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TWO PHASE FLOW REGIME TRANSITION IN A 37-ROD NUCLEAR FUEL BUNDLE HORIZONTAL FLOW

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ABSTRACT

Two-phase flow regime transition inside flow tube with 37-rod bundles has been investigated experimentally for horizontal air-water flow at room temperature and pressure of 1.01 bar, and compared with numerical results of Osamusali and Chang[1]. The results show that the experimental results of rod bundles are significantly different from those observed from normal pipe flow, and the results predicted by REGIME-4 code for 37-rod bundle flow agree well with present experiments.

INTRODUCTION

The ability to predict the transition locations between the various flow patterns occurring in a two phase flow system is important for the determination of the heat and mass transfer rates, as well as the flow pressure drop of the system. In nuclear power plants, this information is also useful for modelling postulated Loss of Coolant Accidents (LOCA). For the cocurrent pipe flow, extensive research has been conducted and there now exist some acceptable mechanistic models capable of predicting the approximate locations of these transition boundaries. However, it has not been well established whether these pipe flow models can be applicable to rod bundle geometries.

Earlier investigations on the rod bundle geometry include Bergles and Roos[2], Williams and Peterson[3], Aly[4], Nicholson et al.[5], Krishnan and Kowalski[6], Minato et al.[7] and Venkateswararao[8]. These were mostly experimental, using probe methods for flow regime characterization. Venkatessararao[8] and Minato et al.[7], also theoretically studied the vertical 24-rod and horizontal 37-rod bundle geometries, respectively.

In this work, experimental studies have been conducted for an air-water two phase flow system at room temperature and at atmospheric pressure (~1.01 bar) to investigate flow regime transition pressure drop and void fraction in a CANDU type 37-rod bundle flow. The experimental results are also compared with those of REGIME-4[1] computer code.

FLOW REGIME

As in single-phase fluid mechanics, various 'flow regimes' are found to exist in a two-phase flow system. However, unlike single-phase systems where the regimes are basically restricted to two structures, laminar and turbulent, two-phase systems are capable of producing a much wider range of flow patterns. These regimes result from the particular manner in which the two phases are distributed in the pipe.

Though authors define each flow regime somewhat differently, most agree that there are six basic structures. Examples of these flows are shown in figure 1. In this study the flow regime analysis will be based on the definitions below.

Stratified smooth flow (SS) occurs when the liquid is flowing at the bottom of the pipe and the gas flows along the top. The gas-liquid interface is smooth. Stratified Wavy flow (SW) is similar to Stratified Smooth flow, however, the gas-liquid interface is wavy in the former case. Both elongated bubble (this is designated as Plug (PL) flow) and Slug (SL) flow are what Taitel and Dukler[9] call Intermittent (I) flow, and are characterized by the liquid bridging the gap between the gas-liquid interface and the top of the pipe. The difference between Slug and Plug flow depends on the degree of agitation of the bridge. Plug flow is considered to be the limiting case of Slug flow where no entrained bubbles exist in the liquid bridge.

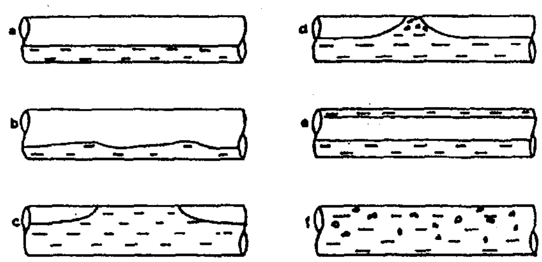


Figure 1a Flow regimes in Horizontal Two-Phase Flow
(a) Stratified Smooth
(b) Stratified Wavy
(c) Plug
(d) Slug
(e) Annular
(f) Dispersed Bubble

Annular flow (A) occurs when the walls are wetted by a thin film of liquid while the gas, at high velocity, flows through the centre of the pipe. Liquid droplets are usually entrained in this gas core. When the upper walls are periodically wetted by large aerated waves it is neither Slug flow, which requires a complete fluid bridge, nor annular flow, which requires a stable film. Taitel and Dukler[9] designated this flow pattern as Wavy Annular flow. However, this regime was not recognized by Mandhane et al.[10] and was considered to be Slug flow.

In the Dispersed Bubble (DB) or Bubbly flow regime small gas bubbles are distributed throughout the liquid phase which otherwise completely fills the pipe. The transition to this regime is characterized by the gas bubbles losing contact with the top of the tube. At first, the bubbles are near the upper portion of the pipe but at higher liquid flow rates become uniformly distributed throughout the system.

In the model (REGIME-4 code) presented in this study, the process of analyzing the transitions between flow regimes starts from the condition of stratified flow following the approach of Taitel and Dukler[9]. An equilibrium stratified flow is assumed and the mechanism whereby a change from stratified flow can be expected to take place is imposed on the system.

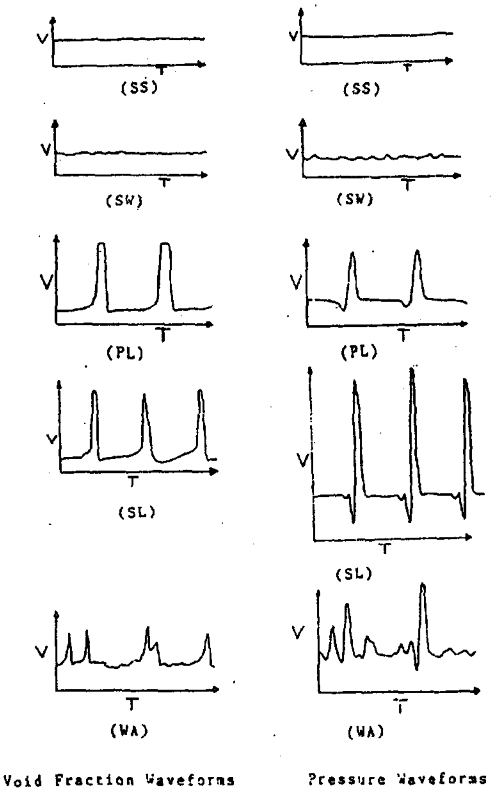


Figure 1b Pressure Drop and Void Fraction Signal Waveforms for 37-Rod Bundle Flow Geometry

LOOP DESCRIPTION AND EXPERIMENTAL PROCEDURE

A schematic diagram of the experimental loop is as shown in Figure 2. This is a recirculating air-water system having a 10.16 cm I.D. aluminum tube in the upstream section and a transparent section made of acrylic tubing, 10.16 cm I.D., and of total length 345 cm. Two 100 cm long 37-rod bundles with rods of diameter 1.27 cm were placed next to each other in the test section. Figure 2 also shows the 37-rod bundle cross-section. Water is pumped from a large separator tank through a rotameter (Fischer and Porter Co. type) calibrated up to a maximum flow rate of 1.11 [ℓ/s]. Air from the laboratory supply is flowed past a pressure regulator, an air filter and through a rotameter (Brooks Instruments type, Model #1110-10H3A1D) calibrated up to a maximum flow rate of 11.33 [ℓ/s]. The air and water flow through a homogeneous type mixing section into the test section.

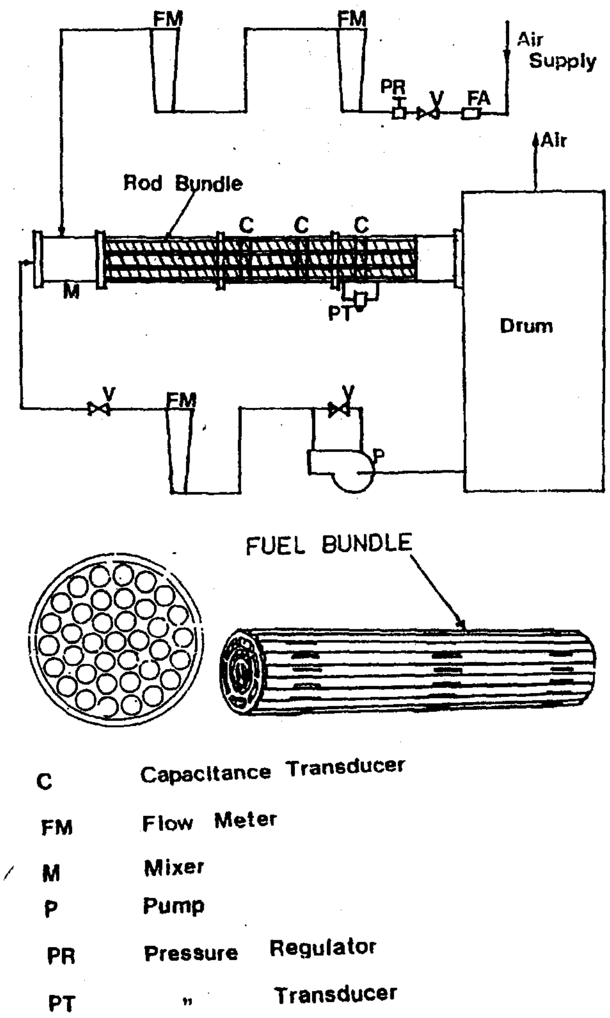


Figure 2 Schematics of Experimental Loop.

The redistribution of the two phases within the test section for different flow rates of air and water are monitored with the analogue output signals of the ring-type capacitance transducers[11] via a Boonton capacitance meter, Model No. 72B (1 MHz). We also characterized the flow patterns by direct visual observation through the transparent test section.

NUMERICAL RESULTS

For completeness, we introduced some numerical results of REGIME-4 code for 37-rod bundle flow. Figures 3 and 4 show the predicted flow regime maps for the 37-rod bundle geometry and for the case of different rotation angles from 0° to 45°, respectively. The Stratified to Intermittent or Annular transitions for the 37-rod bundle geometry map shown in figure 3 indicates the existence of unstable transition locations at high superficial gas velocities. This may be due to the nonmonotonically varying interfacial perimeter of the 37-rod bundle geometry which is observed to strongly affect this transition.[1] Figure 4 shows that the particular orientation of the 37-rod bundle in the enclosing tubeshell affects the flow regime transitions. The transition boundaries are therefore shown as bands rather than sharp lines. These results account for an arbitrary orientation of the rod bundle within the enclosing tubeshell as may be the case in a practical situation.

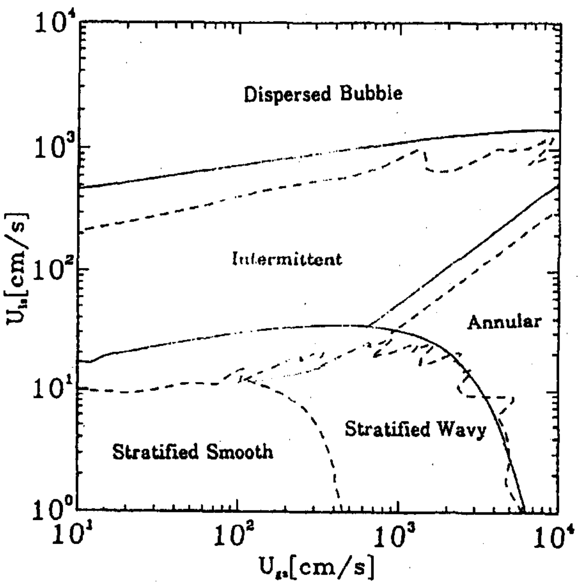


Figure 3 Predicted Flow Regime Map for 37-Rod Bundle Geometry (D = 10.16 cm I.D., Pin Diameter, d = 1.27 cm) and a 10.16 cm I.D. Pipe at Room Temperature, T = 25°C and Pressure, P = 1.01 bar.

Figure 3 also shows the flow regime transitions for a 10.16 cm I.D., and the results seem to confirm the predicted effects on flow regime transitions due to the presence of rods in the system as was already discussed for the annulus geometry[1]. However, this difference in the flow regime transitions is enhanced by the increased number of rods in the rod bundle geometry case. The Stratified to Intermittent and Intermittent to Dispersed Bubble flow transitions occur at lower superficial liquid velocities, for the rod bundle geometry, and the Intermittent to Annular flow transition occurs at higher superfacial gas velocities than the pipe case. This may be due to differences in force distribution and flow acceleration in the rod bundle, respectively.

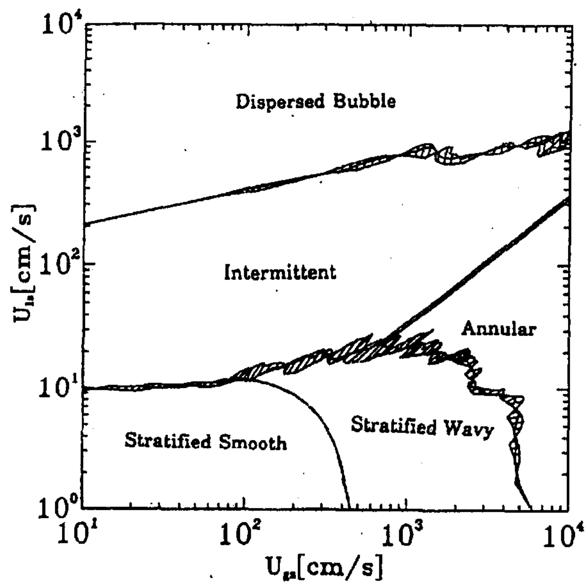


Figure 4 Calculated Flow Pattern Transitions for 37-Rod Bundle Geometry at Different Angles of Orientation.

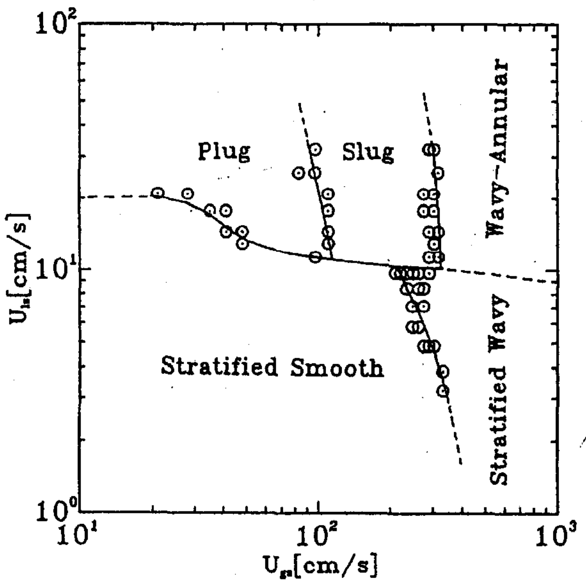
EXPERIMENTAL RESULTS AND DISCUSSION

Experimental flow regime maps for the 37-rod bundle geometry are presented here. Two conditions of the entrance region were studied, namely, dispersed bubbly and stratified or separated entrance flow conditions.

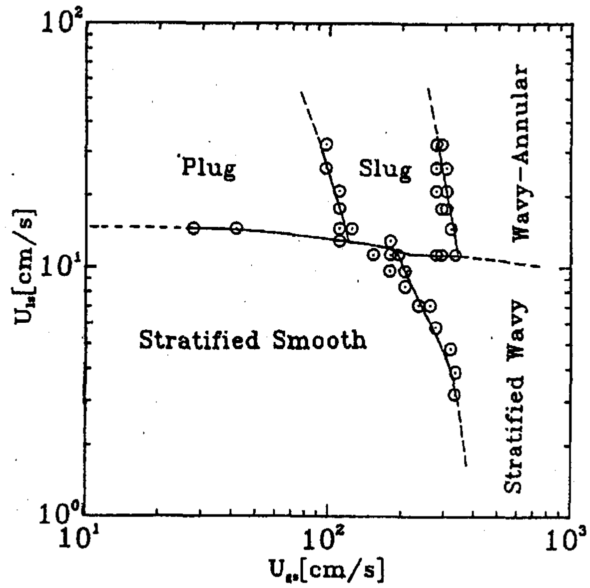
Figures 5 shows the flow regime maps obtained for the bubbly and stratified entrance cases, respectively. In this study, the Stratified Smooth, Stratified Wavy, Elongated Bubble/Plug, Slug and Wavy-Annular flow regimes were successfully characterized. Figure 6 shows a comparison of the flow regime maps for the different entrance conditions studied and the theoretical results of REGIME-4 code for the 37-rod bundle geometry. The theoretical results are observed to agree well with experiment. The results show that the entrance conditions affect the Stratified Smooth to Plug, Stratified Wavy to Plug and the Stratified Smooth to Stratified Wavy transitions. At low gas flowrate, the Stratified Smooth to Plug transition occurs earlier for the case with stratified entrance condition. At the flow conditions in which this transition occurs, the body of liquid was observed to oscillate resembling sinusoidal waves at the air-water interface. This phenomeon grows with increasing liquid flowrate, and eventually leads to Plug flow. Taitel and Dukler[9] considered the Bornouille effect to be the dominant mechanism for this transition in pipe flow. But additioinal effects, namely, turbulent fluctuation in the liquid and interfacial surface tension may also be significant. For the rod bundle case, REGIME-4 code considers the effect of surface tension and obtained good results with experiments.. At higher gas flow rates, the Stratified to Plug or Slug flow transition occurs at lower gas and liquid superficial velocities for the bubbly entrance condition. Since the phases are flowing very fast at these conditions, this may correspond to the uncertainty region. The Stratified Smoooth to Stratified Wavy transition was observed to be insensitive to the different entrance conditions.

The Stratified-Wavy flows was sometimes seen to be generated by the rod bundle end plates. Interfacial waves could be visually observed only when the liquid level does not intersect the rod, but were successfully characterized by the pressure drop and void fraction signal waveforms (see Fig. 1b). These were generally small amplitude waves, confined to the space between the rods and seen to occasionally touch the rods in the upper row.

The Plug and Slug flow regimes observed were typical of the well known cases for the pipe geometry. In the cases observed for 37-rod bundles, however, the liquid in the Slug bridge was flushed down the bundle flow passage. The process was confined mainly to the upper part of the bundle. In the Annular or Wavy-Annular flow regime, the liquid flowed as thin film at the upper part of the tube periphery around the bundle. The entrained droplets in the gas core deposited on the rods. This consequently was swept downstream as very thin film on the rods located at the upper part of the bundle, and a much thicker liquid film was observed to flow permanently at the lower part of the test section.



(a) Bubbly Entrance Condition



(b) Stratified Entrance Condition

Figure 5 Experimental Flow Pattern Transitions for 37-Rod Bundle Geometry (Tube I.D., D = 10.16 cm, Pipe Diameter, d = 1.27 cm) at Different Entrance Conditions for Temperature, T = 25°C and Pressure, P = 1.01 bar.

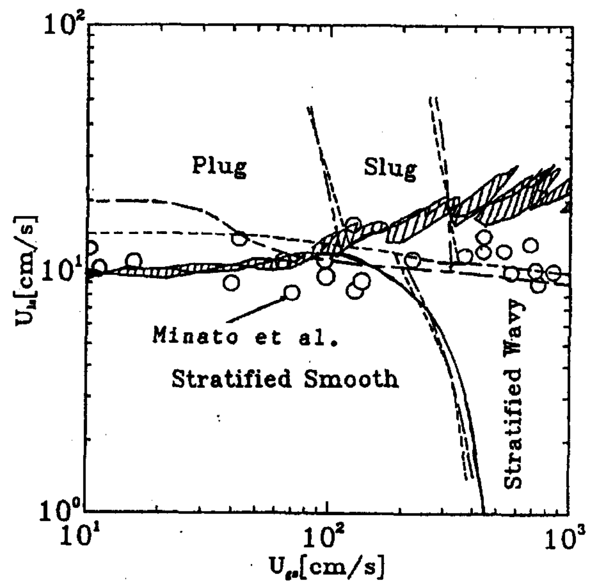


Figure 6 Comparison of Present Results with the Data of Minato et al.[7] for a 37-Rod Bundle Geometry at Room Temperature and Pressure, P = 1.01 bar.

At the flow conditions leading to Plug, Slug or Wavy-Annular transitions, bundle misalignment was observed to have no significant effect on the transitions due to the violent nature of the flow. However, interfacial waves occupying one bundle were sometimes dissipated on encountering a misaligned bundle, and the liquid in the wave was splashed onto the rods in the next upper row. Bundle misalignment also led to the generation of waves at the end plates. This occurred at different liquid flow rates from those in which dissipation of waves at the end plates due to bundle misalignment was observed.

Figure 6 also shows a comparison between the calculated, experimental results of present work and those of Minato et al.[7] for the 37-rod bundle geometry at room temperature and pressure of 1.01 bar. The results show that the REGIME-4 model predicts not only well the Stratified to Intermittent transition boundary, but also agrees with the uncertainty region caused by arbitrary orientation of the bundles in the enclosing tube. Also the experimental results of the present work agree well with the experimental results of Minato et al.[7]

CONCLUSIONS

Horizontal two-phase flow regime transition studies in a 37-rod bundle flow geometry have been conducted experimentally. The experimental results of the present work have been compared with theoretical results of previous investigation[1] and experimental results from the literature. The results show good agreement with both theory and other experimental investigations for horizontal 37-rod bundle two-phase flow transitions. Furthermore, we observed that:

(1) The flow patterns occurring in the rod bundle geometry fit the flow pattern descriptions already established for pipes, in this study, the Stratified Smooth, Stratified Wavy, Slug, Plug and Wavy-Annular flow patterns were successfully characterized.

(2) The flow pattern transitions for rod bundle geometries are significantly different from those of the pipe flow. The Stratified to Intermittent and Intermittent to Dispersed Bubble transition occurring at the lower superficial liquid velocities, while the Intermittent to Annular transition occurs at higher superficial gas velocities for rod bundle geometries than pipe flow cases.

(3) The flow pattern transitions are insensitive to different entrance conditions, except the Stratified to Intermittent transition at low superficial gas velocities occurring at lower liquid flow rates for the case of the stratified entrance condition.

(4) Small amplitude interfacial waves may be generated and dissipated at the rod bundle end plates, depending on the flow rates And the end plates have little effect on the Plug, Slug, Annular or Wavy-Annular flow regimes occurring in rod bundles, due to the violent nature of these flow patterns.

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