalescence in planar serpentine arrangements were studied as a composite system. The flow patterns, transition regions and bubble size distributions generated by the T-junction were identified and subsequently compared to previous literature. Scaling laws derived for square micro T-junctions were extended to a mini-scale circular T-junction operating at $545 < Re_{CD} < 4675$, $0.0035 < Ca_c < 0.025$ and $0.0015 < Ca_{D,\mu c} < 0.03$; successfully predicting bubble lengths for bubbly and plug/unstable-plug flow and enabling the use of an analytical expression to describe the transition between bubbly and plug flow.

Bubble breakup maps were developed for each of the serpentine geometries, identifying curvature-induced shifts in the transitions between flow patterns. The mechanisms of bubble breakup, grouping and coalescence were discussed, whereby a smaller radius of curvature was found to enhance breakup while inhibiting the transition from plug flow to unstable plug flow within the first bend of the serpentine geometry.

Finally, single-phase dimensionless analysis for curved geometries was extended to multi-phase flow to identify the geometric dependence of the critical bubble breakup. For the purpose of quantifying the intensity of curvature induced secondary flow in the continuous phase, the characteristic length for curved geometries encountered in the derivation of the Dean number for single-phase flow successfully captured the effects of curvature on the initiation of bubble breakup. A critical value of $We_{CDLc} = 10$ was found for the given air–water system, above which varying degrees of bubble breakup were observed.

The generation of similar bubble breakup maps for different process fluids and serpentine designs could lead to the eventual development of a more universally applicable characteristic parameter describing not only the effects of radius of curvature, but also fluid properties and distance between alternating serpentine bends.

Acknowledgements

One of the authors (A.A. Donaldson) would like to acknowledge the support of the National Research Council of Canada (NRC) and the Natural Sciences and Engineering Research Council of Canada (NSERC) for this research.

References

- Akbar, M.K., Plummer, D.A., Hgiaasaaan, S.M., 2003. On gas-liquid two-phase flow regimes in microchannels. *Int. J. Multiphase Flow* 29, 855–865.
- Angeli, P., Gavrilidis, A., 2008. Hydrodynamics of Taylor flow in small channels: a review. *Proc. Inst. Mech. Eng. Part C – J. Mech. Eng. Sci.* 222, 737–751.
- Aussilous, P., Qur, D., 2000. Quick deposition of a fluid on the wall of a tube. *Phys. Fluids* 12, 2367–2371.
- Barajas, A.M., Panton, R.L., 1993. The effect of contact angle on two-phase flow in capillary tubes. *Int. J. Multiphase Flow* 19, 337–346.
- Barnea, D., Luninski, Y., Taitel, Y., 1983. Flow in small diameter pipes. *Can. J. Chem. Eng.* 61, 617–620.
- Coleman, J.W., Garimella, S., 1999. Characteristics of two-phase patterns in small diameter round and rectangular tubes. *Int. J. Heat Mass Transfer* 42, 2869–2881.
- Cristini, V., Tan, Y.C., 2004. Theory and numerical simulation of droplet dynamics in complex flows – a review. *Lab Chip* 4, 257–264.
- Damianides, C.A., Westwater, J.W., 1988. Two-phase flow patterns in a compact heat exchanger and in small tubes. In: *Proc. Second UK National Conf. On Heat Transfer*, Glasgow, 14–16 September. Mechanical Engineering Publications, London, pp. 1257–1268.
- Fries, D.M., von Rohr, P.R., 2009. Liquid mixing in gas-liquid two-phase flow by meandering microchannels. *Chem. Eng. Sci.* 64, 1326–1335.
- Fukano, T., Kariyasaki, A., 1993. Characteristics of gas-liquid two-phase flow in a capillary. *Nucl. Eng. Des.* 141, 59–68.
- Garstecki, P., Fuerstman, M.J., Stone, H.A., Whitesides, G.M., 2006. Formation of droplets and bubbles in a microfluidic T-junction – scaling and mechanism of break-up. *Lab Chip* 6, 437–446.
- Hassan, I., Vaillancourt, M., Pehlivan, K., 2005. Two-phase flow regime transitions in microchannels: a comparative experimental study. *Microscale Thermophys. Eng.* 9, 165–182.
- Huh, C., Kim, J., Kim, M.H., 2007. Flow pattern transition instability during flow boiling in a single microchannel. *Int. J. Heat Mass Transfer* 50, 1049–1060.
- Kawahara, A., Chung, P.Y., Kawaji, M., 2002. Investigation of two-phase flow pattern void fraction and pressure drop in a microchannel. *Int. J. Multiphase Flow* 28, 1411–1435.
- Kirpalani, D.M., Patel, T., Mehrani, P., Macchi, A., 2008. Experimental analysis of the unit cell approach for two-phase flow dynamics in curved flow channels. *Int. J. Heat Mass Transfer* 51, 1095–1103.
- Laborie, C., Cabassud, L., Durand-Bourlier, Laine, J.M., 1999. Characterisation of gas-liquid two-phase flow inside capillaries. *Chem. Eng. Sci.* 54, 5723–5735.
- Liu, H., Vandu, C.O., Krishna, R., 2005. Hydrodynamics of Taylor flow in vertical capillaries: flow regimes, bubble rise velocity, liquid slug length and pressure drop. *Ind. Eng. Chem. Res.* 44, 4884–4897.
- Martin, J., Oshkai, P., Djilali, N., 2005. Flow structures in a U-shaped fuel cell flow channel: quantitative visualization using particle image velocimetry. *J. Fuel Cell Sci. Technol.* 2, 70–80.
- Menech, M.D., Garstecki, P., Jousse, F., Stone, H.A., 2008. Transition from squeezing to dripping in a microfluidic T-shaped junction. *J. Fluid Mech.* 595, 141–161.
- Mishima, K., Hibiki, T., 1996. Some characteristics of air–water two-phase flow in small diameter vertical tubes. *Int. J. Multiphase Flow* 22, 703–712.
- Mishima, K., Hibiki, T., Nishihara, H., 1995. Some characteristics of air–water two-phase flow in small diameter tubes. In: *Proc 2nd Int. Conf. Multiphase Flow*, vol. 4, April 3–7, 1995, Tokyo, Japan, pp. 39–46.

- Nisisako, T., Torii, T., Higuchi, T., 2002. Droplet formation in a microchannel network. *Lab Chip* 2, 24–26.
- Niu, H., Pan, L., Su, H., Wang, S., 2009. Flow pattern, pressure drop, and mass transfer in a gas–liquid concurrent two-phase flow microchannel reactor. *Ind. Eng. Chem. Res.* 48, 1621–1628.
- Qian, D., Lawal, A., 2006. Numerical study on gas and liquid slugs for Taylor flow in a T-junction microchannel. *Chem. Eng. Sci.* 61, 7609–7625.
- Shekarraz, R., 2000. Challenges in thermal systems miniaturization. *Heat Transfer Eng.* 21, 1–2.
- Suo, M., Griffith, P., 1964. Two-phase flow in capillary tubes. *J. Basic Eng.* 86, 576–582.
- Thorsen, T., Roberts, R., Arnold, F., Quake, S., 2001. Dynamic pattern formation in a vesicle-generating microfluidic device. *Phys. Rev. Lett.* 86, 4163–4166.
- Tice, J.D., Song, H., Lyon, A.D., Ismagilov, R.F., 2003. Formation of droplets and mixing in multiphase microfluidics at low values of the Reynolds and the capillary numbers. *Langmuir* 19, 9127–9133.
- Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khalik, S.I., Sadowski, D.L., 1999a. Gas–liquid two-phase flow in microchannels. Part I: two-phase flow patterns. *Int. J. Multiphase Flow* 25, 377–394.
- Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khalik, S.I., LeMouel, A., McCord, B.N., 1999b. Gas–liquid two-phase flow in microchannels. Part II: void fraction and pressure drop. *Int. J. Multiphase Flow* 25, 395–410.
- Wang, C., Chen, I.Y., Yang, Y., Chang, Y., 2003. Two-phase flow pattern in small diameter tubes with the presence of horizontal return bend. *Int. J. Heat Mass Transfer* 46, 2975–2981.
- Wang, C., Chen, I.Y., Yang, Y., Chang, Y., Hu, R., 2004. Influence of horizontal return bend on the two-phase flow pattern in small diameter tubes. *Exp. Therm. Fluid Sci.* 28, 145–152.
- Wang, C., Chen, I.Y., Huang, P., 2005. Two-phase slug flow across small diameter tubes with the presence of vertical return bend. *Int. J. Heat Mass Transfer* 48, 2342–2346.
- Xiong, R., Chung, J.N., 2007. Flow characteristics of water in straight and serpentine micro-channels with miter bends. *Exp. Therm. Fluid Sci.* 31, 805–812.
- Xu, J.H., Luo, G.S., Li, S.W., Chen, C.G., 2006a. Shear force induced monodisperse droplet formation in a microfluidic device by controlling wetting properties. *Lab Chip* 6, 131–136.
- Xu, J.H., Li, S.W., Tan, J., Wang, Y.J., Luo, G.S., 2006b. Preparation of highly monodisperse droplet in a T-junction microfluidic device. *AIChE J.* 52, 3005–3010.
- Xu, J.H., Li, S.W., Tan, J., Wang, Y.J., Luo, G.S., 2006c. Controllable preparation of monodisperse O/W and W/O emulsions in the same microfluidic device. *Langmuir* 22, 7943–7946.
- Xu, J.H., Li, S.W., Tan, J., Luo, G.S., 2008. Correlations of droplet formation in T-junction microfluidic devices: from squeezing to dripping. *Microfluid. Nanofluid.* 5, 711–717.
- Yang, C.Y., Shieh, C.C., 2001. Flow pattern of air–water and two-phase R-134a in small circular tubes. *Int. J. Multiphase Flow* 27, 1163–1177.
- Zhao, T.S., Bi, Q.C., 2001. Co-current air–water two-phase flow patterns in vertical triangular microchannels. *Int. J. Multiphase Flow* 27, 765–782.