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Void fraction and pressure drop in gas-liquid downflow through narrow vertical conduits-experiments and analysis

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HIGHLIGHTS

- Experiments & flow pattern specific analysis for void fraction and pressure drop.
- Droplet-laden gas core surrounded by annular liquid film analysed in annular flow.
- Study useful for design of meso-scale devices in downflow orientation.

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ABSTRACT

The present paper investigates void fraction and pressure drop characteristics of vertical air-water downflow through millichannels ($0.83 \leq$ Eotvos Number ≤ 20.6). Experiments have revealed the hydrodynamics to be a function of tube diameter and phase velocities with the functional form being different for different flow patterns. Accordingly, separate mechanistic models have been proposed to predict the aforementioned parameters for bubbly, slug, falling film and annular flow distributions. The proposed analysis have been validated with experimental results of the present study and those reported in literature.

1. Introduction

The phenomenon of gas-liquid two-phase flow is common in chemical, petrochemical, pharmaceutical, nuclear and power industries. It is encountered in condensers, cooling towers, distillation columns, reactors, boiler tubes etc. Currently, researchers and engineers are interested in achieving process intensification by miniaturization of devices. This results in increased surface to volume ratio, reduces diffusion length and enhances mass transfer and reaction rate. Millichannels mark a transition between the macro and the micro domain. Gravitational and surface forces both play important roles in these dimensions and the effect of surface forces increase progressively with decreasing conduit size. Accordingly, diameter as well as orientation influence the hydrodynamics of two phase flow in millimeter size tubes and several studies (Kannan et al., 2015; Biswas et al., 2015a, 2015b; Mishima and Hibiki, 1996) have focused on the unique physics of two phase flow through millichannels as distinct from micro and macro systems. Downflow in reduced dimensions is extensively used in monolith reactors (typically of dimension 1–3 mm) and is preferred in industry since maldistribution is often encountered during upflow (Kreutzer et al., 2005; Liu et al., 2005). Design of such reactors call for proven models and correlations that can be used for estimating flow morphology and corresponding hydrodynamic parameters. In addition, past studies (Biswas et al., 2015a) have reported enhanced transport properties in the downflow orientation of millichannels.

A summary of the relevant literature reported on minichannels in the past few decades is presented in Table 1. We observe that the majority of the studies are confined to horizontal or vertical upflow of gas-liquid systems and not much is known about the characteristics during downflow. The studies on downflow (Anderson and Mantzouranis, 1960; Kashinsky and Randin, 1999; Oshinowo and Charles, 1974) are primarily confined to commercial pipes of diameter 2.54 cm and higher. There is no guarantee that the information available for such dimensions can be applied to smaller scales. For example, in the smaller scale, surface tension dominates flow pattern transition, whereas for larger pipe Kelvin-Helmholtz instability is the dominant factor (Barnea et al., 1983).

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Nomenclature

Notation	
D	conduit diameter
A	annular flow
FF	falling film flow
S	slug flow
B	bubbly flow
FA	falling film flow to annular flow transition
SA	slug flow to annular flow transition
BS	bubbly flow to slug flow transition
f	friction factor
J	inlet velocity
U	in situ velocity
Re	Reynolds no.
We	Weber no.

Greek symbols	
ρ	density
σ	surface tension
α	void fraction
τ	shear stress

Subscripts and superscripts	
G	gas
L	liquid
i	gas-liquid interface
WL	wall-liquid

Table 1
Pertinent literature on gas-liquid flow through millichannels.

References	Hydraulic diameter (mm)	Fluid	Orientation	Estimated Parameter	Method	Reported studies and results
Lazarek and Black (1982)	3.1	Vapor/R–113	V(U&D)	h, ΔP		Frictional, spatial acceleration and pressure drop for saturated boiling are correlated. Developed correlation for Critical heat flux and predicted the experimental heat flux within 5% of error.
Barnea et al. (1983)	04–12	Air/water	V(U&H)	FP	Image	Surface tension affects only stratified slug transition in horizontal flow.
Biswas and Greenfield (1985)	0.5–7.1	Air/water	V(D)	FP	Image	Stratified flow observed for tube diameter < 3 mm in Y Junction.
Usui and Sato (1989)	16	Air-Water	V(D)	α	Conductance probe	Theoretical and semi empirical model proposed
Wambsganss et al. (1993)	2.92	Vapor/R–113	H	FP and VF	Image processing	High boiling number and slug flow pattern leads to nucleation mechanism.
Fukano and Kariyasaki (1993)	1, 2.4, 4.9	Air/water	V(U&D), H	FP, VF and ΔP	Constant current method	Flow patterns do not change much with flow direction in small conduit dimension.
Jiang and Rezkallah (1993))	9.53	Air-Water	V(U&D)	α	Gamma Densitometer	Higher α in downward as compared to upward flow. Experiments show no significant effect of tube diameter on void fraction.
Bao et al. (1994)	0.7–3	Air/water, air/ glycerine	H, V	VF and ΔP	–	Lockhart-Martinelli and CISE correlations for α agree closely with the measured α.
Mishima and Hibiki (1996)	1–4	Air/water	V(U)	FP, α, ΔP	Neutron Radiology	α and slug velocity are correlated by drift flux model. Frictional pressure loss has been correlated well by modified Chisholm's correlation.
Kew and Cornwell (1997)	1.39–3.69	R–141b	H	ΔP, h	–	Developed correlation for h predicted reasonably well for the D = 3.69 but performed poor when applied to D = 1.39
Kureta et al. (1998)	2–6	Steam/water	H	ΔP, h	–	Experimental results of pressure drop and heat transfer for flow boiling compared well with existing correlations and model in literature
Sujunmnong (1997)	12.7	Air-Glycerin	V(U)	α	Quick closing valve	Experimental results of bubbly and froth flows show good predictions with existing correlations.
Lin et al. (1998)	0.5–4	Air/water	V(U)	FP and h	Image processing, Pressure transducer signals	A pair of dimensionless number for gas-liquid flow is used to construct the flow regime map.
Liu et al. (2005)	0.9–3	Air-Water/ Ethanol	V(U)	α, ΔP, Slug Length	Image Processing	Flow-regime-dependent method for estimating the total pressure drop in two-phase vertical capillary flows.
Bhagwat and Ghajar (2012)	12.7	Air-Water	V(U&D)	FP, α	Quick closing Valve	Compared α in upward and downward flow and reported significant difference in bubbly and slug flow regime.
Milan et al. (2013)	8.8	Air-Water	V(D)	FP	Image processing	Entry section has crucial role in flow pattern transition boundaries.
Bhagwat and Ghajar (2014)	12.7	Air-Water	V(U&D)	α	Quick closing Valve	Empirical correlations proposed to void fraction downward flow.
Milan et al. (2014)	8.8	Air-Water	V(D)	FP	Image processing	A new type of flow pattern, membrane flow observed.
Kumar et al. (2017)	2.5–12.5	Air-Water	V(D)	FP	Image processing	Mechanistic models for FP transition have been proposed and validated
Present studies	2.5–12.5	Air-Water	V(D)	α, ΔP	Quick closing, Image processing	Based on experiments, mechanistic models proposed for prediction of void fraction and pressure drop.

V = Vertical, U = Upward, H = Horizontal, D = Downward, FP = Flow pattern, α = Void fraction, ΔP = Pressure drop, h = Heat transfer coefficient.