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Inlet effects on vertical-downward air–water two-phase flow

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HIGHLIGHTS

- Inlet effects on two-phase flow parameters in vertical-downward flow are studied.
- Flow regimes in the vertical-downward two-phase flow are defined.
- Vertical-downward flow regime maps for three inlet configurations are developed.
- Frictional pressure loss analysis for three different inlets is performed.
- Database of local two-phase flow parameters for each inlet configuration.

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ABSTRACT

This paper focuses on investigating the geometric effects of inlets on global and local two-phase flow parameters in vertical-downward air–water two-phase flow. Flow visualization, frictional pressure loss analysis, and local experiments are performed in a test facility constructed from 50.8 mm inner diameter acrylic pipes. Three types of inlets of interest are studied: (1) two-phase flow injector without a flow straightener (Type A), (2) two-phase flow injector with a flow straightener (Type B), and (3) injection through a horizontal-to-vertical-downward 90° vertical elbow (Type C). A detailed flow visualization study is performed to characterize flow regimes including bubbly, slug, churn-turbulent, and annular flow. Flow regime maps for each inlet are developed and compared to identify the effects of each inlet. Frictional pressure loss analysis shows that the Lockhart–Martinelli method is capable of correlating the frictional loss data acquired for Type B and Type C inlets with a coefficient value of C = 25, but additional data may be needed to model the Type A inlet. Local two-phase flow parameters measured by a four-sensor conductivity probe in four bubbly and near bubbly flow conditions are analyzed. It is observed that vertical-downward two-phase flow has a characteristic center-peaked void profile as opposed to a wall-peaked profile as seen in vertical-upward flow. Furthermore, it is shown that the Type A inlet results in the most pronounced center-peaked void fraction profile, due to the coring phenomenon. Type B and Type C inlets provide a more uniform distribution of the void fraction profile with a reduced coring effect.

1. Introduction

Two-phase flow is a widely observed phenomenon present in many engineering applications such as nuclear reactors as well as industrial systems. Most of these practical applications have different sizes of coolant channels in varying orientations with different types of inlets, all of which can affect the two-phase flow characteristics. The flow regimes and interfacial structures have a dependence on the flow orientations. For example, stratified flow and wave flow exist in horizontal two-phase flow but not in vertical-upward two-phase flow (Mandhane et al., 1974). Bubble coring is observed in vertical-downward two-phase flow while it is not observed in other orientations (Oshinowo and Charles, 1974; Usui and Sato, 1989; Goda et al., 2002). Unlike the flow-regime map in vertical-upward and horizontal two-phase flow, a universal vertical-downward flow regime map has not reached a consensus. One of the reasons is that downward two-phase flow may be more sensitive to the channel shape and size, inlet type, development length and historic effects (Milan et al., 2013). This paper focuses on investigating the geometric effects of inlets on global and local two-phase flow parameters in vertical-downward air–water two-phase flow.

A number of researchers have investigated two-phase flow in vertical-downward channels over the decades. Table 1 summarizes a list of previous investigations that includes the channel size, measurement location, inlet configuration, conditions, instrumentation, etc. Most of the studies were performed under or close to

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Table 1
Summary of the adiabatic vertical-downward two-phase flow studies found in the literature.

Literature	ID (mm)	Inlet configuration	Instrumentation	Conditions	Focuses
Golan and Stenning (1969)	38.1	U-bend	Direct visual observations	–	Flow regime map
Oshinowo and Charles (1974)	25.4	U-bend	High speed camera	m_f: up to 3.8 lb/min, m_g: up to 140 lb/min	Flow regime map
Spedding and Nguyen (1980)	45.5	–	–	m_f: up to 500 kg/s, m_g: up to 5000 kg/s	Flow regime map
Barnea et al. (1982)	25, 51	–	Conductivity probe	j_f = 0.1–5 m/s, j_g = 0.02–30 m/s	Flow regime prediction correlation
Yamaguchi and Yamazaki (1984)	40, 80	Porous plate	Direct visual observations	j_f = 1–1.02 m/s, j_g = 1.15–1.58 m/s	Flow regime map
Abdullah and Ai-khatab (1994)	38	T mixer	Direct visual observations	j_f = 0.191–1.81 m/s, j_g = 0.024–0.98 m/s	Flow regime map, pressure measurement
Usui and Sato (1989)	16, 24	U-bend	Conductivity probe	–	Local void fraction and prediction correlation
Goda (2001), Goda et al. (2002), Hibiki et al. (2003, 2004, 2005), Kim et al. (2004)	25.4, 50.8	Porous sparger	Conductivity probe	j_f = 0.4–3.4 m/s, j_g = 0.02–3 m/s	Neural network methodology, local two phase parameter, interfacial structure
Lee et al. (2008), Enrique Julia et al. (2013)	25.4, 50.8	Porous sparger	Conductivity probe	j_f = 0.4–3.4 m/s, j_g = 0.02–3 m/s	Neural network methodology, flow regime identification
Bhagwat and Ghajar (2012)	12.7	Spiral mixer	High speed camera, conductivity probe	j_f = 0.06–3 m/s, j_g = 0.3–14 m/s	Local void fraction prediction correlation
Milan et al. (2013)	9	Ball mixer, coaxial injector	High speed camera	j_f = ~0.027–0.41 m/s, j_g = ~0.137–2.24 m/s	Flow regime map
Almabrok et al. (2016)	10.16	U-bend	Film thickness probe, wire mesh sensor	j_f = ~0.07–1.5 m/s, j_g = ~0.15–30 m/s	Bend effects, film thickness correlations
Present study	50.8	Sparger without FS, sparger with FS, 90° elbow	High speed camera, conductivity probe	j_f = 0.2–4 m/s, j_g = 0.015–5.89 m/s	Flow regime map, local two phase parameter, pressure drop analysis

standard ambient temperature and pressure (SATP) using air and water as working fluids except for Oshinowo and Charles (1974) who studied water and aqueous glycerol solutions of various concentrations.

Among the studies, U-bend is a widely used inlet configuration to create vertical-downward two-phase flow. Golan and Stenning (1969) investigated the downward flow from a U-bend with a vertical-upward riser. They identified the transition from slug and bubbly flow to annular flow in the downcomer section after a U-bend. Oshinowo and Charles (1974) performed vertical downward air–water and air-glycerol two-phase flow experiments in 25.4 mm pipes interconnected with a U bend. They observed and defined six flow regimes: bubbly-coring, bubbly-slug, falling film, falling bubbly-film, froth flow, and annular flow. Data from the investigation was used to formulate an empirical flow pattern correlation for both upward and downward flow in terms of the volumetric gas to liquid velocity ratio and a mixture Froude number incorporating the effect of fluid properties. Usui and Sato (1989) and Usui (1989) also performed air–water two-phase flow visualization in vertical downward pipe with a U bend. They identified bubbly, slug, churn and annular flow regimes. A correlation was developed to predict the average void fraction for each flow regime and flow regime transition criteria based on two-phase flow data acquired by a conductivity probe.

Beside of the U-bend inlet, Yamaguchi and Yamazaki (1984) studied the flow regimes in vertical tubes of 40 and 80 mm I.D with a porous plate inlet. Air was supplied from a compressor to a mixing chamber and was injected radially through a porous plate having holes of approximately 40 μm in diameter. A combined flow regime map presenting the entire data of the observed flow regimes including bubbly, slug and annular flow for vertical-upward flow, counter-current and co-current downward flow were presented on the superficial gas and liquid velocity plane.

Abdullah and Ai-khatab (1994) proposed a flow regime map for vertical-downward air–water two-phase flow and compared with those by Barnea et al. (1982) and Golan and Stenning (1969). They used a T mixer as inlet and identified bubbly, slug and annular flow regimes. Bhagwat and Ghajar (2012) and Bhagwat (2011) performed flow visualization studies in both vertical-upward and vertical-downward two-phase flow as well as an analysis of the performance of various void fraction correlations available in the literature. A branded spiral mixer was used as the vertical downward inlet.

In addition to the vertical-downward two-phase flow, some researchers studied downward two-phase flow with different pipe inclinations. Spedding and Nguyen (1980) reported flow regime maps for vertical upward, inclined upward, horizontal, inclined downward and vertical downward flows in terms of the volumetric ratio and the Froude number. They discussed in detail the parameters presented as coordinates in a flow regime map, and concluded that the volumetric ratio and the Froude number were the most satisfactory parameters to use in such a flow regime map presentation. Barnea et al. (1982) performed flow visualization in 25.4 and 50.8 mm vertical downward and inclined pipes. Flow regime maps in terms of the superficial gas and liquid velocities for various downward inclinations and a model for predicting flow pattern boundaries were developed. Unfortunately, no inlet configuration information was discussed for both studies.

Most of the work discussed above use flow visualization method to determine the flow regimes. More recently, a less subjective neural network-based identification methodology was developed and applied to flow regime map development. Goda (2001), Goda et al. (2002) and Kim et al. (2004), studied the adiabatic, air–water, co-current, vertically downward two-phase flow in round pipes with internal diameters of 25.4 and 50.8 mm. Flow regime maps were obtained by analyzing 60 s of characteristic signals acquired by an impedance void meter using a neural network-based identification methodology. The method is improved by Lee et al. (2008) to be applicable in determining the flow regime in the rapid transient or the inherently unstable flow. Enrique Julia et al.