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Flow regime transition criteria for co-current downward two-phase flow

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ABSTRACT

Downward two-phase flow is observed in light water reactor accident scenarios such as loss of coolant accident (LOCA) and loss of heat sink accident (LOHS) due to loss of feed water or a secondary pipe break, and so, it is vital to have a thorough understanding of the flow mechanisms and regimes. With this point of view, flow regime transition criteria for vertical downward flow for a range of pipe diameters of 24–101.6 mm has been developed. Several models looked at the radial distribution of the bubbles and the wake effect of leading bubbles while others looked into the Kelvin-Helmholtz instability seen at the gas-liquid interface. The newly developed criteria have been compared to flow regime maps obtained via subjective and objective means, consisting of air-water data at atmospheric conditions as well as at an elevated pressure of 0.2 MPa. The new model is also compared to flow regime maps developed with different inlet conditions. Overall, the present model showed good agreements with the available data, with the exception of several 50.8 mm ID flow regime maps of different inlet conditions as well as a self-organizing neural network. This study also highlights the need for a more objective and consistent flow regime map data for large diameter pipes, the identification of cap-bubbly and churn-turbulent flows in these maps, and the deviations observed between a supervised and self-organizing neural network (SONN).

1. Introduction

A thorough understanding of downward two phase flow is important as it is vital for nuclear reactor safety analysis and is observable in chemical process systems and industrial energy transfer systems. Specifically, downward two phase flow is observed in accident scenarios such as loss of coolant accident (LOCA), loss of heat sink accident (LOHS) and large-break loss of coolant accident (LBLOCA) in pressurized water reactors (PWR). During a LBLOCA scenario, the decrease in saturation temperature due to pressure loss occurs prior to the reflood phase. As such, two phase mixture is encountered during the reflood as the downcomer walls become superheated. The reflood flow rate for core cooling can be affected by downward boiling as it diminishes the hydraulic head to feed the coolant into the core which can inevitably lead to the failure of the nuclear fuel rods (Yun et al., 2008). A boiling water reactor (BWR) can also encounter downward two-phase flow above the core, at a later stage of the emergency core cooling system (ECCS) injection. Due to the importance of downward two phase flow, it is imperative to understand the interactions between both phases which are influenced by surface tension, gravity, buoyancy and liquid inertia forces.

The review by Lokanathan and Hibiki (2016) highlighted the need for a more accurate downward flow regime transition model as well as experimental data maps for larger pipe diameters. Previous transition models (Barnea et al., 1982; Usui, 1989; Crawford et al., 1985; Lee et al., 2008) as studied by Lokanathan and Hibiki (2016) do not agree well with the current flow regime maps and are heavily dependent on empirical coefficients which are insensitive to flow conditions. Moreover, the aforementioned models do not study transition regions between slug to churn-turbulent and bubbly to cap-bubbly (C-B) flows. In this paper, a flow regime map for downward vertical two phase flow was modeled and compared to data from 24, 25.4, 38, 40, 50.8, 80 and 101.6 mm internal diameter (ID) pipes. The data includes subjective methods such as direct visual observation and visual observation with a wire mesh sensor (WMS) and objective methods such as self-organizing neural network (SONN) and supervised neural network as well as ReliefF-Fuzzy C-means clustering algorithm (Table 1). Limited research on co-current downward flow regime maps have been performed over the last few decades. Among the available data, most were collected at atmospheric pressure conditions with air and water except for Crawford et al. (1985) and Sekoguchi et al. (1996). Barnea et al. (1982), Kendoush and Al-Khatab (1994), Yamaguchi and Yamazaki (1984) and Almabrok (2013) identified bubbly, slug and annular flow regimes, but did not mention churn-turbulent regime in their studies. Crawford et al. (1985) combined slug and churn-turbulent flow as intermittent flow (alike to Almabrok (2013)), falling film as separated flow, and droplet

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Table 1
Flow regime map data.

Authors	Pipe diameter (mm)	Superficial gas vel. range, *jg* (m/s)	Superficial liquid vel. range, *jf* (m/s)	Number of data points	Fluids, temperature & pressure	Regimes identified	Regime identification method	Probe axial location (*z*/*D*)	Probe	Bubble injector	Note
Yamaguchi and Yamazaki (1984)	40 80	0 to -1.15	−0.1 to -1.02	90 57	Air-water at 20 °C at 100 kPa	Bubbly Slug Annular	Visual	N/A	N/A	Radial Injection	–
Usui (1989)	24	−0.02 to -17	−0.06 to -1.1	110	Air-water at room temperature at 101 kPa	Bubbly Slug Churn-turbulent Annular drop Falling film	Visual	100	Conductivity probe (Liquid film thickness)	Mixing chamber	–
Kendoush and Al-Khatab (1994)	38	−0.024 to -0.9	−0.5 to -2.0	53	Air-water at 25–30 °C at 140 kPa	Bubbly Slug Annular	Visual	N/A	N/A	N/A	–
Sekoguchi et al. (1996)	25.8	−0.02 to -40	−0.1 to -3	N/A	Air-water at 0.2 MPa & 18–22 °C	Bubbly Plug Foam Huge-wave Annular	Visual	N/A	N/A	N/A	–
Ishii et al. (2004)	25.4 50.8	−0.3 to -10 -0.003 to -10	−1 to -8 -0.2 to -5	N/A	Air-water	Bubbly Slug Churn-turbulent Annular	SONN (Impedance signals from cross-sectional void fraction)	N/A	Impedance-void meter	N/A	Kinematic shock wave identified in 50.8 mm tube
Lee et al. (2008)	25.4 50.8	−0.01 to -26 -0.01 to -4	−0.6 to -7 -0.4 to -2.5	201 156	Air-water	Bubbly Cap-bubbly Slug Churn-turbulent Annular	Supervised Neural network (Impedance signals from cross-sectional void fraction)	68 34	Impedance-void meter	Air-water mixture injection unit	–
Almabrok (2013)	101.6	−0.1 to -40	−0.05 to -2	135	Air-water	Bubbly Intermittent Annular	Visual & cross-sectional phase distribution from WMS	46	Wire mesh sensor (WMS)	U-bend with air-water	–
Qiao et al. (2015)	50.8	−0.01 to -6	−0.2 to -4	N/A	Air-water at 20 °C & ambient pressure	Bubbly Slug Churn-turbulent Annular	Visual	Type A & B: 55.5 Type C: 67.5	N/A	Sparger	Kinematic shock wave identified for Type A inlet
Pan et al. (2016)	25.4	−0.01 to -30	−0.6 to -3.3	119	Air-water at 26 °C	Bubbly Slug Churn-turbulent Annular	ReliefF-FCM (Fuzzy C-means) clustering algorithm (Impedance signals from cross-sectional void fraction)	25, 60, 120	NA	Sparger	–