Preliminary Research on Identification of Flow Pattern in Inclined Pipe

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Abstract

The identification of flow regime is very important for safety analysis, improvement and design of mechanical system. As a preliminary research, experiments for flow regime identification have been conducted and experimental results have been successfully compared with theoretical model.

Key words : flow regime identification, safety analysis, theoretical model

1. Introduction

The flow regime identification is very important for safety analysis, improvement and design of mechanical system including nuclear power plant. Therefore, many scientists have attempted to verify the mechanism of flow regime transitions based on both experiments and theoretical ways. There have been a lot of research on flow regime transition in horizontal and vertical flow, on the other hand, studies for inclined pipe have been rare due to complexity caused by natural instability from inclination. As far as this author knows, Taitel & Dukler firstly proposed a semianalytical model for prediction of flow regime transitions in inclined pipe[1]. Thereafter, Barnea et al. experimentally verified Taitel & Dukler's model showing the good agreement between theory and experimental observations. However, they pointed out wrong approach for transition boundaries between stratified flow and stratified wavy flow saying that didn't consider gravity driven instability[2]. Weisman et al. presented empirical correlations for horizontal flow by adding the effects of the surface tension in their model[3]. Mishima et al. suggested a theoretical model for demonstration of the transition between stratified and nonstratified flow based on Kelvin-Helmholtz theory[4].

In this work, we conducted a number of experiments with various flow conditions and recorded flow region transition for these conditions by using High-speed camera. Also, for the verification of experimental observations comparison of visual interpretations with a theoretical model proposed by Taitel & Dukler[1] have been conducted.

2. Theoretical Model proposed by Taitel & Dukler

Momentum balance

Taitel & Dukler assumed that all flow regime transitions occur from stratified flow and classified flow regimes as five basic flow regions: smooth stratified, stratified wavy, intermittent, annular, dispersed bubbly flow. Consider the steady-state

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stratified flow shown in Fig. 1.

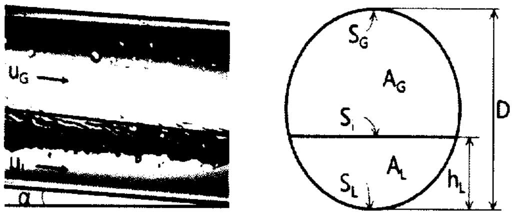


Figure 1: Schematic of stratified flow

A momentum balance on each phase yields

For liquid phase:

$$-A_L\left(\frac{dP}{dx}\right)-\tau_{wL}S_L+\tau_iS_i+\rho_LA_Lgsin\alpha=0 \tag{1}$$

For gas phase:

$$-A_G\left(\frac{dP}{dx}\right)-\tau_{wG}S_G+\tau_iS_i+\rho_GA_Ggsin\alpha=0 \tag{2}$$

Eliminating pressure drop term in Eq. (1) and (2) gives

$$\tau_{wG}\frac{S_G}{A_G}-\tau_{wL}\frac{S_L}{A_L}+\tau_iS_i\left(\frac{1}{A_L}+\frac{1}{A_G}\right)+(\rho_L-\rho_G)gsin\alpha=0 \tag{3}$$

The fluid-surface and interfacial shear stress can be expressed as

$$\tau_{wL}=f_L\frac{1}{2}\rho_Lu_L^2 \tag{4}$$

$$\tau_{wL}=f_L\frac{1}{2}\rho_Lu_L^2 \tag{5}$$

$$\tau_i=f_i\frac{1}{2}\rho_G(u_G-u_i)^2 \tag{6}$$

It has been established that for smooth stratified flow, $f_i\approx f_G$. At flow rate conditions, where flow transition can take place, $u_G\gg u_i$. Thus, we can rewrite Eq. (6) as

$$\tau_i=f_G\frac{1}{2}\rho_Gu_G^2 \tag{7}$$

The liquid and gas friction factors can be evaluated in conventional manner:

$$f_L=C_L\left(\frac{D_Lu_L}{\nu_L}\right)^{-n},\quad f_G=C_G\left(\frac{D_Gu_G}{\nu_G}\right)^{-m} \tag{8}$$

where $C_L=C_G=0.046$, $m=n=0.2$ for turbulent flow and $C_L=C_G=16$, and $m=n=1.0$ for laminar flow. For convenience, converting dimensional momentum balance (Eq. (3)) into dimensionless form by using D for length, D^2 for area, and superficial velocities for velocities, we get the following dimensionless momentum balance:

$$X^2\left[(u_L^*D_L^*)^{-n}u_L^{*2}\frac{S_L^*}{A_L^*}\right]-\left[(u_G^*D_G^*)^{-m}u_G^{*2}\left(\frac{S_G^*}{A_G^*}+\frac{S_i^*}{A_L^*}+\frac{S_i^*}{A_G^*}\right)\right]-4Y=0 \tag{9}$$

where X is Lockhart and Martinelli parameter and Y is gravity force to pressure ratio. These dimensionless variables are respectively defined as

$$X^2=\frac{\frac{4C_L}{D}\left(\frac{j_LD}{\nu_L}\right)^{-n}\frac{\rho_Lj_L^2}{2}}{\frac{4C_G}{D}\left(\frac{j_GD}{\nu_G}\right)^{-m}\frac{\rho_Gj_G^2}{2}}=\frac{|(dp/dx)_{L\,j_L}|}{|(dp/dx)_{G\,j_G}|} \tag{10}$$

and

$$Y=\frac{(\rho_L-\rho_G)gsin\alpha}{\frac{4C_G}{D}\left(\frac{j_GD}{\nu_G}\right)^{-m}\frac{\rho_Gj_G^2}{2}}=\frac{(\rho_L-\rho_G)gsin\alpha}{|(dP/dx)_{G\,j_G}|} \tag{11}$$

Other dimensionless variables are given by

$$A_G^*=0.25[\cos^{-1}(2h_L^*-1)-(2h_L^*-1)\sqrt{1-(2h_L^*-1)^2}] \tag{12}$$

$$A_L^*=0.25[\pi-\cos^{-1}(2h_L^*-1)+(2h_L^*-1)\sqrt{1-(2h_L^*-1)^2}] \tag{13}$$

$$S_G^*=\cos^{-1}(2h_L^*-1) \tag{14}$$

$$S_L^*=\pi-\cos^{-1}(2h_L^*-1) \tag{15}$$

$$S_i^*=\sqrt{1-(2h_L^*-1)^2} \tag{16}$$

$$u_L^* = \frac{A^*}{A_L^*} \quad (17)$$

$$u_G^* = \frac{A^*}{A_G^*} \quad (18)$$

Transition between stratified and non-stratified flow

Taitel & Dukler derived the following criteria based on the fact that if pressure acting on a solitary wave overwhelms the gravity force attracting a wave, wave grows.

$$Fr^{*2}\left[\frac{1}{C_2^2}\frac{u_G^* dA_L^*/dh_L^*}{A_G^*}\right] \geq 1 \quad (19)$$

where Fr^* is a Froude number modified by the density ratio:

$$Fr^* = \sqrt{\frac{\rho_G}{(\rho_L-\rho_G)}}\frac{j_G}{\sqrt{Dg\cos\alpha}} \quad (20)$$

and

$$\frac{dA_L^*}{dh_L^*} = \sqrt{1-(2h_L^*-1)^2} \quad (21)$$

Transition between intermittent and annular flow

According to Taitel & Dukler's theory, a stable slug can form when the supply of liquid in the film is large enough to provide the liquid needed to maintain such a slug. When the level is inadequate, the wave is swept up around the wall, and annular or annular mist flow takes place. This suggests that whether intermittent or annular flow will develop depends on the liquid level in the stratified equilibrium flow. It is suggested that when the equilibrium liquid level in the pipe is above the pipe center line, $h^* > 0.5$, intermittent flow will develop, on the other hand, if $h^* < 0.5$ annular or annular dispersed liquid flow will result.

Transition between intermittent and dispersed bubbly flow

According to Taitel & Dukler's theory, it is suggested that the transition to dispersed bubble flow takes place when the turbulent fluctuations are strong enough to overcome the buoyant forces tending to keep the gas at the top of the pipe. That is,

$$\frac{1}{2}\rho_L u_L^2\left(\frac{f_L}{2}\right)S_i \geq g\cos\alpha(\rho_L-\rho_G)A_G \quad (22)$$

Converting above equation into dimensionless form we get the following:

$$T^2 \geq \left[\frac{8A_G^*}{S_i^* u_L^{*2}(u_L^* D_L^*)^{-n}}\right] \quad (23)$$

where T is the ratio of turbulent to gravity forces acting on the gas defined as

$$T = \left[\frac{\frac{4C_L}{D}\left(\frac{Dj_L}{\nu_L}\right)^{-n}\frac{\rho_L j_L^2}{2}}{g\cos\alpha(\rho_L-\rho_G)}\right] = \left[\frac{|(dP/dx)_{L,j_L}|}{g\cos\alpha(\rho_L-\rho_G)}\right] \quad (24)$$

3. Effect of pipe diameter and inclination on flow regime transition

In order to demonstrate the effect of pipe diameter and inclination on flow patterns some calculations have been conducted based on Taitel & Dukler's model. Figure 2 and 3 shows the diamter and inclination effect on flow regime, respectively. Figure 2 implies that as pipe size increases more flow rate may be supplied for flow regime transition from stratified to others. Similarly, figure 3 shows that stratified flow region is expanded as inclination increases. This is because increase of inclination causes increase of gravity force so that water level ultimately decreases.

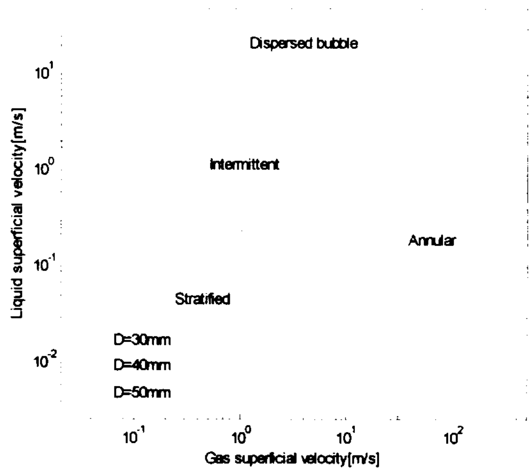


Figure 2 : Effect of pipe diameter on flow regime transition for $\alpha = 0°$.

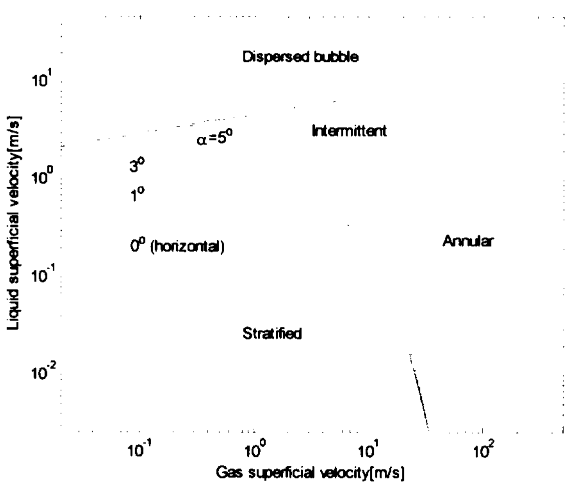


Figure 3 : Effect of pipe inclination on flow regime transition for $D = 45mm$.

4. Experimental facility

The inclined test section is made from circular acryl pipe with 45mm inner diameter, and inclination angle is 3°. The inclined test facility is composed of two inclined pipes with roughly 3500mm length and U-tube connecting them, and also contains air and water injector, collection tank, pipe lines and measurement instruments. The water is supplied into the test section by operation of 5HP pump lifting water in the main collection tank, and water amount is controlled by globe valves and measured by the Coriolis mass flow meter whose sensor model is RHM20 and transmitter model is RHE08. In case of air supply, air compressed by 15HP compressor is injected into the test section and this is controlled by rotameter and air amount is measured by the Coriolis flow meter (CMF100M). The maximum superficial velocity of liquid and gas are approximately 2.5m/s and 12m/s on a design basis.

5. Experimental results

Characteristic of flow patterns

In general, flow regime in horizontal or near horizontal pipe is classified as four regions whose characteristics are summarized as followings:

1) Stratified flow

- Liquid flows at the bottom of the pipe with gas at the top.
- Interface can either be smooth or wavy.

2) Intermittent flow

- Liquid in the pipe is non-uniformly distributed axially.

3) Annular flow

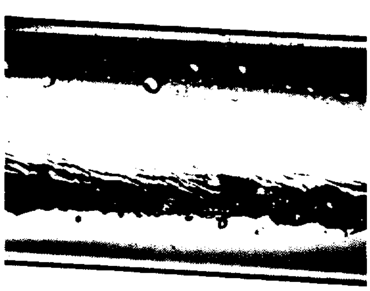
- Liquid flows as a film around the pipe wall.
- Liquid film surrounds a core of high velocity gas which may contain entrained liquid droplets.

4) Dispersed bubbly flow

- Gas phase is distributed as discrete bubbles within a continuous liquid phase.

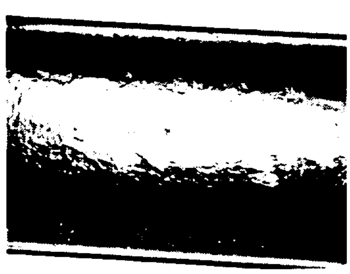
Experimental observations

For the investigation of flow regime transition in an inclination pipe several experiments have been performed with respect to various liquid and gas superficial velocities under standard temperature and pressure. The water and air have been used as operating fluids. In order to accurately evaluate flow patterns high-speed camera which can monitor two-phase flow in maximum 198,000 fps has been employed. This high-speed camera has been located at the point roughly 3000mm away from the inlet of inclined pipe for describing fully-developed condition. Figure 4 shows some examples of experimental observations obtained from high-speed camera for various liquid and gas superficial velocities.



(a) jL=0.5 m/s, jG=9.0 m/s

(b) jL=1.7 m/s, jG=2.1 m/s



(c) jL=0.5 m/s, jG=18.0 m/s

Figure 4 : Captured images of flow regimes for various flow conditions.

In Fig. 4, jL and jG represent water and gas superficial velocities, and each image (a), (b), and (c) shows stratified, intermittent and annular flow, respectively. For the verification of these experimental observations, a comparison with Taitel & Dukler's model has been conducted and result is shown in Fig. 5. According to Fig. 5, experimental data from high-speed camera image shows good agreement with a theoretical model, even though some mismatches appear near the intersection point where three transition boundaries meet.

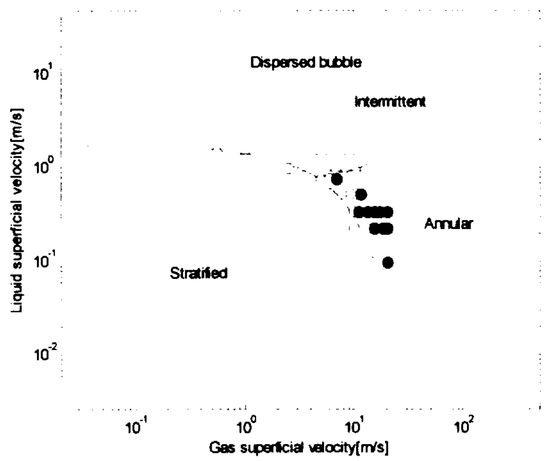


Figure 5 : Comparison of flow regime transition between experimental observations and Taitel & Dukler's model, (- Taitel & Dukler's model, ○ stratified, ● annular, and △ intermittent flow)

6. Conclusions

For flow regime identification several experiments have been conducted and experimental data has been successfully compared with a theoretical model proposed by Taitel & Dukler.

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경사관에서 유동형상 확인을 위한 기초연구

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적 요

유동영역 확인은 기계 시스템의 안전해석, 개선 및 설계를 위해 매우 중요하다. 기초연구로서 유동영역 판별을 위한 실험을 수행하였고, 실험 결과를 기존 이론 모델과 성공적으로 비교하였다.