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ชื่อโครงการ

การศึกษาการไหลสองสถานะแบบแยกชั้นในท่อกลม

(A STUDY ON THE STRATIFIED TWO-PHASE FLOW IN A CIRCULAR PIPE)

เสนอต่อสำนักงานกองทุนสนับสนุนการวิจัย (สกว)

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กิติกรรมประกาศ

งานวิจัยเรื่องนี้คงไม่สามารถทำให้สำเร็จลุล่วงไปได้ ถ้าผู้เขียนไม่ได้รับทุนพัฒนานักวิจัย "เมธีวิจัย สกว รุ่นที่ 2" จากสำนักงานกองทุนสนับสนุนการวิจัย (สกว) ผู้เขียนขอกราบขอบพระคุณผู้บริหาร สกว. อาทิ ศ.นพ. วิจารณ์ พานิช , ศ. ดร. วิชัย บุญแสง, ผศ. วุฒิพงศ์ เตชะดำรงสิน ตลอดจนผู้บริหาร สกว. ทุกระดับชั้น ความกรุณาจาก สกว.ในครั้งนี้ทำให้ผู้เขียนมีกำลังใจในการทำวิจัยเพื่อช่วยให้ สกว.บรรลุถึงเป้าหมายที่ได้ตั้งปณิธาณไว้

ผู้เขียนขอกราบขอบพระคุณ รศ. ดร. หริส สูตะบุตร, ศ.ดร. วริธ อึ๊งภากรณ์ , รศ. มานิจ ทองประเสริฐ ที่ได้ออกใบรับรอง (recommendation letter) ให้ผู้เขียน เมื่อครั้งที่ผู้เขียนสมัครขอรับทุนนี้

ผู้เขียนขอกราบขอบพระคุณ กรรมการผู้ทรงคุณวุฒิผู้ประเมินผลงานของผู้เขียน ผู้เขียนไม่สามารถระบุชื่อเพื่อแสดงความกตัญญูได้ เนื่องจากผู้เขียนมิอาจรู้ว่าคือท่านใด

ท้ายที่สุดงานนี้จะไม่สำเร็จลุล่วงได้เลย ถ้าปราศจากความช่วยเหลือจาก ผู้บริหาร เจ้าหน้าที่ ทุกระดับชั้น และ นักศึกษา คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ผู้เขียนขอแสดงความกตัญญูไว้ ณ ที่นี้

Abstract

Two-Phase Flow is the most common flow of fluids in nature. The flow of blood, the drift of clouds in the atmosphere, the fluidized beds, the pneumatic conveyance of granular solids, boiling liquid are only a few examples of two-phase systems. Of the four types of two-phase flow (gas-liquid, gas-solid, liquid-liquid and liquid-solid) gas-liquid flows are the most complex, since they combine the characteristics of a deformable interface and the compressibility of one of the phases. For given flows of the two phases in a given channel, the gas-liquid interfacial distribution can take any of an infinite number of possible forms.

Many studies have been carried out both experimentally and analytically on two-phase flow. However, there are still some topics which has received comparatively little attention in the literature. In the present study, the main concern is to develop the flow regime map for cocurrent two-phase flow in horizontal pipes, to determine the wall and interfacial shear stress in stratified flow in a horizontal pipe, to study the slug formation in the horizontal countercurrent two-phase flow and to study the flooding in inclined pipes.

บทคัดย่อ

การไหลสองสถานะเป็นปรากฏการณ์จริงที่เกิดขึ้นในกระบวนการต่างๆทั้งในธรรมชาติและในอุตสาหกรรมโดยเฉพาะอย่างยิ่ง การไหลร่วมกันของก๊าซและของเหลวซึ่งถือว่าเป็นการไหลสองสถานะที่มีปรากฏการณ์ซับซ้อนที่สุดในจำนวนการไหลสองสถานะประเภทอื่นๆ (ของแข็ง - ของแข็ง , ของแข็ง - ของเหลว, ของแข็ง - ก๊าซ) ทั้งนี้เนื่องจากก๊าซเป็นของไหลที่อัดตัวได้ ทำให้เกิดความซับซ้อนที่ผิวที่สัมผัสกันระหว่างทั้งสองสถานะ อันเป็นผลให้เกิดรูปแบบการไหลต่างๆ

ได้มีการศึกษาเกี่ยวกับการไหลสองสถานะกันอย่างกว้างขวางทั้งจากการทดลองและการคำนวณ อย่างไรก็ตามยังคงมีแง่มุมที่ได้รับความสนใจน้อยหรือไม่ก็ยังไม่เคยมีคนทำมาก่อน สำหรับในงานวิจัยนี้จะมุ่งเน้นเพื่อศึกษาในสิ่งต่อไปนี้ เพื่อพัฒนาผังแสดงรูปแบบการไหลสำหรับการไหลสองสถานะแบบไหลตามกันในท่อราบ, เพื่อหาความเค้นเฉือนที่ผนังท่อและที่ผิวสัมผัสของของไหลทั้งสองสถานะของการไหลแบบแยกชั้นในท่อราบ, เพื่อศึกษาถึงการก่อตัวของสลักสำหรับการไหลสองสถานะแบบไหลสวนกันในท่อราบ และ เพื่อศึกษาถึงการไหลท่วมของกระแสไหลสวนกันของของเหลวและก๊าซในท่อเอียง

Content

1. PROJECT TITLE

A STUDY ON THE STRATIFIED TWO - PHASE FLOW IN A CIRCULAR PIPE

2. RESEARCHER

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3. FIELD OF RESEARCH Two - Phase Flow, Fluid Mechanics, Heat Transfer

4. BACKGROUND AND RATIONALE

Two-Phase Flow is the most common flow of fluids in nature. The flow of blood, the drift of clouds in the atmosphere, the fluidized beds, the pneumatic conveyance of granular solids, boiling liquid are only a few examples of two-phase systems. Of the four types of two-phase flow (gas-liquid, gas-solid, liquid-liquid and liquid-solid) gas-liquid flows are the most complex, since they combine the characteristics of a deformable interface and the compressibility of one of the phases. For given flows of the two phases in a given channel, the gas-liquid interfacial distribution can take any of an infinite number of possible forms.

Problems involving the simultaneous flow of a gas and liquid are commonly met in engineering practice. Film coolers, falling-film-absorption towers, condensers, and the transportation of liquid-vapour mixtures are examples of processes involving such two-phase flow problem. A more through understanding of these processes could be derived from a better understanding of the nature of the interaction at the interface of the liquid and gas. If a gas is blown parallel to a liquid surface, it will exert a drag on the surface and cause the liquid to flow. The drag will increase with gas flow. At high enough flows the surface will become unstable and waves will form. The drag of the gas on the liquid and the velocity profile in the gas then will be dependent upon the structure of the liquid surface. At extremely high flows liquid will be torn from the surface and dispersed in the gas stream. Flow regime transitions in two phase flows are, therefore, of great importance to engineers because the analysis of mass transport, pressure drop, heat transfer, and other processes, depends on a knowledge of the physical distribution of the phases and phase velocities in the flow channel.

Gas-liquid countercurrent flow has been applied extensively in industries for heat and mass transfer. Usually, for a given piece of equipment there is a maximum velocity at which steady countercurrent flow can be maintained. This point, known as the onset of flooding, is the point at which the flow rates of both gas and liquid phases cannot be further increased. Usually, especially in chemical engineering, this limiting condition is called flooding or countercurrent flow limitation (CCFL). Further increases in gas or liquid input rates results in partial delivery of the liquid out of the bottom. In recent years, further impetus for flooding research has been provided by concern over the restriction of emergency core cooling (ECC) in the pressurized water reactor (PWR) during a postulated loss of coolant accident (LOCA). In the event of a LOCA , which is caused by the damage at any position of the primary circuit, steam will be created in PWR. This generated steam will flow upward through the hot leg, countercurrent to the flow of cooling water. In another case, this steam will condense in the steam generator and flow back to the PWR (as shown in Fig. 1). It is essential that the injected cooling water be sufficient and that it be able to penetrate into the core. This ECC is limited by the flooding phenomena. To be able to evaluate the ECC response of the reactor during this accident, the countercurrent flow of the phases should be fully determined.

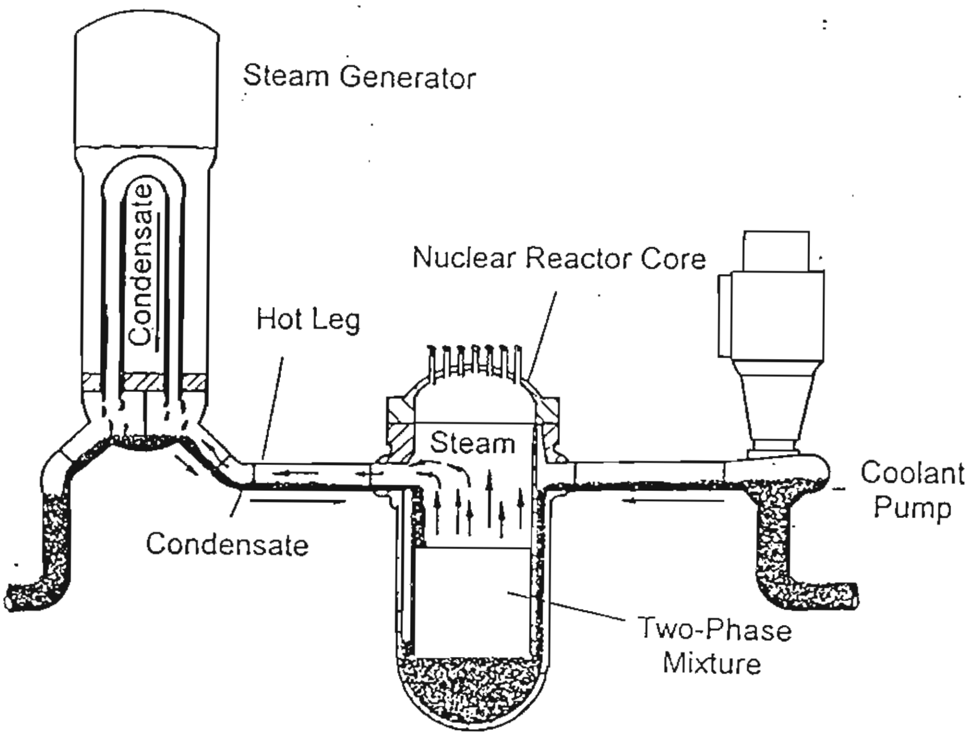

Fig. 1. Countercurrent Flow of Steam and Water in Hot Leg of PWR during LOCA

5. OBJECTIVES

5.1 to develop the flow regime map for cocurrent two-phase flow in horizontal pipes

5.2 to determine the wall and interfacial shear stress in stratified flow in a horizontal pipe

5.3 to study the slug formation in the horizontal countercurrent two-phase flow

5.4 to study the flooding in inclined pipes

6. LITERATURE REVIEW AND REFERENCE

6.1 Literature review for objective (5.1)

Two-phase flow is classified into two groups from the dynamical view-point : a steady flow and a transient flow. Further, the steady flow is divided into a fully developed flow and a developing flow. The flow characteristics of fully developed flow have been investigated and sufficient information has been obtained [1-5]. On the other hand, the flow characteristics of developing flow and transient flow have been not sufficiently and systematically investigated except for the flow characteristics in and downstream bend [6] and the propagation phenomena of pressure wave [7]. In studies of flow instabilities [8] and the dynamic behaviour [9] of flow in steam generating system, the flow pattern and the values of flow variables such as two-phase flow frictional losses, void fraction, liquid holdup, slip ratio between both phases, and heat transfer coefficient in the steady conditions have been used because the dynamic behavior of the two-phase flow might be expressed approximately as quasi-steady flow and no suitable data and values have been recommended. Useful informations have been obtained on qualitative characteristics by this method, but there is certain limitation to this application. Therefore, the values of flow variables in the transient conditions might be desirable informations for the analysis of dynamic behavior.

Then, the fundamental knowledge of the transient characteristics as well as the static characteristics is required in order to precisely analyze the dynamic behavior in two-phase flow systems. In the circumstance, the dynamic behaviors of the two-phase flow have been investigated by Nädler et al. [10]. That is, the first report which presented that the two-phase flow in the transient conditions showed the extraordinary behaviors which could not be deduced from its static characteristics. In their second paper [11], the dynamic behaviours of transient slug flow have been analyzed and the fair agreement between its calculated values and the experimental results has been obtained for various test tubes. Althrough a few studies carried out so far, there is a general feeling that much tidy work should still be necessary either from an experimental viewpoint or for a general modeling of the phenomena. Especially, the influences of the pipe,diameter and the pipe length on the boundary between the flow patterns should determined.

In the present work, the flow regime maps for the developing two-phase flow will be presented. These maps will be useful to estimate the flow pattern of developing flow in the various flow systems at steady conditions and will be used as the fundamental data to derive the flow regime maps for the transient conditions. The influences of the pipe diameter and the pipe length on the boundary between the flow patterns will also be discussed.

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6.2 Literature review for objective (5.2)

Stratified two-phase flow in pipes may occur in various chemical and industrial processes.Examples include the flow of oil and natural gas in pipelines and flow of steam and water in horizontal pipe networks during certain postulated LOCA. Knowledge of the wall and interfacial shear stresses is required for modeling the flow in these applications.The structure of the moving gas-liquid interface plays a considerable role in determining thermal-hydraulic behaviours of two-phase flows. Waves appearing on the interface significance affect the mechanism of momentum, heat and mass transfer through the interface as well as the characteristics of flow parameters. The interfacial shear stress, which is one of the important parameters featuring the nature of the interface, is largely controlled by local properties of the waves, and is closely connected to a flow pattern transition.

Experimental studies of the wall and interfacial shear stress have been presented in a number of papers over the past thirty years [12-15] mostly for cocurrent two-phase flow. However, all of the investigations reported to date have involved rectangular conduits at atmospheric pressure. In most cases, the wall and interfacial shear stress were expressed in terms of macroscopic flow parameters, such as the void fraction, the gas and liquid Reynolds numbers, and/or fluid physical properties for direct applications. This type of correlation has been widely used in the stability analysis and heat and mass transfer investigation of two-phase flow [16]. At the present time no methods exist to measure the interfacial shear directly; however, this quantity may be deduced indirectly from:

- Gas velocity profile measurements [12,17]
- Turbulent kinetic energy profiles [14]
- The momemtum balance using the wall-to-gas shear stress, liquid level, and pressure drop measurements [13,19,20]
- The extrapolation of the shear stress profiles at the gas-liquid interface [14,18]

In the present work, the wall and interfacial shear stress for stratified both cocurrent and countercurrent flow in a circular horizontal pipe will be measured. In addition, the empirical correlation of the wall and interfacial friction factors will be developed for practical applications.

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6.3 Literature review for objective (5.3)

During LOCA in a PWR, countercurrent flow of steam and cold water may take place in horizontal channel when the ECC water is injected into the pipe. This type of flow also appears in the auxiliary feed water system of the steam generator in PWR after stopping the main feed water pump. The flow stability in the two cases is very important in relation to the safety analysis of the nuclear reactor. It is necessary to explicate the mechanism of the transition from stratified flow to slug flow in horizontal countercurrent gas-liquid flow.

When the difference of gas and liquid velocities becomes large enough the interface waves grow quickly to block the cross-section of the duct. For countercurrent flow, most of the studies infer the transition condition from cocurrent flow which based on Kelvin-Helmholtz instability theory. As for cocurrent flow, Mishima and Ishii [21] developed the classical Kelvin-Helmh oltz instability theory [22] using the concept of 'the most dangerous wave' with the largest growth rate. In order to obtain the criterion for slug formation in closed conduit, they considered waves of finite amplitude. However the viscous term effecting flow stability was not included in their analysis. Lin and Hanratty [23] applied the Kelvin-Helmholtz instability mechanism to a small-amplitude long wave length disturbance at the interface for cocurrent two-phase flow. The liquid phase viscous and inertia terms are included in their analysis. Flooded discharge of water from a vessel and along a short horizontal tube (length/diameter ratio of approx. 10) with a countercurrent of air has been studied experimentally by Richter et al. [24], Krolewski [25] and Gardner [26].

Similar flooded discharge of carbon dioxide against air and brine against water has been studied by Leach and Thompson [27]. Some experiments were conducted with a scale model of the hot leg of a PWR. Kukita et al. [28-30] studied the characteristics of two-phase flow during natural circulation at the hot legs of PWR using a large-scale test facility. Tehrani et al. [31] conducted experiments of air/water low and high head flooding from the model of the hot leg, and the distinction between the two types of flooding was determined.Hence, we can say the transition of flow patterns on cocurrent flow has been studied in some detail. On the other hand, the study on countercurrent two-phase flow is not enough. Since countercurrent flow has some special features that differ from cocurrent flow, it is necessary to deal with it directly but not to extrapolate from cocurrent flow.

The objective of this research is to characterize the flow patterns observed for countercurrent gas-liquid flow in a horizontal pipe and to propose a criterion for the onset of slug flow by experimental and theoretical analyses.

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6.4 Literature review for objective (5.4)

As described, Flooding in countercurrent gas liquid flow is the term used to describe the limiting flow input of liquid against rising gas or vapour. This phenomena has been investigated in connection with the performance of wetted wall columns, packed towers, condensers, cooling towers, geothermal flows of steam and water mixtures and in connection with LOCA in nuclear reactors.

Flooding experiments have been carried out usually with adiabatic air-water flow in vertical tubes [32-35]. Liquid is introduced into the tube either through a porous injection located at the middle of the tube or from a top tank where the liquid flows by gravity. The porous injection is generally considered to be the smoothest entry which generates the least disturbances in the liquid flow [36,37]. Wallis et al. [38] showed that the tube diameter and entrance conditions are important parameter in Flooding. They tested various geometries of entry and end effects in a top flood entry arrangement. It was found for various tested tube sizes that entry geometries affect the limiting air and water flows.

Tien et al. [39] also examined the effect of tube size and flow entry conditions on the flooding velocities in a vertical tube where the liquid was introduced by spilling it over the top of the tube under gravity. They found that when the flow entry conditions of liquid and gas were designed to mimimize entry effects flooding was primarily a result of the interfacial instability inside the tube, and the tube size did not significantly affect the flooding phenomenon. When a sharp edge liquid inlet was used, flooding always took place around the inlet due to local thickening of the liquid film. In addition when the flow inlet-exit conditions are not smooth the effect of tube size becomes more pronounced.

Most of the flooding experiments have been performed in vertical tubes. Very little work has been reported on the effect of inclination on the flooding phenomenon. Hewitt [40] performed experiments in inclined tubes using a porous injector to introduce the liquid. He found that the liquid flooding velocity increases and then decreases as the inclination angle was changed from vertical to 10°. The stability of countercurrrent stratified inclined flow with condensation was investigated by Lee and Bankoff [41] in a rectangular channel. Beckmann et al. [42] performed the experiments with countercurrent flow of air and water in inclined pipes. The experimental analysis covered th effects of pipe inclination and diameter.

The flow pattern and the physical process of countercurrent flow were studied based on measurement of liquid holdup and pressure drop. A correlation for the interfacial momentum exchange was derived from the experiments. Wongwises [43] investigated the experimental data of the countercurrent flow limitation for air and water in a bend between a horizontal pipe and a pipe inclined to the horizontal. He found that the different mechanism that lead to flooding and that are dependent on the water flow rate. The influence of the inclination angle of the bends, the water inlet condition, and the length of the horizontal pipes is of significance for the onset of flooding.

In the present work new experimental data will be taken on initiation of flooding in inclined pipes in the whole range of inclinations. A Model for the prediction of the flooding inception will be developed.

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8. RESEARCH METHODOLOGY

8.1 An experimental setup (as shown in Fig. 2) will be developed. It can also be modified to obtain each objective in (5)

8.2 From the apparatus in (8.1), the flow patterns for cocurrent flow will be studied by visual observation, the flow regime map can be developed from these flow patterns.

8.3 The instrument for measuring liquid holdup and void fraction will be developed. The most of work in this step concern the design of electrical circuit and the data acquisition system.

8.4 The wall and interfacial shear stress in stratified cocurrent flow will be determined by

- using the instrument in (8.3) to measure liquid holdup
- using Laser Doppler Anemometer to determine the velocity profile of gas phase. Reynold stress can, therefore, be found.
- using flow meter to determine the superficial velocity of liquid and gas

8.5 From all data in (8.4) and momentum balance between phase, the mathematical model to determine the wall and interfacial shear stress can be developed.

8.6 The experimental rig in (8.1) will be modified. The flow direction of gas will be reversed.

8.7 Onset of slugging for countercurrent flow in the horizontal pipe will be experimental studied.

8.8 Mathematical model for predicting the onset of slugging by instability analysis will be developed. The results will be compared with experimental data in (8.7).

8.9 From the experimental rig in (8.6), the interfacial friction factor will be developed in the same way with (8.4), except the pressure drop will be included.

8.10 The inclination angle of pipe will be adjusted.

8.11 The flooding in the inclined pipe will be studied by using the experimental rig in (8.10)

8.12 The mathematical model for predicting the onset of flooding will be developed and the results will be compared with the data from (8.11)

9. SCOPE OF RESEARCH

9.1 It is the experimerltal and theoretical investigation

9.2 Cocurrent and countercurrent flow will be studied.

9.3 For cocurrent flow, only the horizontal flow in the circular pipe will be studied.

9.4 For countercurrent flow, the horiontal and inclined pipe flow will be studied.

9.5 The results of each step in the research has some relationship with each other. The results of each step will be used to obtain the object in the next step.

10. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental system is shown in Fig.2. Air and water are used as the working fluids. The main components of the system consist of the test section, air supply, water supply, instrumentation, and data acquisition system.

The test section is made of transparent acrylic glass to permit visual observation of the flow patterns. The length of horizontal pipe can be varied during the experiments.The connections of the piping system are designed such that parts can be changed very easily. Air is injected from a compressor to pass through the reservoir, the regulation valve, the rotameter and the test section. Water is pumped from the storage tank through the rotameter, the water inlet section and the test section.

The inlet flow rates of air and water are measured by two sets of rotameters. The entrained water flow rate is registered by flow meter and the water is returned to the storage tank while the separated air is exhausted into the atmosphere. The pressure in the test section can be regulated and kept constant automatically during the experiment by an absolute pressure transducer and a control valve in the air discharge line. The temperature of air and water are measured by thermocouples. The two-phase pressure drop between the specific range in the test section is registered by a capacitive pressure transducer. The Impedance and Capacitance Method will be developed for measuring liquid holdup, which is defined as the ratio of the cross-sectional area filled with liquid to the total cross-sectional area of the pipe. All signals of the measuring transducers are registered by a data acquisition system and finally they are averaged over the time elapsed.

In generally, the experiments are conducted with various flow rates of air and water, various lengths of the pipe. The system pressure is kept constant during experiments. In the experiments the air flow rate is increased by small increments while the water flow rate is kept constant. After each change in inlet air flow rate, both the air and water flow rates are recorded. The pressure

drop across the test section, the entrained water, and the liquid holdup are registered through the transducets and transferred to the data acquisition system. The flow phenomena are detected by visual observation

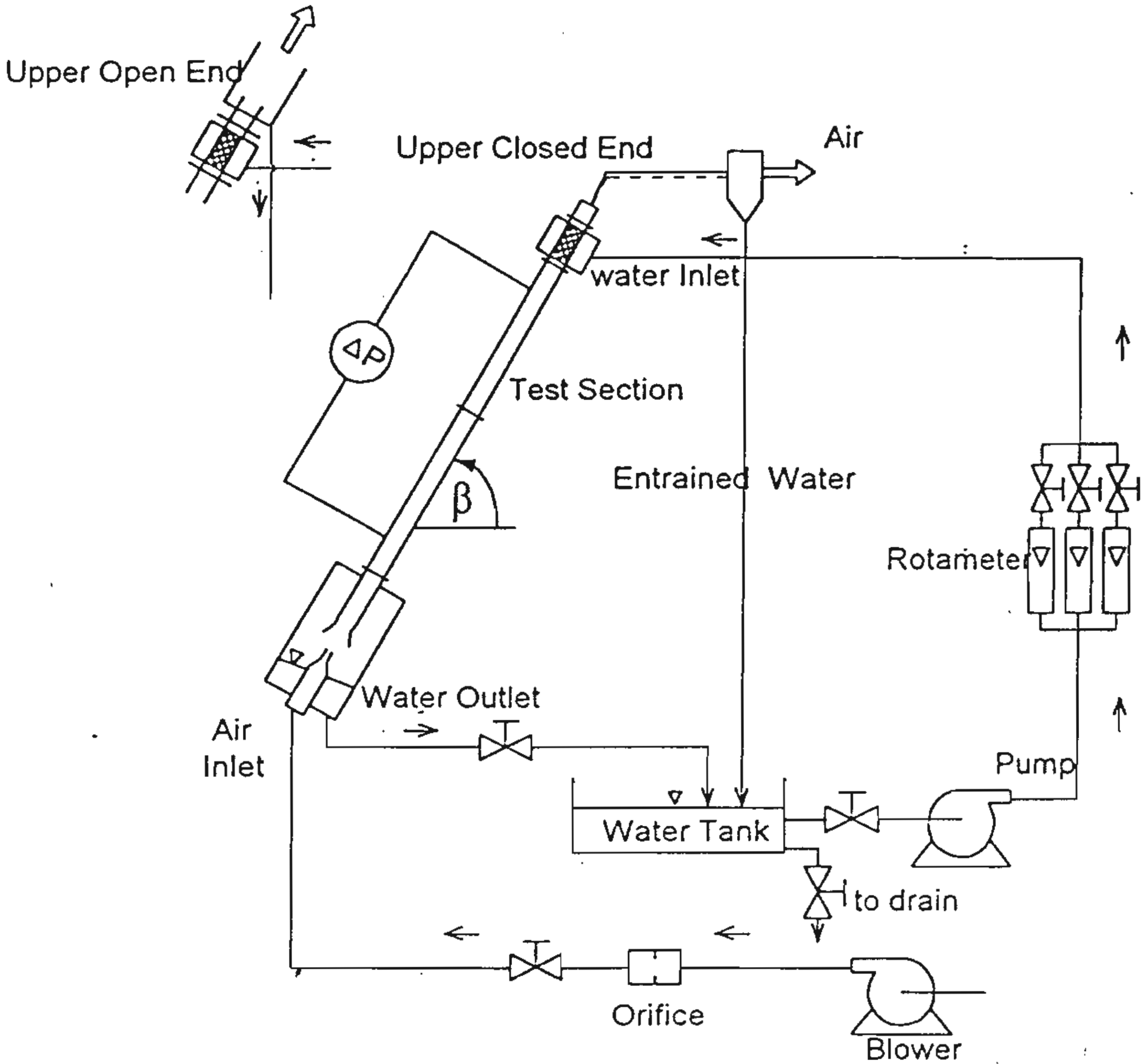

Figure 2. Schematic diagram of experimental apparatus

11. THREE YEARS RESEARCH PLAN

Activity	Time (year) 0	1	2	3
8.1 - 8.3	***********			
8.4 - 8.8		**********		
8.9 - 8.12			**********	

12. PRACTICAL SIGNIFICANCE & USEFULNESS

The results of the research are of technological importance for the design and analysis of various chemical and industrial processes, particularly is important for reliable design of gas-oil pipe line transportation systems and of thermal-hydraulic responses of nuclear reactors during accidental conditions

13. OUTPUT

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(with acknowledgement for the Thailand Research Fund (TRF) at the end of the paper)

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Two-phase countercurrent flow in a model of a pressurized water reactor hot leg

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Abstract

The onset of flooding or countercurrent flow limitation (CCFL) determines the maximum rate at which one phase can flow countercurrently to another phase. In the present study, the experimental data of the CCFL for gas and liquid in a horizontal pipe with a bend are investigated. The different mechanisms that lead to flooding and that are dependent on the liquid flow rate are observed. For low and intermediate liquid flow rates, the onset of flooding appears simultaneously with the slugging of unstable waves that are formed at the crest of the hydraulic jump. At low liquid flow rates, slugging appears close to the bend; at higher liquid flow rates, it appears far away from the bend, in the horizontal section. For high liquid flow rates, no hydraulic jump is observed, and flooding occurs as a result of slug formation at the end of the horizontal pipe. The effects of the inclination angle of the bends, the liquid inlet conditions and the length of the horizontal pipes are of significance for the onset of flooding. A mathematical model of Ardron and Banerjee is modified to predict the onset of flooding. Flooding curves calculated by this model are compared with present experimental data and those of other researchers. The predictions of the onset of flooding as a function of the length-to-diameter ratio are in reasonable agreement with the experimental data.

1. Introduction

Countercurrent flow limitation (CCFL) corresponds to the limiting condition where the flow rates of neither the gas nor the liquid phase can be increased further without altering the flow pattern. Various authors have given different definitions of flooding, but the flooding point generally refers to the onset of flooding (Lee and Bandoff, 1983). Recently, the thermal-hydraulic analysis of countercurrent two-phase flow has been of importance in connection with the safety analysis of nuclear reactor systems. In the event of a loss of coolant accident (LOCA), which is caused by damage at any position of the primary circuit, steam will be created in the pressurized water reactor (PWR). This generated steam will flow upward through the hot leg, moving countercurrently to the flow of cooling water (Fig. 1). In another case, this steam will condense in the steam generator and flow back to the PWR (Fig. 2). It is essential that the injected cooling water be sufficient and that it be able to penetrate into the core. This emergency core cooling (ECC) is limited by the flooding phenomena. To

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be able to evaluate the ECC response of the reactor during this accident, the countercurrent flow of the phases should be fully determined.

The CCFL has been studied by a large number of researchers, both experimentally and analytically, mostly in vertical pipes. The CCFL in horizontal or nearly horizontal geometries has received comparatively little attention in the literature. Some of the earliest work was performed by Wallis and Dobson (1973), Gardner (1977), Lee and Bankoff (1983), Choi and No (1995). However, to study the phenomenon of flooding in a PWR hot leg, the results from CCFL studies in horizontal flow paths are not enough, because the flow behavior near the bend that connects the horizontal pipe with the inclined riser governs the CCFL characteristics of PWR hot legs (Ohnuki et al., 1988).

Relatively little information is currently available on CCFL or flooding phenomena in horizontal pipes with bends (Ardron and Banerjee, 1986; Dillistone, 1992; Kawaji et al., 1991; Mayinger et al., 1993; Ohnuki et al., 1988; Siddiqui et al., 1986; Siemens, 1992; Sonnenburg, 1993; Tehrani et al., 1990; Wan and Krishnans 1986; Wang, 1993; Wang and Mayinger, 1995). In the present study, the main concern is to obtain and analyze the experimental results of CCFL of air and water. The effects of the pipe lengths, the water inlet conditions and the inclination angle of bends on the flooding phenomena are also investigated.

2. Experimental apparatus and method

The experimental apparatus is shown schematically in Fig. 3. Air and water are used as the working fluids. The main components of the system consist of the test section, air supply, water supply, instrumentation and data acquisition system. The test section (Fig. 4), with an inside diameter of 64 mm, is made of transparent acrylic glass to permit visual observation of the flow patterns. It is composed of a horizontal pipe, an upwardly inclined pipe and a bend that connects them. The inner and outer bend radii of curvature are 60 and 135 mm respectively. The bends with different angles are constructed accurately by machining an ingot of acrylic glass.

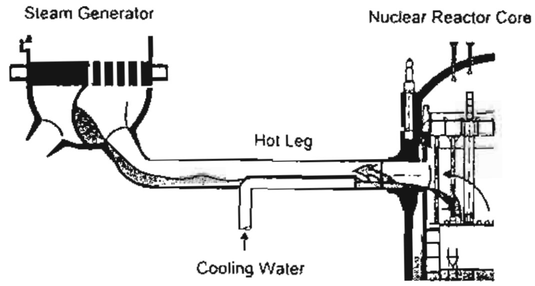

Fig. 1. Countercurrent flow of steam and cooling water in hot leg of PWR during LOCA.

The lower leg of the bend is connected to the horizontal pipe, while the other end of the bend is connected to the supply tank. The supply tank is a cylindrical vessel 400 mm in diameter and 1060 mm tall. The length of horizontal pipe can be varied during the experiments. The upper leg of the bend is connected to a straight pipe 1300 mm in length, the other end of which is connected to the water inlet section and the separation unit. Air is injected from a compressor to pass through the reservoir, the regulation valve, the rotameter, the supply tank and the test section. Water is pumped from the storage tank through the rotameter, the water inlet section, the test section and the supply tank, and flows back to the storage tank. The entrained water is separated from the two-phase mixture by the cyclone separator and flows back to the storage tank.

Two types of water inlet section, i.e. an inner pipe inlet section and a porous inlet section, are

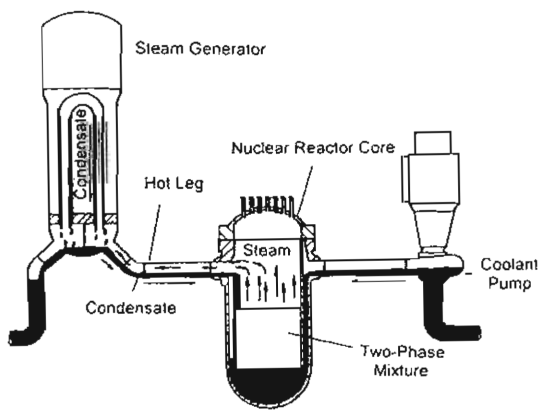

Fig. 2. Countercurrent flow of steam and condensate in hot leg of PWR during LOCA.

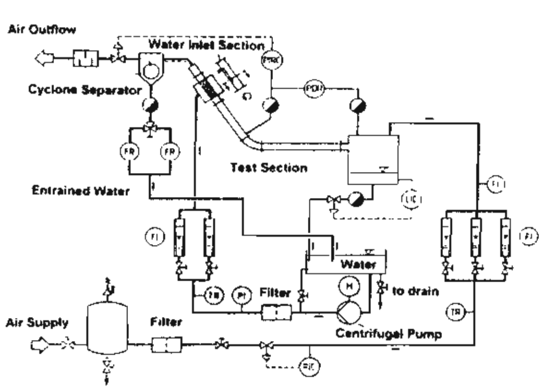

Fig. 3. Schematic diagram of apparatus.

used in the experiments. The inner pipe inlet section consists of a circular pipe of inside diameter 32 mm and length 150 mm that is installed in the pipe at the water inlet section. The porous section is made of sintered steel of 200 μm filter grade, 100 mm long. The water from the inlet section flows downward to the bend, into the horizontal section and then to the supply tank, while the air flows countercurrently. The level of water in the supply tank is kept constant and excess water is returned to the storage tank.

Two sets of rotameters are used to measure the inlet flow rates of air and water. The entrained water flow rate is registered by two flow meters and the water is returned to the storage tank while the separated air is exhausted into the atmosphere. The pressure in the test section can be regulated and automatically kept constant during the experiment, by an absolute pressure transducer and a control valve in the air discharge line. The temperatures of the air and water are measured by thermocouples. The two-phase pressure drop between the supply tank and the upper part of the bend is registered by a capacitive pressure transducer.

Liquid hold-up ε_L is measured by conductance cells. The position of measuring is shown in Fig. 4. Stainless ring electrodes are mounted flush in the tube wall, for measuring the liquid hold-up, which is defined as the ratio of the cross-sectional area filled with liquid to the total cross-sectional area of the pipe. The measuring positions are located 70 mm along the horizontal part from the bend. The electrical conductivity of water between the electrodes constitutes an electrical resistance that can be registered via a Wheatstone bridge, by a carrier frequency amplifier (Fig. 5). The bridge is fed by an alternating voltage fo 5 kHz. This frequency is sufficiently high to avoid polarization effects at the electrode surfaces. However, this frequency is low enough to neglect capacitive effects. The measured electrical resistance is a function of the electrode distance, the electrode width and the level of liquid between the electrodes. A micrometer is used to measure the liquid height and then the liquid hold-up is calculated. The non-linear correlation from calibration between the measured signal and the liquid hold-up is estimated. It was also found by calibration that, for electrode distances greater than 40 mm and an electrode width of 5 mm, the measured liquid hold-up is independent of the interface curvature. In this work, an electrode width of 5 mm and electrode distance of 60 mm are used. The uncertainty in the measured liquid hold-up is estimated to be $\pm 2\%$. All the signals of the measuring transducers are registered by a data acquisition system with a frequency of 20 Hz and, finally, they are averaged over the time elapsed.

Experiments are conducted with various flow rates of air and water, various inclination angles of the bend (θ), various lengths of the horizontal pipe, and various water inlet conditions. The system pressure is constant at 130 kPa during the experiments. In the experiments, the air flow rate is increased by small increments, while the water flow rate is kept constant. After each change in inlet air flow rate, the air and water flow rates are recorded. The pressure drop across the test section, the entrained water and the liquid hold-up are registered through the transducers and transferred to the data acquisition system. The experiments are carried on until the point of zero liquid penetration appears, when all the water at the outlet is carried over by the air flow.

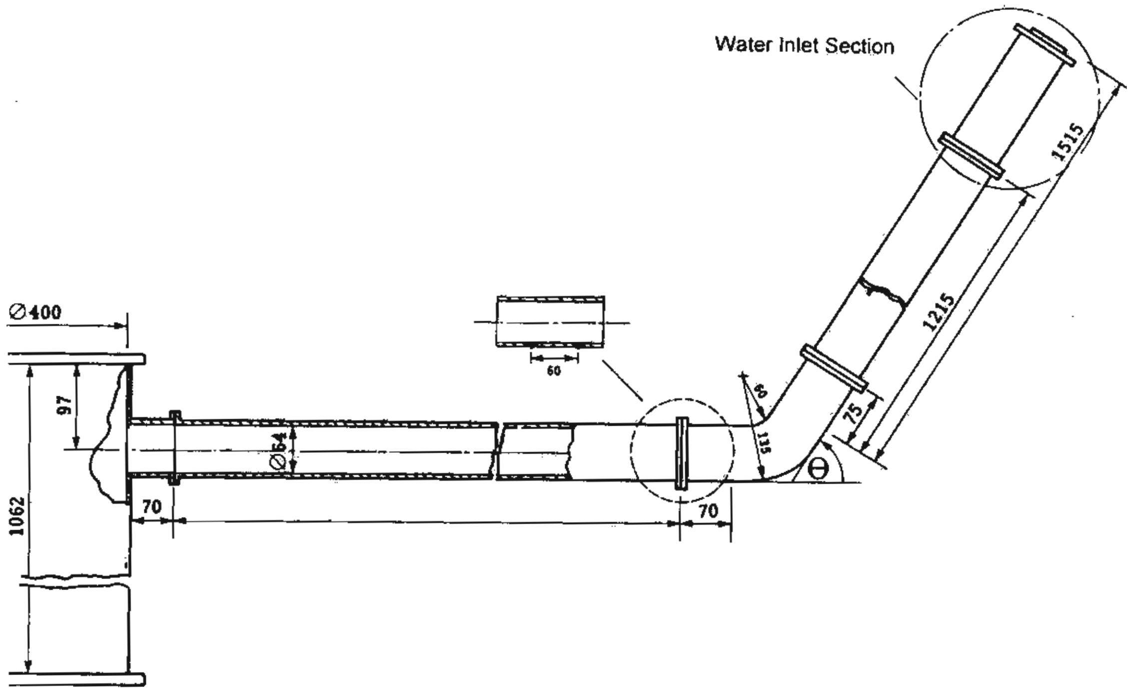

Fig. 4. Test Section

3. Results and discussion

3.1 Description of the flooding phenomena

The CCFL was determined by keeping the injected water flow rates constant, and the air flow rate was increased in small increments up to the onset of flooding and the point of zero liquid penetration. Flooding may be characterized by visual observation and pressure drop. Under specific experimental conditions, the onset of flooding is found to depend on the inlet feed water flow rate. Figs. 6 and 7 show the relation between the square root of the dimensionless superficial velocity of water at the outlet of the horizontal pipe $(j^*_{L,o})^{1/2}$ and the pressure drop (ΔP), respectively, with the square root of the dimensionless superficial velocity of air $(j^*_G)^{1/2}$. The variables j^*_G and j^*_L are defined by

$$j^*_k = \left[\frac{\rho_k}{(\rho_L - \rho_G)gD}\right]^{1/2} j_k \qquad (1)$$

where j_k and ρ_k denote the superficial velocity and density, respectively, of phase k; g is the gravitational acceleration and D is the pipe diameter. In both figures, the phenomena of flooding are shown.

For single-phase flow, the pressure drop increases slightly as the air flow rate is increased. In the case of two-phase countercurrent flow, the interfacial shear force increases at high air flow rates. Before the onset of flooding is reached, the superficial velocities of the water at the inlet and outlet of the pipe are equal. The pressure drop of two-phase flow increases slightly until the onset of flooding is reached. As a result of instabilities at the interface, slugging occurs and the pressure drop suddenly increases. The slugs carry a fraction of the injected water to the outlet; thus, the water flow at the outlet of the horizontal pipe is smaller and, afterwards, the pressure drop decreases.

3.2. Flooding curve

A typical flooding curve that connects all points

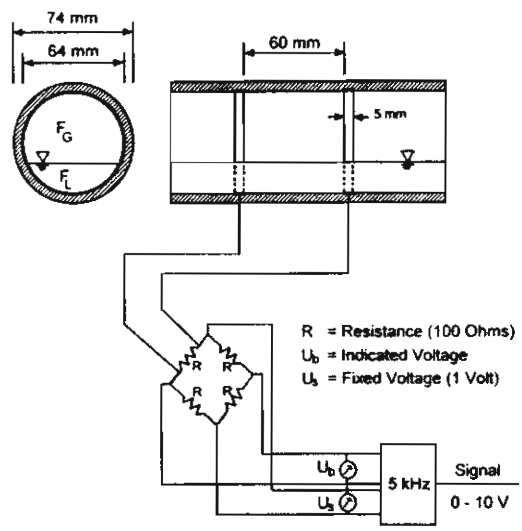

Fig. 5. Method of measurement of liquid hold-up.

of the onset of flooding is shown in Fig. 8, which presents the relation between $(j_L^*)^{1/2}$ and $(j_G^*)^{1/2}$. The flooding curve is divided into three regions, in each of which the mechanism of flooding is different. These three mechanisms are dependent on the water flow rate.

In the first region ($(j_L^*)^{1/2} < 0.2$), the air flow rate that creates the onset of flooding decreases, while the water flow rate increases. Because the water flow rate is accelerated by gravity, the supercritical flow suddenly changes to subcritical flow in the horizontal part, and a hydraulic jump is observed. The position of the hydraulic jump is dependent

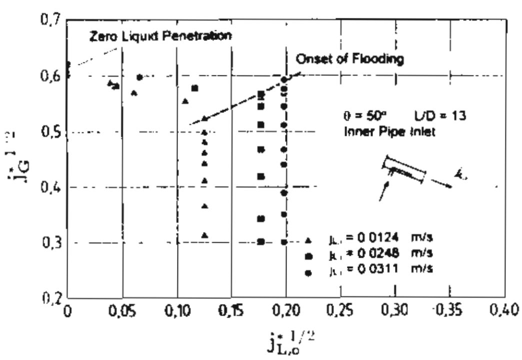

Fig. 6. Relationship between water outflow and air flow at constant inlet feed water flow.

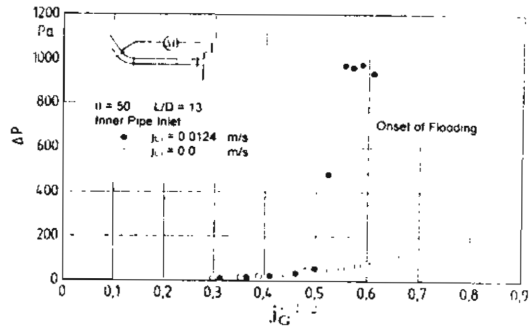

Fig. 7. Relationship between pressure drop and air flow at constant inlet feed water flow.

on the water flow rate. At low water flow rates, the hydraulic jump is very thin and appears near the bend. At a higher water flow rate, the hydraulic jump is larger and shifts away from the bend.

At a certain air flow, the flooding point is reached. The hydraulic jump is shifted back to the bend and the air–water interface in this region becomes more wavy. The large-amplitude roll wave appears. This creates an instability of the interfaces and a decrease in the flow path of air. Thus, air velocities near the crest of the waves are higher, leading to the blowing up of the wave crests, which break up into droplets and splash up to the inner wall of the bend. The interface in the horizontal section, except for the vicinity of the bend, is calmer. With further gradual increasing of the air flow, some water is eventually carried over by air to the separation unit. Finally, at the

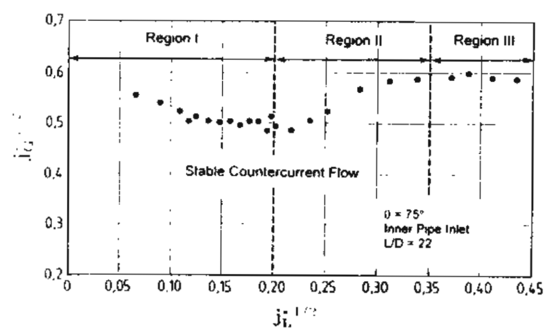

Fig. 8. Typical flooding curve.

onset of the zero liquid penetration limit, there is no flow to the outlet of the horizontal pipe.

In the second region ($0.2 < (j_L^*)^{1/2} < 0.35$), the air flow rate that initiates flooding increases with increases of the water flow rate. In this region, two different phenomena are observed.

For $(j_L^*)^{1/2}$ slightly greater than 0.20, the hydraulic jump happens in the horizontal section near the supply tank, and the height of the jump is greater as the air flow is increased. Eventually, at a specific air flow rate, the onset of flooding is reached. As a result of the instability of the interface at the front face of the hydraulic jump, an unstable wave is formed. The flow area is reduced and the high velocity of the air pushes the injected water ahead like a froth slug. The formation of the slug is accompanied by a sharp increase in the pressure drop across the horizontal pipe, and the slug leads to a continuous carry-over of water from the horizontal pipe to the separation unit. Bridging of the pipe occurs inside the horizontal part near the bend, before the slug moves through the bend to the inclined pipe.

For $(j_L^*)^{1/2} > 0.20$, a slight increase in air flow causes the hydraulic jump to occur at the water outlet or near the outlet. Unstable waves are formed and splash up to the upper wall of the horizontal pipe, forming a slug. The slug is swiftly pushed upstream. Bridging occurs relatively far away from the lower leg of bend. In this region, the location of the onset of flooding coincides with the location of the onset of slugging in the horizontal pipe, accompanied by partial or total carry-over of the injected water.

In the third region, the water flow is large ($(j_L^*)^{1/2} > 0.35$) and the air flow rate that initiates the flooding tends to decrease with increasing water flow rate. The flow is supercritical throughout the horizontal leg and no hydraulic jump is observed. Just before the onset of flooding, there is a thickening of the water film at the outlet. Many small droplets are carried back from the free water to the upper wall of the pipe, near the outlet. At a sharply defined air flow rate, a slug is formed at the end of the horizontal pipe; it blocks the whole tube section and is then pushed strongly by the air with very high velocity to the bend through the separation unit, limiting the outflow of water.

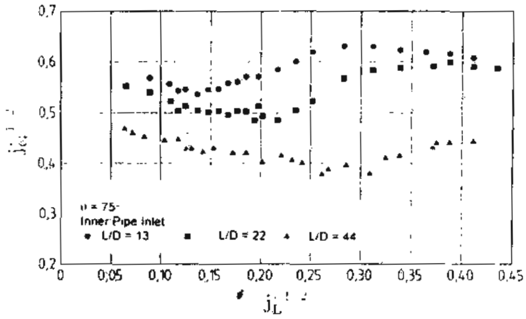

Fig. 9. Effect of horizontal length on flooding.

3.3. *Effect of pipe length on flooding*

In Fig. 9, the flooding curves for the three pipes with different length-to-diameter ratios are shown. With increasing horizontal pipe lengths, the air velocity at which flooding occurs decreases for the whole range of water flow rates. Considering the first region of flooding curves for all pipe lengths, the water level at the connection between the bend and the horizontal part is greater for the case of the longer pipe. Thus, the height of the hydraulic jump is greater for a specific water flow. The air flow in the vicinity of the crest of the hydraulic jump will be accelerated, so will have a higher air velocity, leading to earlier wave growth at the crest of the hydraulic jump; eventually, the flooding is initiated earlier. For shorter horizontal lengths, the flooding in this region occurs in a narrower interval than in the case of the longer pipes.

At intermediate water flow rates, a similar reason can be given. The effect of pipe length becomes clearer in this region. The reason is that, because of the increase in friction when the pipe is longer, the water flow is decelerated and the liquid hold-up will be higher. A hydraulic jump is formed and the flooding appears simultaneously with the onset of slugging somewhere in the horizontal part of the pipe.

At high water flow rates and for shorter pipes, the water flow rates create supercritical flow through the horizontal part; thus, the hydraulic jump is swept out from the end of the horizontal part, and the mechanisms of flooding are changed to the formation of slugging at the end of the horizontal pipe. This requires much higher air flow rates to initiate the flooding than with the longer horizontal lengths at the same water flow rate, or lower water flow rates at the same pipe length. It can also be seen that the effect of pipe length becomes clearer when the water flow rate is greater.

3.4. Effect of inclination angle of the bend on flooding

In Fig. 10, the flooding curves for different inclination angles of bend at the same water inlet condition and length-to-diameter ratio are shown. In the low water flow rate regions, for larger inclination angles, the change in water flow direction causes greater turbulence to develop in the lower leg of the bend. The considerable turbulence leads to a decrease in energy. This encourages the development of a hydraulic jump that is closer to the bend and higher. As the air flow rate is gradually increased further, an unstable wave is formed earlier at the crest of the hydraulic jump. Therefore, the air velocity necessary to cause flooding at a greater inclination angle seems a little bit lower. The range of water flow rates in this region for smaller inclination angles is narrower than the rates for larger inclination angles. At intermediate and high water flow rates, for smaller inclination angles, the water stream flows quickly and directly to the end of the horizontal pipe. The height of the hydraulic jump and the water level along the horizontal pipe are slightly less. Thus, in the case of the high water flow rate, the flow is more supercritical through the horizontal pipe than are the flow rates of larger inclination angles. The flow along the horizontal pipe is accelerated by gravity and tends to depress the growth of unstable waves. Therefore, a greater air flow rate is required to cause flooding.

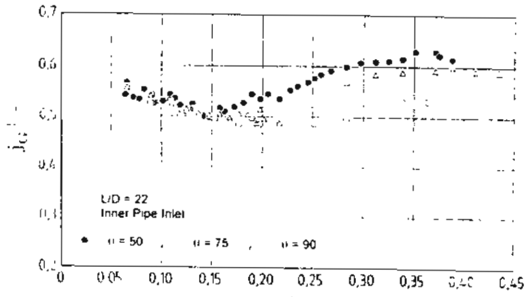

Fig. 10. Effect of inclination angle of bend on flooding.

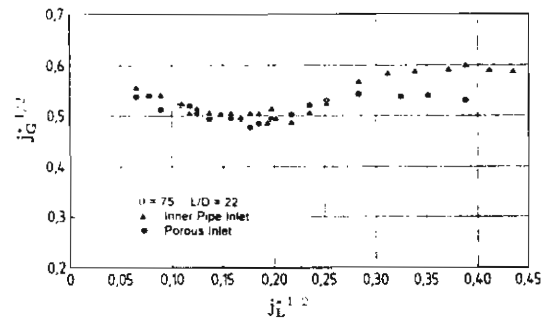

Fig. 11. Effect of water inlet conditions on flooding.

3.5. Effect of the water inlet section on flooding

The effect of the water inlet condition is closely associated with the inclination angles. For the regions of low water flow rate, the onset of flooding is nearly the same for both types of water inlet. In regions of high water feed rates, the onset of flooding from the porous water inlet occurs at a lower air velocity. This is because of the local disturbance at the water inlet section. At higher inclination angles, as a result of the effect of gravity, the axial velocity of water from the porous water inlet increases and the local disturbance at the porous water inlet decreases. The difference in the onset of flooding for the two types of water inlet is reduced, but the porous water inlet has a slightly lower flooding velocity. The effect of the inclination angles and water inlet conditions can be investigated; these play an important role in the regions of intermediate and high water flow rates. Fig. 11 shows the effect of the water inlet conditions on flooding.

3.6. Zero liquid penetration limit

The zero liquid penetration limit is reached when the water flow rate at the water outlet or the air inlet of the horizontal pipe reaches zero. In Fig. 12, the air velocity is given at zero liquid

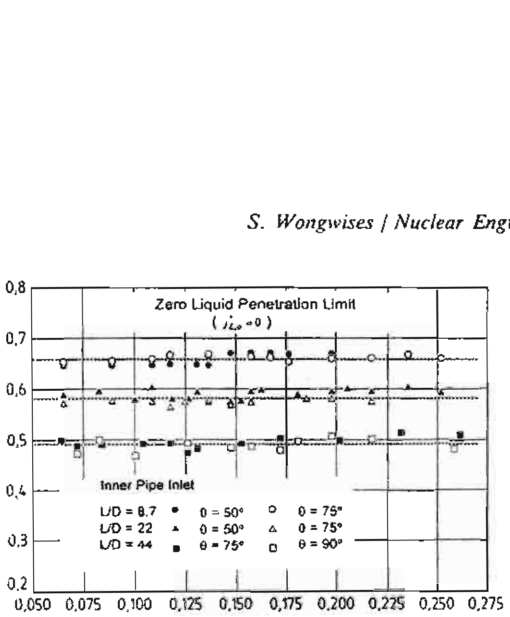

Fig. 12. Air flow at zero liquid penetration limit for specific water feed rate.

penetration for specific water feed rates with length-to-diameter ratios of the pipe and different types of inclination angles of the bend. The zero liquid penetration limit depends slightly on the inclination angle of the bend the water inlet conditions but depends strongly on the length of the pipe. With longer pipes, the zero liquid penetration limit is reached at a lower air velocity.

3.7. *Void fraction at the onset of flooding*

Fig. 13 shows the relationship between the void fraction (ε_G) 70 mm from the bend and the dimensionless superficial velocity of air (j_G^*) at the onset of flooding, for the interval of low liquid flow rate in which the flooding coincides with the onset of slugging near the bend (first region of the flooding curve). The void fraction is defined by $\varepsilon_G = 1 - \varepsilon_L$,

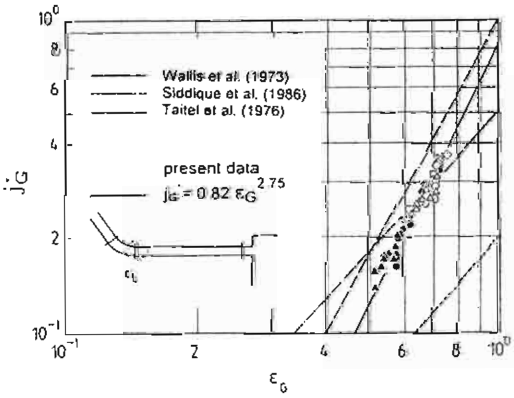

Fig. 13. Relationship between ε_G and j_G^*.

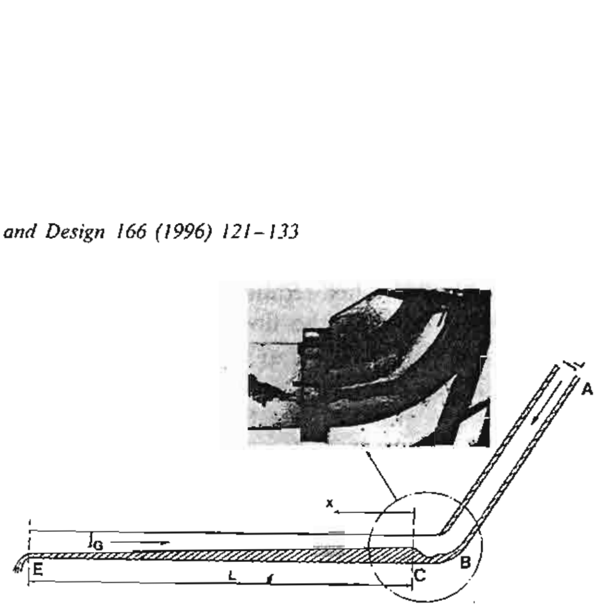

Fig. 14. Model for countercurrent two-phase flow during flooding in a horizontal pipe with a bend.

where ε_L is the liquid hold-up and can be measured directly by the method described in the previous section. The correlation can be represented as

$$j_G^* = 0.82\varepsilon_G^{2.75} \tag{2}$$

Fig. 13 also shows the correlation from the work of Siddiqui et al. (1986) for the countercurrent stratified flow in an elbow between a vertical and a horizontal or near-horizontal pipe, and shows the correlation from Wallis and Dobson (1973) and Taitel and Dukler (1976) for the cocurrent stratified flow in a horizontal pipe.

4. Mathematical model

For comparison with the experimental results, the theoretical flooding curves will be derived to show the curves as functions of the gas and liquid flow rates. Ardron and Banerjee (1986) presented a model based on the instability of the gas–liquid interface and the formation of a hydraulic jump in the horizontal pipe. The model will be modified for this study. The flow phenomenon which is observed from the experiment and is used as the basis for the calculation is shown in Fig. 14.

A horizontal pipe is connected to an inclined pipe by a bend. Liquid is injected at A through the liquid inlet section at a constant flow rate, and flows down the wall of inclined pipe and then along the bottom of the horizontal pipe in stratified flow to the liquid outlet section. Gas is injected into the system at E and flows counter-

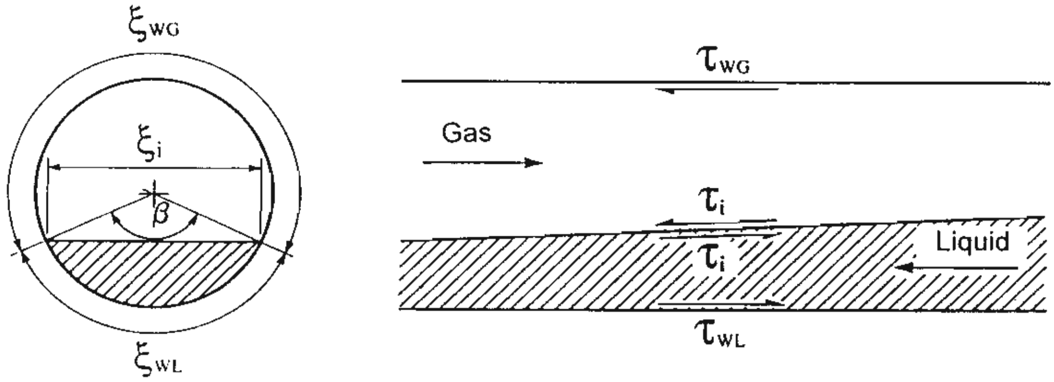

Fig. 15. Stratified countercurrent flow.

currently to the liquid flow. The critical conditions for flooding for this kind of pipe geometry are those at C, and the interaction between the inclined and horizontal pipes is vital to understand the phenomenon. The flow of liquid from the inclined pipe is initially supercritically at B. The transition of the flow to subcritical flow occurs near the bend, at the horizontal section. This transition forms a hydraulic jump at C, which is the point of maximum liquid depth. The level of liquid in the horizontal pipe decreases continuously in the direction of the liquid outlet (E), where the liquid level is at a minimum.

The described flooding conditions can be solved by using the conservation equations for steady stratified two-fluid flow between the hydraulic jump and the liquid outlet. Neglecting viscous interactions and ignoring pressure changes at the interface caused by surface tension, the one-dimensional equations for momentum and mass conservation for the gas and liquid phases for the steady horizontal stratified flow can be written as

$$\varepsilon_G \rho_G \bar{v}_G \frac{\partial \bar{v}_G}{\partial x} + \varepsilon_G \frac{\partial P_i}{\partial x} - \frac{F}{\xi_i}\varepsilon_G \rho_G g \frac{\partial \varepsilon_G}{\partial x} = |\tau_{wG}|\frac{\xi_{wG}}{F} + \tau_i \frac{\xi_i}{F} \quad (3)$$

$$\varepsilon_L \rho_L \bar{v}_L \frac{\partial \bar{v}_L}{\partial x} + \varepsilon_L \frac{\partial P_i}{\partial x} + \frac{F}{\xi_i}\varepsilon_L \rho_L g \frac{\partial \varepsilon_L}{\partial x} = -|\tau_{wL}|\frac{\xi_{wL}}{F} - \frac{\tau_i \xi_i}{F} \quad (4)$$

$$\frac{\partial \bar{v}_G}{\partial x} = \frac{-\bar{v}_G}{\varepsilon_G}\frac{\partial \varepsilon_G}{\partial x} \quad (5)$$

$$\frac{\partial \bar{v}_L}{\partial x} = \frac{\bar{v}_L}{\varepsilon_L}\frac{\partial \varepsilon_L}{\partial x} \quad (6)$$

where x is the distance from point C, τ_{wG}, τ_{wL} and τ_i are the gas–wall, liquid–wall and interfacial shear stresses, and ξ represents the perimeters which can be expressed in terms of the angle β (Fig. 15).

Eliminating $\partial \bar{v}_L/\partial x$, $\partial \bar{v}_G/\partial x$ and $\partial P_i/\partial x$ between Eqs. (3)–(6), the following equation is obtained:

$$\frac{\partial \varepsilon_G}{\partial x} = \frac{4}{\pi D^2} \frac{(|\tau_{wG}|\xi_{wG}/\varepsilon_G + |\tau_{wL}|\xi_{wL}/\varepsilon_L + \tau_i\xi_i/\varepsilon_G + \tau_i\xi_i/\varepsilon_L)}{[(\rho_L - \rho_G)Fg/\xi_i - \rho_L \bar{v}_L^2/\varepsilon_L - \rho_G \bar{v}_G^2/\varepsilon_G]} \quad (7)$$

Recalling the definition of the dimensionless superficial velocity of phase k, where the superficial velocity j_k is defined by $j_k = \varepsilon_k \bar{v}_k$, Eq. (7) may be written as

$$D\frac{\partial \varepsilon_G}{\partial x} = \frac{4\varepsilon_L\varepsilon_G/[(\rho_L - \rho_G)g\pi D^2] \, (|\tau_{wG}|\xi_{wG}/\varepsilon_G + |\tau_{wL}|\xi_{wL}/\varepsilon_L + \tau_i\xi_i/\varepsilon_G\varepsilon_L)}{\pi D\varepsilon_G\varepsilon_L/4\xi_i - \varepsilon_L(j_G^*)^2/\varepsilon_G^2 - \varepsilon_G(j_L^*)^2/\varepsilon_L^2} \quad (8)$$

The wall and interface momentum transfer terms are expressed as

$$\tau_{wk} = (-1)^a \tfrac{1}{2}\,\psi_{wk}\rho_k \bar{v}_k^2$$

where $a = 1$, for $k = G$ and $a = 2$, for $k = L$. Also, we have

$$\tau_i = \tau_{wG}$$

with

$$\psi_{wG} = C_G\,\mathrm{Re}_G^{-n}, \qquad \psi_{wL} = C_L\,\mathrm{Re}_L^{-m}$$

where

$$\mathrm{Re}_k = \frac{\rho_k \bar{v}_k D_{kh}}{\mu_k}$$

The hydraulic diameter D_{kh} is defined by Agrawal et al. (1973) as

$$D_{Gh} = \frac{4F_G}{(\xi_{wG} + \xi_i)}, \qquad D_{Lh} = \frac{4F_L}{\xi_{wL}}$$

For turbulent flow, $C_k = 0.046$, $n = m = 0.2$; for laminar flow, $C_k = 16$, $n = m = 1$.

At a free outflow, such as obtained in the experiments, $\partial\varepsilon_G/\partial x \to \infty$, and, from Eq. (8), we have

$$\frac{\pi D \varepsilon_G \varepsilon_L}{4\xi_i} - \frac{\varepsilon_L (j_G^*)^2}{\varepsilon_G^2} - \frac{\varepsilon_G (j_L^*)^2}{\varepsilon_L^2} = 0 \qquad (9)$$

Gardner (1988) obtained the same equation from his derivation. The equation represents the condition for the transition to supercritical flow, where any small interfacial disturbance will be held stationary and cannot propagate against the flow. The equation is recognized as the equation for two-phase critical flow. Eq. (8) can be integrated from the location of the hydraulic jump (at which the void fraction is $\varepsilon_{G,C}$) to the outlet of the horizontal pipe (at which the void fraction is $\varepsilon_{G,e}$). The distance between these is nominally taken to be the length L of the horizontal section. Thus, we have

$$\frac{L}{D} = \int_{\varepsilon_{G,C}}^{\varepsilon_{G,e}} \frac{d\varepsilon_G}{\phi} \qquad (10)$$

where ϕ represents the right-hand-side term of Eq. (8) and is a function of ε_G, ε_L, j_G^*, j_L^*, μ_G, μ_L.

Eq. (10) will be solved iteratively for j_G^* and j_L^*, with $\varepsilon_{G,e}$ determined from Eq. (9) and $\varepsilon_{G,C}$ determined from Eq. (2). The solution is a pair of dimensionless superficial velocities which, for the particular choice of pipe geometry, define the flooding point.

4.1. *Flooding curves from calculations*

The results obtained from the calculation using the method described above are shown in Fig. 16. It shows the different flooding curves which are produced from the calculation at the different length-to-diameter ratios. Air and water are used as working fluids. The wall momentum transfer terms are calculated based on $n = m = 0.2$, $C_G = C_L = 0.046$ for turbulent flow and $n = m = 1$, $C_G = C_L = 16$ for laminar flow. The phase Reynolds numbers are evaluated from the hydraulic diameter, as suggested by Agrawal et al. (1973). It is interesting to consider that the interface momentum transfer term is taken as being equal to the wall momemtum transfer term in the part of the pipe occupied by the gas phase. The same assumption was used for the work of Ohnuki et al. (1988) and Ardron and Banerjee (1986). With this method, the flooding curves for many combinations of working fluids, such as steam–water, can also be produced. However, suitable fluid properties and a suitable interfacial friction factor are needed.

4.2. *Comparison with experimental data*

Figs. 17 and 18 show a comparison of the air–water data with the present model. The agreement of the present model with the experimental

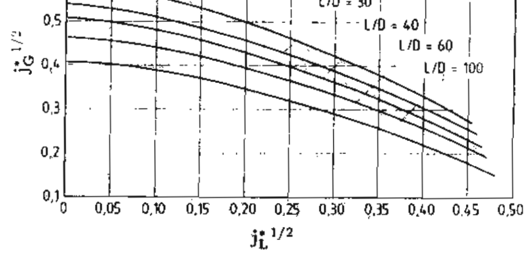

Fig. 16. Predicted flooding curves.

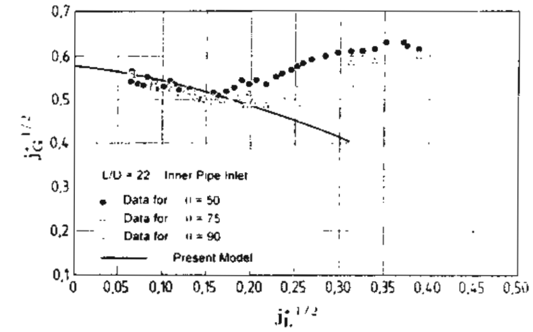

Fig. 17. Comparison of present data with the predictions.

data is satisfactory, especially for a large length-to-diameter ratio. In the case of a pipe with a large length-to-diameter ratio, the error from two-dimensional effects is overcome. This is why, for large length-to-diameter ratios, the experimental data agree quite well with the model. However, for greater liquid flow rates, the prediction fails, because of a change in the flooding mechanism. For very high liquid flow rates, the liquid flow remains supercritical in the horizontal part, and the model is also not applicable to this situation. The model gives the zero liquid penetration limit ($j_L^* = 0$) that corresponds to the experimental data.

The data obtained by Wan and Krishnan (1986), Siddiqui et al. (1986) and Kawaji et al. (1991) are compared with the predictions from the present model. Figs. 19–21 show comparisons with air–water data. Reasonable agreement between the model and the experiment is obtained for $j_L^{*1/2} < 0.5$. Above this limit, the mechanism of flooding is different in the absence of a hydraulic jump at the horizontal part close to the bend, as explained previously.

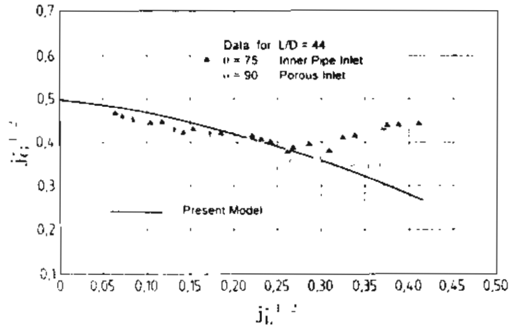

Fig. 18. Comparison of present data with the predictions.

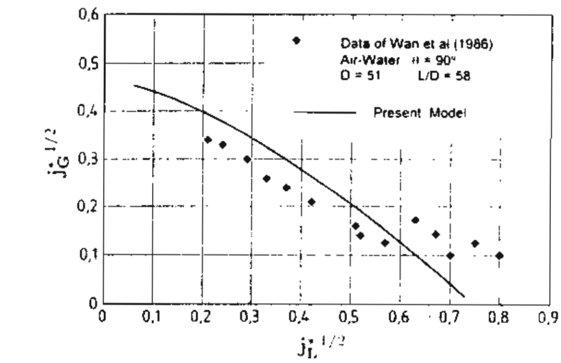

Fig. 19. Comparison of air–water flooding data of Wan et al. (1986) with the predictions.

Fig. 22 shows a comparison of the steam–water data from Wan (1986) with the calculation. Because there is some discrepancy in interfacial friction coefficient ψ_i between a combination of fluid (between air–water and steam–water), the interfacial friction coefficient for steam–water from Kim (1983) is used in the mathematical model. Again, good agreement is seen until inlet water subcooling and supercritical water flow effects begin to influence to flooding phenomenon.

5. Conclusions

The paper presents new data for countercurrent flow of a gas and liquid in a horizontal pipe with a bend. Experiments were performed to determine the CCFL and the zero liquid penetration limit. Water was ejected through the test section while

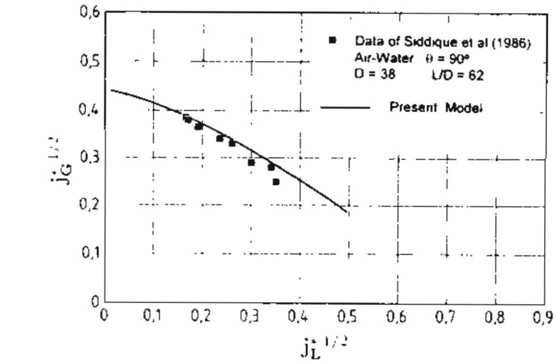

Fig. 20. Comparison of air–water flooding data of Siddiqui et al. (1986) with the predictions.

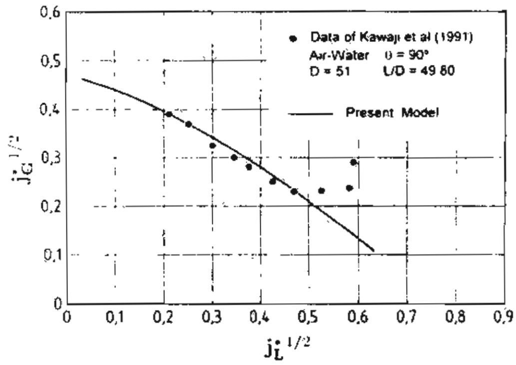

Fig. 21. Comparison of air–water flooding data of Kawaji et al. (1991) with the predictions.

air flowed countercurrently. The phenomena observed visually are described in detail, together with the other data obtained during the experiment. Different flow regimes appear, depending on the conditions of air and water inflow. At low and intermediate water flow rates, the onset of flooding coincides with the onset of slugging of unstable waves that formed at the crest of the hydraulic jump. The position of the onset of slugging indicates different phenomena in the test section. At low water flow rates, slugging appears at the lower leg of the bend; at higher water flow rates, it appears far from the bend. For high water flow rates, no hydraulic jump is observed and flooding occurs as a result of slug formation at the end of the horizontal pipe. In addition, the onset of flooding is found to depend on the length of the horizontal pipes, the water inlet conditions and the inclination angle of the bends.

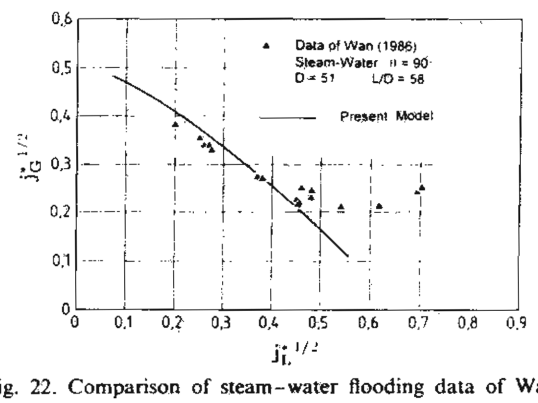

Fig. 22. Comparison of steam–water flooding data of Wan (1986) with the predictions.

An analytical two-fluid model is developed for predicting the CCFL for a horizontal pipe with a bend. The model development is based on visual observation that liquid entering the bend formed the hydraulic jump close to the bend in the horizontal part. The flow conditions between the hydraulic jump and critical outflow of water are determined by solving the two-fluid mass and momentum conservations for steady horizontal stratified flow. An empirical correlation, which is the relation between the dimensionless superficial gas velocity and the void fraction at the hydraulic jump near the bend, is used in the mathematical model. The predicted flooding limit, as a function of the length-to-diameter ratio, is in reasonable agreement with experimental results. The model can predict the onset of flooding at the specific interval of liquid flow rate in which the flooding coincides with slugging at the crest of the hydraulic jump near the bend.

The results of this study are of technological importance for the design and analysis of thermal-hydraulic responses of nuclear reactors during accidental conditions.

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Appendix A: Nomenclature

C_G parameter (dimensionless)
C_L parameter (dimensionless)
D pipe diameter (m)
F cross-sectional area of pipe (m^2)
g gravitational acceleration ($m\ s^{-2}$)
L pipe length (m)
m parameter (dimensionless)
n parameter (dimensionless)
p pressure (Pa)

ΔP pressure drop (Pa)
j superficial velocity ($m\,s^{-1}$)
$\bar{v}$ average velocity ($m\,s^{-1}$)
j^* dimensionless superficial velocity defined by Eq. (1)

Greek symbols
ε_L liquid hold-up (dimensionless)
ε_G void fraction (dimensionless)
θ inclination angle of bend (degrees)
ρ density ($kg\,m^{-3}$)
β angle defined in Fig. 15
ξ perimeter (m)
τ shear stress ($N\,m^{-2}$)

Subscripts
k gas or liquid
i interface or inlet
o outlet
G gas
L liquid
wG wall–gas
wL wall–liquid
kh hydraulic

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แบบจำลองทางคณิตศาสตร์เพื่อทำนายการไหลท่วมของกระแสไหลสวนกันของของเหลวและก๊าซในท่อเอียง

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ศูนย์วิจัยกลศาสตร์ของไหลและเครื่องจักรเทอร์โบ (FUTURE)

ภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์

สถาบันเทคโนโลยีพระจอมเกล้าธนบุรี

บทคัดย่อ

การไหลสวนกันของของเหลวและก๊าซเป็นรูปแบบหนึ่งของการไหลสองสถานะ (Two Phase Flow) ในการไหลสวนกันของของไหลสองสถานะในท่อซึ่งวางในแนวเอียง ของเหลวจะไหลเป็นชั้นผ่านลงมาตามผนังของท่อและก๊าซไหลสวนทางขึ้นไป เมื่อมีการเปลี่ยนแปลงอัตราการไหลของของเหลวหรือก๊าซแล้วไม่ทำให้รูปแบบของการไหลเปลี่ยนแปลง แสดงว่าสภาวะนั้นยังสมดุลย์ต่อการไหลสวนกัน แต่ถ้ามีการเปลี่ยนแปลงอัตราการไหลของของไหลจนกระทั่งถึงจุดที่เรียกว่าการไหลท่วมของกระแสไหลสวน (Countercurrent Flooding) หรือจุดจำกัดในการไหลสวนกัน (Countercurrent Flow Limitation:CCFL) รูปแบบของการไหลจะเปลี่ยนจากการไหลสวนกันเป็นการไหลตามกัน

ในงานวิจัยนี้เป็นการศึกษาการจำกัดในการไหลสวนกันของของเหลวและก๊าซในท่อที่วางอยู่ในแนวเอียงจากแบบจำลองทางคณิตศาสตร์ ซึ่งได้จากสมการสมดุลย์โมเมนตัมของของไหลทั้งสอง ประกอบกับพารามิเตอร์อื่นๆที่ได้จากงานวิจัยในอดีต เช่น ความเค้นเฉือนที่ผนังท่อ และที่ผิวสัมผัสของของไหลทั้งสอง ตลอดจนสมการซึ่งแสดงสมมุติฐานในการเกิด CCFL ความสัมพันธ์ทั้งหมดจะถูกนำมาประกอบกันเพื่อสร้างแบบจำลองทางคณิตศาสตร์สำหรับใช้ทำนายการจำกัดในการไหลสวนกันของของเหลวและก๊าซในท่อเอียง

แบบจำลองทางคณิตศาสตร์ที่สร้างขึ้นมา สามารถใช้ศึกษาปรากฎการณ์ที่เกิดขึ้นของระบบได้โดยไม่ได้ใช้การทดลองเข้าช่วย จากงานวิจัยนี้พบว่าแบบจำลองทางคณิตศาสตร์สามารถทำนาย CCFL ได้ โดยที่มุมเอียงของท่อที่เปลี่ยนแปลงไปมีผลกระทบต่อการเกิด CCFL ในช่วงที่มุมเอียงของท่อปานกลาง (30^{0} - 60^{0} จากแนวนอน) ผลกระทบของมุมเอียงที่เปลี่ยนแปลงจะมีผลต่อการเกิด CCFL ไม่มากนัก แต่เมื่อมุมเอียงของท่อเข้าใกล้แนวดิ่งมากขึ้น (70^{0} - 80^{0} จากแนวนอน) ผลกระทบของมุมเอียงที่เปลี่ยนแปลงจะมีผลต่อการเกิด CCFL มากขึ้น เนื่องจากมุมเอียงของท่อที่เปลี่ยนแปลงไปจะมีผลต่อค่าพารามิเตอร์ในแบบจำลองทางคณิตศาสตร์

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<u>บทนำ</u>

เราจะพบการไหลสองสถานะของของเหลวและก๊าซอยู่ตลอดเวลาในขบวนการทางอุตสาหกรรม เช่นในอุตสาหกรรมเคมี,โรงไฟฟ้าพลังงานนิวเคลียร์,อุปกรณ์แลกเปลี่ยนความร้อนและอื่นๆ การไหลสวนกันของของเหลวและก๊าซเป็นรูปแบบหนึ่งของการไหลสองสถานะ ในการไหลสวนกันของของไหลสองสถานะในท่อซึ่งวางในแนวเอียงของเหลวจะไหลเป็นแผ่นบางผ่านลงมาตามผนังของท่อและก๊าซไหลสวนทางขึ้นไป เมื่อมีการเปลี่ยนแปลงอัตราการไหลของของเหลวและก๊าซแล้วไม่ทำให้รูปแบบของการไหลเปลี่ยนแปลง แสดงว่าสภาวะนั้นยังสมดุลย์ต่อการไหลสวนกัน แต่ถ้ามีเปลี่ยนแปลงอัตราการไหลของของไหลจนกระทั่งถึงจุดที่เรียกว่าจุดจำกัดในการไหลสวนกัน(Countercurrent flow limitation:CCFL) รูปแบบของการไหลจะเปลี่ยนจากการไหลสวนกันเป็นการไหลตามกัน

ได้มีการศึกษากันพอสมควรทั้งทฤษฎีและการทดลองของการไหลสวนกันของของไหลสองสถานะ โดยเฉพาะกรณีของท่อที่วางอยู่ในแนวดิ่ง Wallis et.al. [1] ศึกษาพบว่าขนาดของท่อและสภาวะของทางเข้าออกของของเหลวและก๊าซ เป็นปัจจัยที่สำคัญต่อการเกิดCCFL

Tien et.al. [2] ศึกษาถึงผลกระทบของขนาดท่อและลักษณะทางเข้าและทางออกของของเหลวที่มีต่อการเกิดCCFL ในท่อที่วางอยู่ในแนวดิ่ง พบว่าเมื่อทำการออกแบบลักษณะทางเข้าให้มีผลกระทบให้น้อยที่สุดแล้ว ผลจากแรงกระทำระหว่างผิวสัมผัสของของเหลวและก๊าซและขนาดท่อที่เปลี่ยนไปไม่ใช่ ผลกระทบหลักของการเกิดCCFL เมื่อเปลี่ยนลักษณะของทางเข้าของของเหลวและก๊าซเป็นแบบ Sharp edge inlet CCFLจะเกิดขึ้นที่บริเวณทางเข้าของของเหลว เนื่องมาจากผลของความหนาของของเหลวที่บริเวณทางเข้า เมื่อทางเข้าของของเหลวมีลักษณะที่ไม่ราบเรียบ ขนาดของท่อที่เปลี่ยนแปลงไป จะเป็นปัจจัยที่สำคัญอีกปัจจัยหนึ่งต่อการเกิดCCFL

Hewitt [3] ศึกษาการเกิดCCFL ของท่อที่วางอยู่ในแนวเอียงและมีลักษณะทางเข้าของของเหลวแบบรูพรุน(porous section) และทางออกของของเหลวสองรูปแบบคือแบบปลายตัดตรงและแบบปลายตัดทำมุม 30° พบว่าทางออกของของเหลวและมุมของท่อที่เปลี่ยนแปลงไปมีผลต่อการเกิดCCFL ที่ความเร็วของก๊าซคงที่ความเร็วของของของเหลวที่CCFL จะสูงขึ้นเมื่อมุมเอียงของท่อเพิ่มขึ้นจากแนวนอน และท่อที่มีทางออกของของเหลวแบบปลายตัดทำมุม 30°จะทำให้ความเร็วของของเหลวที่CCFL สูงกว่าท่อที่มีทางออกของของเหลวแบบปลายตัดตรง

Lee and Bankoff [4] ทำการศึกษาถึงผลกระทบจากการกลั่นตัวของน้ำต่อการเกิดCCFL ในท่อหน้าตัดรูปทรงเหลี่ยมที่วางอยู่ในแนวเอียง โดยทำการเปลี่ยนแปลงอุณหภูมิของของเหลว

ที่จ่ายเข้าสู่ท่อทดสอบ พบว่าเมื่อท่อมีขนาดยาวอุณหภูมิของของเหลวที่เปลี่ยนแปลงไม่มีผลต่อการเกิดCCFL และที่ความเร็วของก๊าซคงที่ความเร็วของของของเหลวที่CCFL จะสูงขึ้น เมื่อมุมเอียงของท่อลดลงจากแนวนอนและเมื่อหน้าตัดท่อมีขนาดใหญ่ขึ้น

Barnea et.al. [5] ศึกษาถึงผลกระทบของทางเข้าและทางออกของของเหลวสองรูปแบบ คือทางเข้าเป็นรูพรุน (porous section) และการใช้ท่อเล็กส่งของเหลวเข้าไป (inner tube section) ที่มีต่อการเกิดCCFL ของท่อที่วางในแนวเอียง พบว่าทางเข้าแบบรูพรุนและมุมเอียงมีผลต่อการเกิดCCFL เนื่องจากทางเข้าแบบรูพรุนทำให้เกิด local hump ซึ่งจะหายไปเมื่อมุมเอียงของท่อเพิ่มขึ้นและมุมเอียงที่เปลี่ยนแปลงทำให้พื้นที่ผิวสัมผัสระหว่างของไหลทั้งสองเปลี่ยนแปลงไป

Beckmann and Mewes [6] ศึกษาถึงการเกิดCCFL ในท่อเอียง พบว่าท่อที่มีมุมเอียงน้อยจากแนวนอน (5^0-20^0) มุมเอียงของท่อที่เปลี่ยนแปลงมีผลต่อการเกิดCCFL มากกว่าท่อที่มีมุมเอียงปานกลางจากแนวนอน (25^0-50^0) และที่ความเร็วของก๊าซคงที่ความเร็วของของเหลวที่CCFL จะสูงขึ้นเมื่อมุมเอียงของท่อเพิ่มขึ้น

Gardner [7] ได้พัฒนาบรรทัดฐานสำหรับทำนายการเกิดCCFLของเหลวและก๊าซในท่อที่อยู่ในแนวนอน ซึ่งปรับปรุงจากบรรทัดฐานของ Wallis [1] โดยนำอัตราส่วนของความหนาแน่นของของเหลวมาเพิ่มเติมจากบรรทัดฐานเดิม

Daly and Harlow [9] ได้ศึกษาระเบียบวิธีเชิงตัวเลขของการไหลสวนกันของน้ำและไอน้ำในท่อขนาดใหญ่ที่วางอยู่ในแนวนอน เพื่อหาข้อมูลสำหรับอธิบายถึงการแลกเปลี่ยนกันของมวล,โมเมนตัม และ พลังงาน ระหว่างของไหลสองสถานะในขณะที่มีการจ่ายน้ำเข้าสู่ระบบท่อใน Nuclear Power Plant

Shearer and Davidson [10] , Centinbudakler and Jameson [11] และ Imura et.al. [12] ทำการศึกษาทฤษฎีที่ใช้ทำนายการเกิดCCFL และได้แนะนำว่าการเริ่มต้นของCCFLจะเกิดขึ้นเนื่องจากเกิดคลื่นในการไหลสวนกันอย่างรวดเร็ว

Wallis et.al. [13] อธิบายถึงรูปแบบของฟิล์มของเหลวสำหรับการไหลสวนกันในท่อที่วางอยู่ในแนวดิ่ง ซึ่งพบว่าความหนาของของเหลวในท่อเป็นตัวแปรหนึ่งที่มีผลกระทบต่อการเกิด-CCFL

เนื่องจากในปัจจุบันการศึกษาถึงการไหลสวนกันของของไหลในท่อเอียงยังไม่แพร่หลายเมื่อเปรียบเทียบกับการศึกษาสำหรับท่อในแนวดิ่งและในแนวราบ ในงานวิจัยนี้จะเป็นการศึกษาการเกิดCCFLของเหลวและก๊าซในท่อที่วางอยู่ในแนวเอียงจากแบบจำลองทางคณิต-

ศาสตร์ซึ่งได้จากสมการสมดุลย์โมเมนตัมของของไหลทั้งสองประกอบกับตัวพารามิเตอร์ที่ได้จากการทดลองในอดีต เช่น ความเค้นเฉือนที่ผนังท่อและที่ผิวสัมผัสของของไหลทั้งสอง ตลอดจนสมการซึ่งแสดงสมมุติฐานในการเกิดCCFL โดยใช้อากาศแทนก๊าซ และน้ำแทนของเหลวผลลัพธ์ที่ได้จะถูกใช้เป็นแนวทางในการออกแบบอุปกรณ์ในระบบที่มีการไหลสวนกันของของไหลสองสถานะ

<u>แบบจำลองทางคณิตศาสตร์</u>

ก่อนที่จะเกิดCCFLขึ้นในท่อที่วางอยู่ในแนวเอียงการไหลของของไหลจะอยู่ในรูปของการไหลแบบแบ่งแยกชั้นซึ่งเราสามารถหาความสัมพันธ์ของการไหลได้จากสมการสมดุลย์โมเมนตัมในสภาวะสม่ำเสมอ (steady state momentum balance) จากรูปที่ 1 เราจะได้

$$-\tau_L S_L - \tau_i S_i + A_L \rho_L g \sin\beta - A_L \frac{dp}{dx} = 0 \qquad (1)$$

$$\tau_G S_G + \tau_i S_i + A_G \rho_G g \sin\beta - A_G \frac{dp}{dx} = 0 \qquad (2)$$

จากการรวมสมการที่ (1) และ (2) จะทำให้สามารถกำจัด $\frac{dp}{dx}$ ออกไปได้ และได้ผลลัพธ์ดังนี้

$$\tau_G \frac{S_G}{A_G} + \tau_L \frac{S_L}{A_L} + \tau_i \left(\frac{S_i}{A_G} + \frac{S_i}{A_L} \right) - \left(\rho_L - \rho_G \right) g \sin\beta = 0 \qquad (3)$$

โดยที่ Shear Stress หาได้จาก

$$\tau_L = f_L \frac{\rho_L U_L^2}{2}$$

$$\tau_G = f_G \frac{\rho_G U_G^2}{2} \qquad (4)$$

$$\tau_i = f_i \frac{\rho_G (U_G + U_L)^2}{2}$$

friction factor ของก๊าซและของเหลวจะหาได้จาก

$$f_L = C_L \left(\frac{D_L U_L}{\nu_L} \right)^{-n}$$

$$f_G = C_G \left(\frac{D_G U_G}{\nu_G} \right)^{-m} \tag{5}$$

D_L และ D_G คือ hydraulic diameter ซึ่งถูกตั้งขึ้นโดย Agrawal et.al.[13]

$$D_L = \frac{4A_L}{S_L}$$

$$D_G = \frac{4A_G}{S_G + S_i} \tag{6}$$

ความเร็วของของเหลว และก๊าซจะหาได้จาก

$$U_L = \frac{U_{LS} A}{A_L}$$

$$U_G = \frac{U_{GS} A}{A_G} \tag{7}$$

ค่า A_L, A_G, S_L, S_G และ S_i เป็นปริมาณเชิงเรขาคณิตของรูปทรงจะขึ้นอยู่กับ ระดับของของเหลวที่สมดุล h_L และ f_i, f_L, f_G, C_L, C_G, m และ n เป็นพารามิเตอร์ที่ได้จากการทดลองในอดีต

สมการที่ (3) ถึงสมการ (6)ใช้สำหรับหาระดับของของเหลวที่จุดสมดุลย์ซึ่งสามารถหาได้จาก วิธี Iterative techniqne

พารามิเตอร์สำหรับกรณีการไหลแบบราบเรียบและการไหลแบบอลวน จะให้ไว้ดังนี้

กรณีการไหลแบบราบเรียบ (Laminar flow)	$C_G = C_L = 16$
	$n = m = 1.0$
กรณีการไหลแบบอลวน (turbulent flow)	$C_G = C_L = 0.046$
	$n = m = 0.2$