CHAPTER III
EXPERIMENTAL

3.1 Material Preparation

    3.1.1   Air from a compressor [Taiwan, Fu Sheng HTA-100H] at constant outlet pressure of 1 bar.

    3.1.2   Pure water and glycerol [Fisher Scientific UK Limited, UK] mixed with water are used as working fluids.

3.2 Experimental Apparatus

### 3.2.1 Design and Experimental Setup of Two-phase Flow

The experimental setup is shown schematically in Figure 3.1. Air, pure water, and glycerol with water were used as the working fluids. The main components of the system consist of a vertical test section, air supply, liquid supply, and instrumentation. There are two main columns; one is for the test section, and the other is the return line to the reservoir tank. The test section, with an inside diameter of 0.019 m and a length of 3 m, is made of a transparent acrylic glass to permit visual observation of the flow patterns. The return section is also made with an acrylic glass which has an inside diameter of 0.054 m and is 3 m in length. The connections of the piping system are designed such that parts can be changed very easily. The smaller column of 0.019 m in diameter was used as the main column and the hydrodynamics of two-phase flow from bubble to annular were studied in it. Air compressor with inside pressure 10 bars was connected with air pressure regulator [Norgren, U.S.A, R74G-6GK-RMN] to reduce the outlet pressure at 1 bar. The variety of volumetric flow-rates of air used in this experiment was fixed at constant pressure of 1 bar. Compressed air with constant pressure of 1 bar entered at the bottom of the main column and flow rates were measured by a calibrated air-rotameter [Cole-Parmer, U.S.A, A-32466-68]. Liquid (pure water or aqueous glycerol solution) was pumped from the storage tank through the liquid-rotameter [Cole-Parmer, U.S.A, A-32461-42] to the column below the air injection line and mixed with air at the bottom. The

flow rates of the liquid were also measured by the liquid rotameter. The liquid from the main column flowed upward together with air and then flowed back to the storage tank. The experimental conditions were as follows: superficial air velocity j_{air}: 0.0021~58.7 m/s, superficial water velocity j_{water}: 0~0.121 m/s, and superficial aqueous glycerol solution velocity $j_{solution}$: 0~0.1053 m/s, respectively. The pressure at the exit of the tube was about 100 kPa and the air and liquid temperatures were 31~32°C.

Experiments were conducted at various air and liquid flow rates in two-phase flow. The air flow rates were increased by small increments while the liquid (pure water or aqueous glycerol solution) flow rates were kept constant. The aqueous glycerol solution viscosity was measured before and after the experiments by using a viscometer and it was almost the same. The system was allowed to approach the steady condition before any data is recorded. After stabilization, the air and liquid flow rates were recorded. The pressure drops across the test section was detected by a U-tube manometer. Two static pressure tubes connected with the manometer were used to measure the pressure drops along the column.
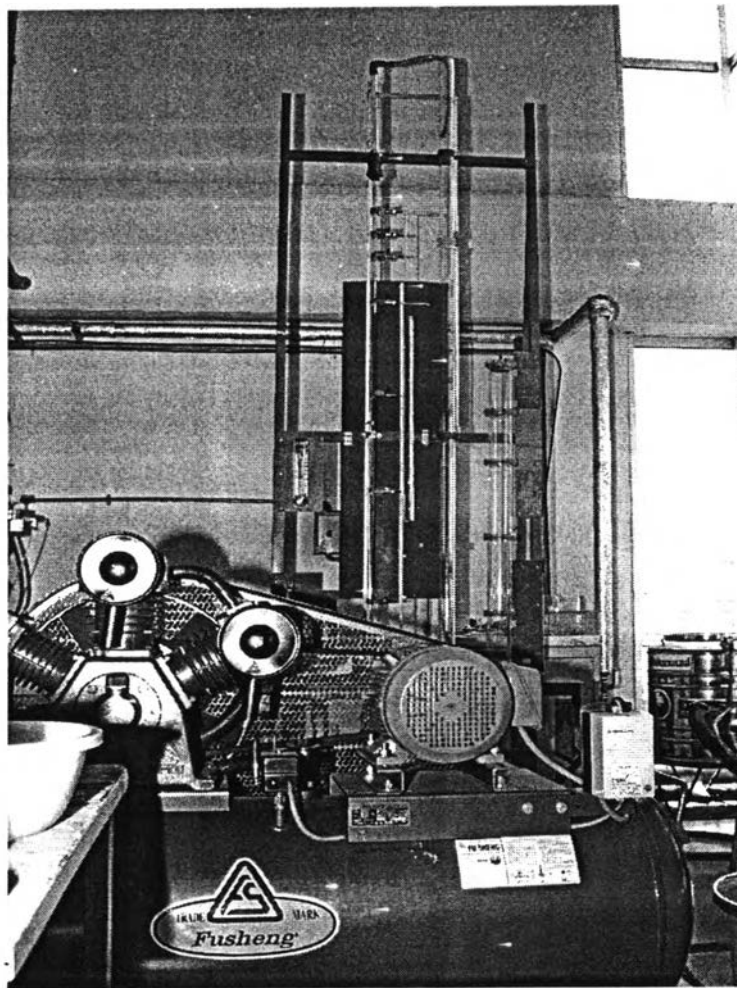
Figure 3.1 Photograph for two-phase flow experiment setup with air compressor.
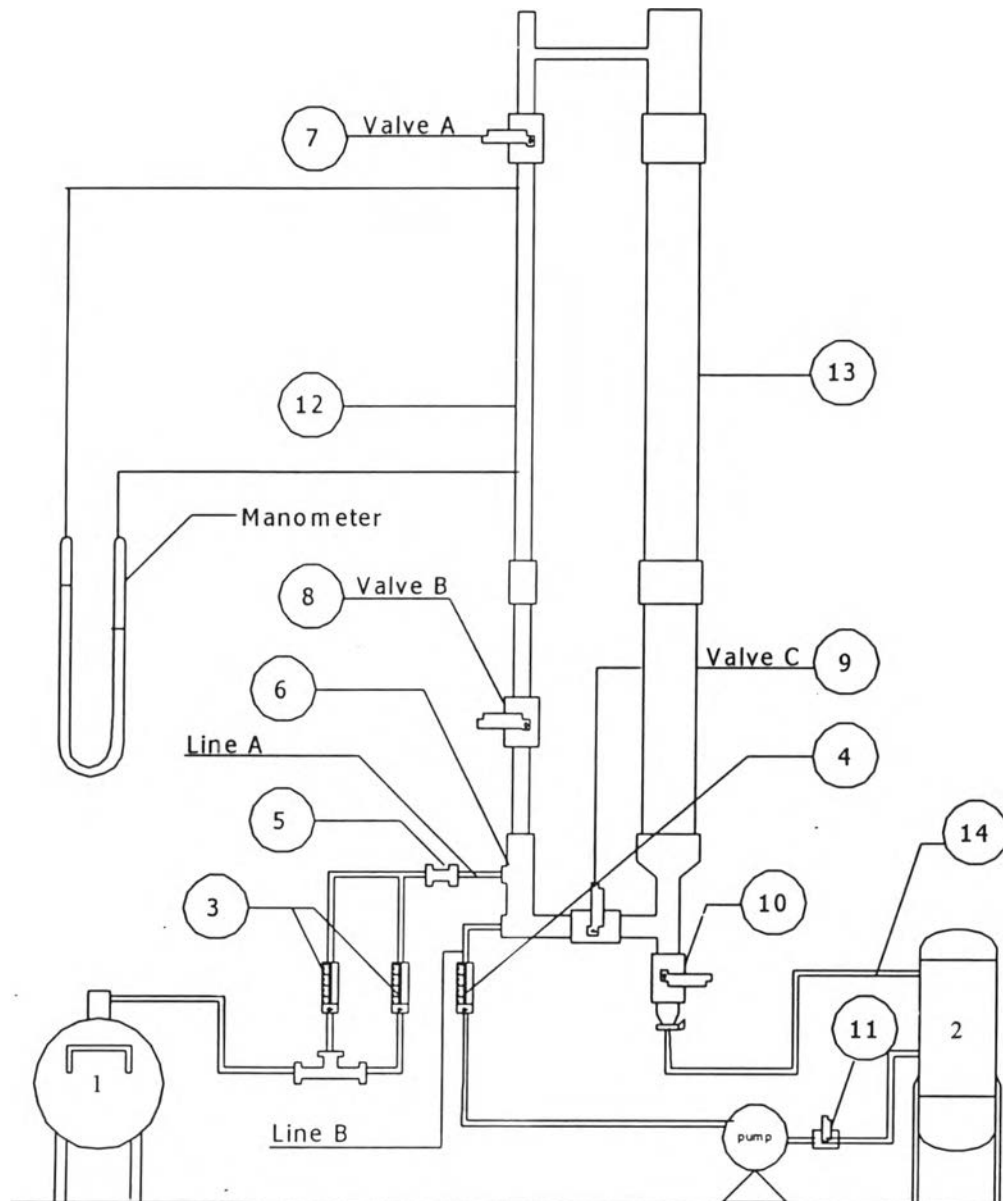
Figure 3.2 Schematic diagram of the experimental setup: 1) air compressor; 2) liquid reservoir tank, 3) air rotameter, 4) liquid rotameter, 5) check valve; 6) air injection tee; 7) isolating ball valve A; 8) isolating ball valve B; 9) isolating ball valve C; 10) draining ball valve; 11) control valve for reservoir tank; 12) vertical tube with the diameter of 0.019 m and the length of 3 m; 13) overflow tube with the diameter of 0.054 m and the length of 3 m; 14) liquid return line to reservoir, Line A for air injection line, and Line B for liquid injection line (modified from Puengpatipan, 2002)

3.3 Methodology

3.3.1 Parameters

3.3.1.1 Controlled Parameters of Two-phase Flow

- Dimensions of both columns
- Temperature of working fluids was controlled at 31°C by putting ice around the reservoir fluid tank.
- Outlet pressure of air compressor was fixed at 1 bar by using air pressure regulator. The air pressure regulator was connected with air compressor's outlet to control the system pressure at constant 1 bar. The inside pressure of air compressor is 10 bars and after connecting with regulator, it can be reduced to 1 bar.

3.3.1.2 Variable Parameters of Two-phase Flow

- Volumetric flow rates of air in main column (0-1000 l/min)
- Volumetric flow rates of liquid in main column (0-2.055 l/min for pure water and 0-1.794 l/min for glycerol solution)
- Percent of glycerol volume concentration in water (50 vol % of pure glycerol in aqueous glycerol solution)

3.3.1.3 Measured Parameters of Two-phase Flow

- Boundaries of flow regimes by video camera or still photographs
- Critical Reynolds numbers of air at each flow regime
- Liquid levels difference in manometer for pressure drops calculation

Table 3.1 Variable parameters of two-phase flow

System	Minimum volumetric liquid flow-rate Q_L (l/min)	Maximum volumetric liquid flow-rate Q_L (l/min)	Minimum volumetric air flow-rate Q_G (l/min)	Maximum volumetric air flow-rate Q_G (l/min)
Air-pure water	0	2.055	0.036	1000
Air-50 vol% glycerol solution	0	1.794	0.036	800

3.3.2 Experimental Procedures

3.3.2.1 Determination of Kinematic Viscosities by Viscometer
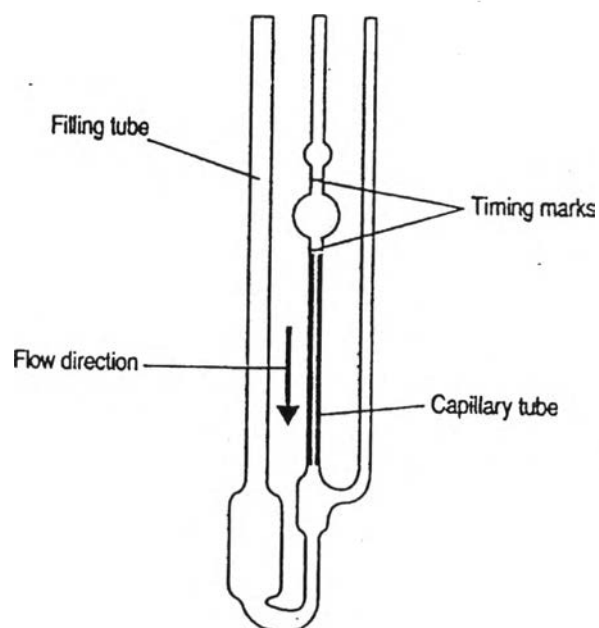
Figure 3.3 Schematic diagram of the viscometer.

Viscosity measurements were made under strictly controlled conditions and prescribed techniques. We selected a clean and dry calibrated

viscometer of an appropriate design [U.S.A, **CANNON 50 B505 and CANNON 100 B941**] and having a range covering the estimated viscosity of the test sample. The kinematic viscosities of pure water and 50 vol% glycerol solution were measured by using a capillary viscometer at 31°C. Two types of capillary tube were used for this experiment depending on their viscosity. For pure water, **CANNON 50 B505,** viscometer was used and for 50 vol% glycerol solution, **CANNON 100 B941,** viscometer was used for measuring their kinematic viscosities. After loading the viscometers with the samples, we allowed it to be suspended in a constant temperature water bath at 31°C for 30 minutes. We noted and recorded the test temperature to the nearest 0.1°C. After the sample has reached temperature equilibrium, we measured the time required for the liquid front to travel between the two timing marks on the viscometer's capillary tube. In all cases, if the measured flow time was less than 200 seconds or more than 1000 seconds, we selected a viscometer with a capillary of respectively smaller or larger diameter and repeated the entire procedure.

3.3.2.2 Calculations of Kinematic Viscosities of Pure Water and 50 vol% Glycerol Solution

We calculated the kinematic viscosity of the test sample from the viscometer constant and the measured flow time according to the following equation:

$$\text{Kinematic viscosity, } v = C \times t \ (\text{mm}^2/\text{s})$$

where C = calibration constant of the viscometer (cSt/s or mm^2/s^2), and t = measured flow time (s).

For pure water

For **CANNON 50 B505** viscometer, C = 0.004 mm^2/s^2 [from specification of CANNON viscometer]

Measured flow time for pure water, t = 213.06 s

Kinematic viscosity of pure water, $v_{water} = C \times t = 0.85 \times 10^{-6}$ m^2/s

Density of pure water, $\rho_{water} = 995$ kg/m^3

So, viscosity of pure water, $\mu_{water} = 8.48 \times 10^{-4}$ kg/m.s

For 50 vol% glycerol solution

For **CANNON 100 B941** viscometer, C = 0.015 mm^2/s^2 [from specification of CANNON viscometer]

Measured flow time for 50 vol% glycerol solution, t = 264.1 s

Kinematic viscosity of 50 vol% glycerol solution, $v_{solution}$ = C x t = 4.0 x 10^{-6} m^2/s

Density of 50 vol% glycerol solution, $\rho_{solution}$ = 1121 kg/m^3

So, viscosity of 50 vol% glycerol solution, $\mu_{solution}$ = 4.48 x 10^{-3} kg/m.s

3.3.2.3 Determination of Flow Pattern Map

With valve C closed, the volumetric flow rates of air, pure water, and glycerol solution were varied in the range of 0.036 to 1000 l/min, 0 to 2.055 l/min, and 0 to 1.794 l/min, respectively. The experimental conditions were as follows: superficial air velocity, j_{air}: 0.0021~58.7 m/s, superficial water velocity, j_{water}: 0~0.121 m/s, and superficial aqueous glycerol solution velocity, $j_{solution}$: 0~0.1053 m/s. When we increased the air flow rates at a constant liquid flow rate, we could observe the bubble, the bubble-slug transition, the slug, the slug-churn transition, the churn, the annular, and the mist flow regimes. Then we increased the flow rate of the solution and made it constant. The flow regimes were observed by visual observation, still photographs, and video camera. First, the experiment was started with an air-pure water mixture and developed into flow pattern map for this mixture. And the working fluid was changed with air-50 vol% glycerol solution mixture in order to investigate the effect of viscosity on the flow pattern maps.

3.3.2.4 Determination of Pressure Drops in The Main Column

Two static pressure tabs were installed at two axially locations with the spacing of 0.4 'm at the main column and connected with a manometer were used to measure the pressure drops along the test section. The system was allowed to approach the steady condition before any data was recorded. The manometer was filled with water. We measured the water levels difference in the manometer and calculated the pressure gradients for each flow regimes by following equation:

$$\left(-\frac{dp}{dz} \right) = \frac{\rho_L g h}{dz} \tag{14}$$

where ρ_L = liquid density (kg/m^3), g = gravitational acceleration (m/s^2), h = water levels difference in the manometer (m), and dz = pressure taps difference (m).

The pressure drops across the test section were recorded and calculated by this method. And the values of pressure drops from the experiments were compared with the theory.

3.3.3 Data Analysis

The flow pattern maps were produced by plotting the Reynolds numbers of air versus the Reynolds numbers of liquids. We plotted the boundary lines of flow regimes by using critical Reynolds numbers of air at each flow regime. After plotting the flow pattern maps for the pure ware and the 50 vol% glycerol solution, we compared and investigated the effect of viscosity on flow pattern maps.

We plotted the measured pressure gradients $(-dp/dz)_{exp}$ against with Reynolds numbers of air, Re_{air}, for pure water and 50 vol% glycerol solution. We compared the behavior of pressure gradients $(-dp/dz)_{exp}$ of both liquids at the same liquid Reynolds numbers and analyzed it.

The pressure gradients $(-dp/dz)_{exp}$ that were measured from the experiment were compared with the pressure gradients $(-dp/dz)_{cal}$ calculated from the theory of the bubble, the slug, the annular, and the mist flow regimes. If the values did not agree with theory, a new empirical correlation for predicting the pressure drop factors in upward two-phase flow was been developed in this research for practical use.