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Flow structure and flow regime transitions of downward two-phase flow in large diameter pipes

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ABSTRACT

Downward two-phase flow in large diameter pipes appears in numerous industrial applications and nuclear reactor accidents. In this study, adiabatic air–water two-phase flow experiments in a 203.2 mm diameter pipe have been conducted to investigate flow regimes and their transitions in downward and horizontal flow. Three flow regimes (cap-bubbly, churn-turbulent and annular flow) were recognized in downward flow, as well three flow regimes (stratified, plug and pseudo-slug flow) were observed in horizontal section. Evolution of void fraction and flow structure along the loop under different flow conditions has been discussed. The Probability Density Function (PDF) and Cumulative Probability Density Function (CPDF) of area-averaged void fraction signals were utilized as the indicators for self-organized neural network (SONN) method to identify horizontal and vertical downward flow regimes, respectively. The downward flow regime maps for 203.2 mm diameter pipes have been proposed and compared with that for different diameter pipes. The results show that the flow regime maps agree well with that of 101.6 mm, but don't agree well with that of smaller diameter pipes (25.4 mm and 50.8 mm). It is found that the transition between churn-turbulent and annular flow occurs at a certain superficial liquid velocity regardless of superficial gas velocity. A set of new transition criteria have been developed for downward flow regime transitions in large diameter pipes, and validated by the experimental data of 203.2 mm and 101.6 mm diameter pipes. Compared with existing models, these criteria provide more accurate predictions for downward flow regime transitions in large diameter pipes.

1. Introduction

Two-phase flow is observed in numerous industrial applications such as nuclear engineering, chemical engineering processes, refrigeration engineering and transportation for liquid, gas and other petroleum products. Flow regimes, defined as several topological configurations, have a profound effect on the two-phase pressure drop and heat transfer. Most of the researches on flow regimes were carried out for vertical and horizontal tubes individually, but less is for integral loops, especially for those consisting of vertical downward flow. On the other hand, extensive experiments were conducted in small diameter tubes, but the applicability of the derived models for prediction of flow regimes in large diameter channels is questionable.

A thorough understanding for characteristics and development of two-phase flow in a loop consisting of downward part is significant for nuclear reactor safety analysis. Regarding small break loss of coolant accident (LOCA) and loss of heat sink accident in nuclear reactors, two-phase flow would emerge in the primary loop and the co-current downward flow happens in the steam generator [1]. In the case of large break LOCA, downward boiling occurs due to overheat by the downcomer wall during the reflood period. As a result, the downward two-phase flow cannot provide sufficient hydraulic head for cooling core, which would cause core meltdown [2]. Downward two-phase flow is also observed in the event of the emergency core cooling system injection of BWR [1]. This paper is aimed to investigate phase distribution characteristics and flow structure development of two-phase flow in the loop of large diameter, especially for downward section.

In the previous studies, two-phase downward flow regime maps were put forward for the 25.4–101.6 mm diameter tubes [3–11]. Most researchers conducted experiments with air and water as working fluid at room temperature and atmospheric pressure. The range of superficial gas and liquid velocity were 0–30 m/s and 0.002–8 m/s, respectively. A total of four flow regimes were

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identified by most investigators, viz. bubbly, slug, churn-turbulent and annular flow regimes. In addition, Crawford et al. defined intermittent flow pattern by the characteristics of alternating vaper and liquid packets (slug and churn flow) [4]. Usui separated falling film flow occurring at the low liquid and gas flow rate from annular flow, and described this flow pattern in which the liquid moved as falling film on the wall and the gas core contained no droplet [5]. Based on the distinction of slip velocity, high wave flow and foam flow were separated from plug and slug flow by Sekoguchi et al. [7]. Lee et al. divided bubbly flow into the dispersed bubbly flow and cap-bubbly flow [10]. The kinematicshock wave phenomenon was observed at a separated region in several studies [9,13], which is characterized as flow rate excursion due to upstream flow regime transition from annular to bubbly flow.

The traditional method in the identification of downward flow regimes is visual observation [3–7], which usually provides subjective results. In order to achieve objective flow regime identification, the neural network was adapted and coupled with impendence meters or conductivity probes [8–12]. Goda et al. and Ishii et al. used the mean, standard deviation and skewness of impedance signals as flow regime indicators [8,9]. Lee et al. began to use CPDF of cross-sectional void fraction as flow regime indicators [10]. Then, the CPDF were widely accepted for flow regime classification due to integral feature [14,15].

Area averaged one-dimensional models for downward flow regime transitions were developed and modified by several authors. Barnea et al. proposed the models for slug to bubbly flow transition and annular to slug flow transition [3]. Usui developed new drift velocity model and flow regime transition criteria for bubbly to slug/churn, slug/churn to annular, falling film to slug/churn and falling film to annular flow transitions [6]. Lee et al. validated the models of Usui, and modified the model for slug/churn to annular flow transition [10]. It should be noted that all models were derived based on the data collected in the 25.4 mm and 50.8 mm diameter pipe. The comparisons with the experimental data of large diameter pipes [11,16] have been carried out, but the agreement between models and data is not good [1]. Thus, it is necessary to develop new models especially for large diameter pipes.

Flow patterns and bubble behavior are closely related to the tube diameter. As for small diameter tubes, the walls limit the configuration and motion of bubbles, and relatively small gas slugs remain stable. Nevertheless, in the case of large diameter tubes, Taylor instabilities of bubble surface causes the breakup of large gas slugs into Taylor cap bubbles, inducing additional interfacial surface area and turbulence fluctuations [17]. The differences between large and small pipes are also supported by previous local experiment data in small pipes [18,19] and large pipes [20]. Many experimental and modeling efforts have been directed to the investigation on the vertical two-phase flow in large diameter pipes [21–26]. However, most studies focus on the upward flow, and downward flow receives less attention. The largest pipe diameter for downward flow found in the existing data is 101.6 mm by Almabrok, much less than that for upward flow [11].

In this paper, flow structures and flow regime transition of vertical downward and horizontal two-phase flow were investigated in a loop of 203.2 mm diameter. The inlet and the outlet of downward sections were connected with 90° vertical elbows, respectively. Six impedance meters were set along the loop to measure void fraction. The neural network, using the CPDF and PDF of the impedance void meter signals, was employed to classify the flow regimes. New flow regime maps and flow regime transitions for downward flow in large pipes were proposed, and compared with previous experimental data and models.

2. Experimental facility

2.1. Experimental loop

The experiments were carried out in an adiabatic two-phase test facility at room temperature, as shown in Fig. 1. The experimental loop is made of 203.2 mm inner diameter (*D*) acrylic pipes,

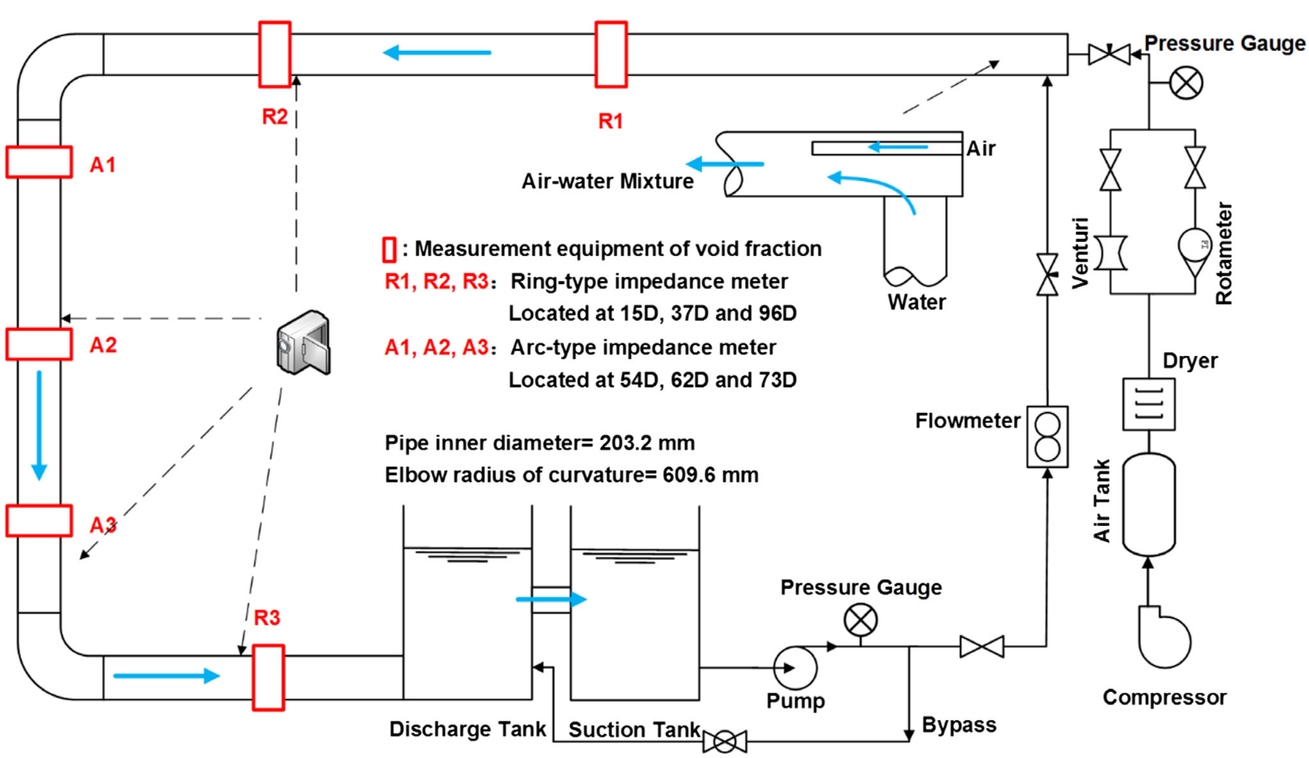

Fig. 1. Simplified schematic diagram of the test facility.