International Journal of Heat and Mass Transfer 125 (2018) 179–189

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Downward two phase flow experiment and general flow regime transition criteria for various pipe sizes

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ARTICLE INFO

Article history:
Received 28 October 2017
Received in revised form 20 March 2018
Accepted 22 March 2018

Keywords:
Downward flow regime
Probability density profile
Neural network method
Flow regime boundary criteria

ABSTRACT

Flow regime map is often used in choosing constitutive correlations for the two-phase flow model. The related research mainly concentrates on the vertical upward and horizontal flow, while it is not sufficient in the vertical downward flow. Downward flow is very important as it is frequently encountered in the industrial applications. To enrich the downward flow research, an experiment is performed on a piping system with an inner diameter of 0.1524 m. Four different flow patterns (bubbly flow, cap bubbly flow, churn turbulent flow, and annular flow) are classified with the artificial neural network method. The probability density function (PDF) profile of each flow pattern is discussed. The proposed flow regime map is compared with the other experiments and the effect of the pipe size is discussed. The existing downward flow regime boundary criteria are assessed with the experiment results. It is found that these criteria cannot fit the experiment results well. A set of general boundary criteria are still needed. In this paper, the criteria for the boundary of the bubbly flow, the boundary between the cap bubbly flow and the slug flow, and the boundary of the falling film regime are proposed. They are verified with the experiments on different size pipes. A significant inlet effect on the flow regime boundary is found. The falling film boundary criterion proposed cannot be applied when a sparger is used to inject gas into the downward test section.

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1. Introduction

Recently, more and more system analysis codes, such as RELAP5 [1], TRACE [2], are developed based on the two-fluid model. The two-fluid model is complex and contains a lot of constitutive correlations. In different flow regimes, different constitutive correlations are utilized to ensure that a correct flow structure is considered. In the past several decades, most of the flow regime analyses are focused on the upward or horizontal directions [3–5]. The flow regime transition and modeling analyses on the downward flow are rare. The downward flow analysis is important in many industrial applications, including the advanced reactor designs where passive safety systems [6–8] are extensively used. For example, a passive containment cooling system is utilized in the AP1000. When this passive system is put into work, the gas-water mixture flows downwardly along the containment inner and outer wall. Moreover, in many gravity driven safety systems, two-phase downward flow is also a common phenomenon. A clear downward flow regime map is of great importance when the thermal hydraulic behaviors of the advanced reactors are simulated and analyzed. However, for most sub-channel, system, and containment analysis codes, a downward flow regime map is lacked. These codes' simulation capability is suspicious when they are applied to advanced reactors.

Some studies have focused on the downward flow regime map. Usui [9,10] performed downward co-current experiments on 0.016 m and 0.024 m inner diameter pipes. In the experiment, two-phase flow was injected into the test section using an inverted U-tube. With the downward flow's local void fraction measured by a conductance needle probe, a center peaked void fraction profile for the downward bubbly flow was proposed. Based on the experiment results, some boundary criteria were proposed. Both upward and downward experiments on 0.0254 m and 0.0508 m pipes were performed by Lee et al. [11], who also developed an instantaneous and objective flow regime identification method. It was found that in the vertical downward flow, flow regimes' boundaries are highly dependent on the pipes' diameter. The kinetic wave propagation was observed in the experiments. Downward co-current flow experiments on 0.0254 m and 0.0508 m pipes were also conducted by Goda et al. [12]. The artificial neural network method was applied to eliminate researcher's subjective error in sorting the

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.072
0017-9310/Published by Elsevier Ltd.

Nomenclature

Symbol	
PDF	probability density function
CPDF	cumulative probability density function
$V_{non\text{-}D}$	non-dimensional voltage
$V_{measured}$	measured voltage
V_{air}	measured voltage when the loop is filled with air
V_{water}	measured voltage when the loop is filled with water
$\langle j_f \rangle$	liquid superficial velocity
$\langle j_g \rangle$	gas superficial velocity
α	void fraction
g	gravity force
D	pipe diameter
C_0	distribution parameter
C_1	drift velocity coefficient
C_w	wall friction factor
Fr_l	liquid froude number
Fr_g	gas froude number
E_o	Eotvos number
σ	surface tension
ρ_l	liquid density
ρ_g	gas density
Ku_g	gas kutateladze number
V_{gj}	drift velocity
$D_{d,\max}$	maximum distorted bubble limit
Re_f	fluid Reynolds number
δ_{mean}	mean film thickness
v	kinematic viscosity
H_{wave}	wave amplitude
RIM	ring type impedance meter
AIM	arc type impedance meter
B	bubbly flow
CB	cap bubbly flow
CT	churn turbulent flow
AN	annular flow
FF	falling film flow

flow regimes. Four flow regimes (bubbly, slug, churn-turbulent, and annular flow) were observed. The flow regime maps classified by the neural network were compared with the results got through conventional flow visualization method. And the neural network classification method was validated. A 0.0254 m diameter pipe downward flow experiment was performed by Pan et al. [13]. A new fuzzy C-means clustering algorithm and relief attribute weighting algorithm method was adopted in classifying flow regimes. Entrance effect on the flow regime transition was discussed. Pan's result was similar to that of Lee's. In the 1980 s, Barnea et al. [14] performed researches on 0.0254 m and 0.0508 m pipes. However, the proposed flow regime map differs from other researchers. Downward and upward flow experiments on a 0.038 m pipe and a 0.04 m pipe were conducted by Kendoush and Al-Khatab [15] and Yamaguchi and Yamazaki [16], respectively. Yamaguchi also performed experiments on a 0.08 m pipe. In Yamaguchi's experiments, the flow reimge maps showed significant difference of flow pattern transition boundaries within upward flow, countercurrent flow and downward flow's comparison. Julia et al. [17] performed vertical co-current downward experiments on a 0.0508 m pipe. Local void fraction was measured by a three double-sensor conductivity probe. With the void fraction signal, local flow regime maps were classified by the neural network method. It was found that only the local flow regimes in the pipe center agree with the global flow regimes. Qiao et al. [18] conducted a downward experiment on a 0.0508 m pipe and studied the inlet effect on two-phase flow parameters. Three types of inlet conditions (elbow, sparger, and sparger with a straightener) were considered. Flow regime maps for each inlet were developed and compared to identify the inlet effects. It was found that in the downward co-current bubbly flow, the void fraction profile is center-peaked. Lokanathan and Hibiki [19] reviewed downward flow experiments, existing boundary criteria, and downward drift flux models in his paper. As mentioned above, it can be found that the existing experiments are mostly conducted on small pipes. The need for large pipe's downward flow experiments is urgent.

As for the flow regime transition analysis, a set of downward flow regime criteria were provided by Usui and Barnea, respectively. Lee proposed a criterion for the boundary between the slug flow and the churn turbulent flow. Crawford et al. [20] provided a set of empirical criteria. When compared with the experiment's data in this paper, most of the existing criteria can only satisfy their own experimental data. The general flow regime boundary criteria are still lacked.

In conclusion, the research on the downward flow regime is still not enough. Besides, experiments for relative large inner diameter pipes are lacked. A set of general flow regime boundary criteria have not been provided yet. Thus, the purpose of this paper is to analyze the experimental data obtained on a 0.1524 m diameter piping loop and propose a set of general flow regime boundary criteria for the downward pipe flow.

2. Experiment setup

The experimental loop utilized in this investigation is an adiabatic, vertical and air-water system. The schematic diagram of the experimental loop is shown in Fig. 1. The test section has three parts: a top horizontal section, a vertical downward section, and a bottom horizontal section. They are all 0.1524 m inner diameter transparent acrylic pipes. It should be noted that the top horizontal section also serves as an inlet to the vertical downward flow. The length of the top horizontal section is 8.47 m, which allows the

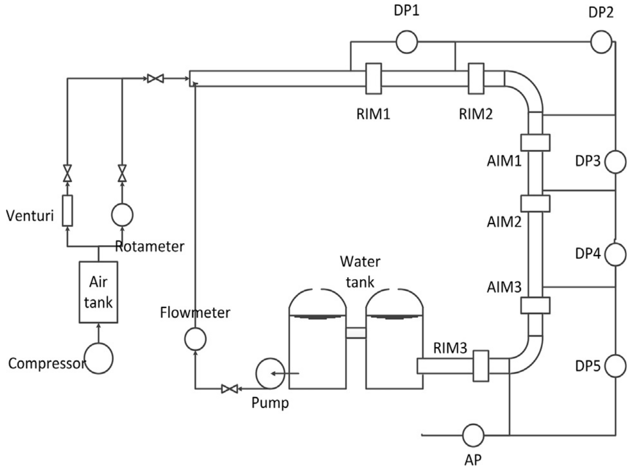

Fig. 1. Schematic of the Experiment Facility.

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