THE AIR-WATER MIXING EXPERIMENT IN A VERTICAL FLOW CHANNEL

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Abstract:

Predicting flow pattern using flow parameters such as void fraction, superficial velocities and interfacial area concentration (IAC), etc, is required to solve conservation equations and field equation for two-phase flow problems. In this paper, relations among the two-phase flow patterns and these flow parameters in a vertical pipe are given by the experimental data obtained with the Vertical Air-Water Loop (VAWL). The flow parameters included pressures, superficial velocities, void fractions and IAC are measured by pressure transmitters, impedance void meters (IVM) and five-sensor conductivity probes at three locations along the pipe. The experiment results show changes of pressure, void fraction and superficial velocity along the pipe under bubbly/slug flow conditions. The design and working principle of the facility and measuring equipments are also presented in this paper.

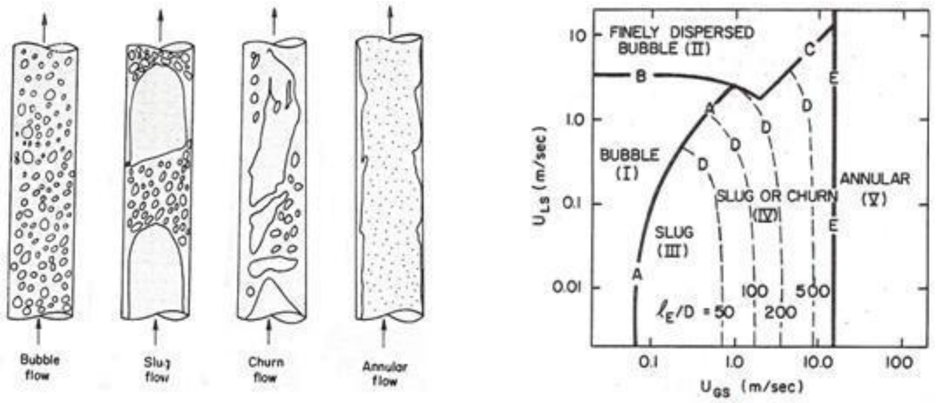
Keyword: *VAWL, Two-phase Flow, Void fraction, IAC*

1. INTRODUCTION

Two-phase flow is the most important in nuclear reactor safety issues. The behavior of two-phase flow affects the heat remove capability of coolant in the reactor. Accidents of nuclear reactor can be induced by significant change of the behavior of two-phase flow. It is known that the departure nucleate boiling (DNB) condition for PWRs can occur when bubbly flow under normal operating condition change to slug flow with vapor clots formed near the surface of fuel cladding. Under the condition, the heat transfer capability of coolant can be decreased drastically; the temperature of fuel elements increases highly and the fuel elements can be molten [1]. Therefore, the predicting two-phase flow patterns matched the flow parameters such as void fraction, superficial velocity or IAC is very necessary. The modeling of flow characteristics is required in solving the conservation equations of mass, momentum and energy, and the field equations of the two-phase flow.

The flow pattern is shape of two phases that change with flow conditions. For vertical flow in a pipe, four representative flow patterns as described in figure (1a) are bubbly, slug, churn and annular [2]. The bubbly flow consists of bubbles distributed in continuous liquid phase. The slug flow contains large bubbles occupying almost the pipe section are known as Taylor bubbles. The liquid film that called as the falling film is formed between the Taylor bubble and the pipe wall. The accumulated liquid goes down and forms continuous liquid bridge crossing the pipe between two Taylor bubbles. The churn flow is more chaos than the slug flow. The Taylor bubbles become narrow and the falling film gradually losses its continuity. The annular flow is characterized by the continuous gas phase in center section of pipe and wavy liquid film near the wall. The liquid near the wall is separated particularly as droplets and entrances gas core. The flow patterns depend on the shape of bubbles. The bubbles can be coalesced in to a lager bubbles because of random collisions of the bubbles or effects of wake entrainment region. The bubbles can be also broken up into smaller bubbles due to the effect of turbulent eddies. The change of shape of bubbles induces change of void fraction and superficial velocities of phases. Therefore, the flow patterns depend on void fraction, flow rate, geometry of pipe as well as properties of working fluids. Many experiments are given criteria as functions of flow parameters such as void fraction or superficial velocity to determine operating region of the flow patterns and their boundaries. The flow maps are formed by plotting the criteria. The criteria are presented by boundaries of regions (fig 1b). The lines can displace under different conditions. Additionally, the agreement of the maps is not obtained. Therefore, the applicability of the criteria and maps are limited. They cannot be applied for different geometries and sets of fluid properties [3].

Almost the flow transition criteria are built from drift-flux model in which two phases are considered as a mixture and conservation equations and field equations are formulated for all the mixture. Therefore, this method is only suitable with steady state, developed flows. It is also invalid in cases that two phases interact weakly together. In order to overcome the limitations, a new tendency using two-fluid model and mechanistic approach with interfacial area transports (IAT) is being developed. The two-fluid model considers two phases separately. The conservation equations and field equations is considered for each phase and interactions between them. The interaction is represented by the gas-liquid interface. The interface always exists, changes along the flow channel, and is expressed as a form of interfacial area concentration (IAC) parameter. IAC is defined as the interfacial area per unit control volume. However, the relations for IAC are still lack and being sought upon experiments. Some studies tried to add the IAT equations into CFD codes, e.g. Fluent, CFX, to predict the flow behavior more exactly. [4,5]



(a) (b)

Fig 1. (a) Flow patterns and (b) flow maps for vertical flow channel

The purpose of the Vertical Air-Water experiment is investigating the change of void fraction and superficial velocity along a vertical pipe under bubbly/slug flow conditions. The experiment also shows how the flow patterns change follow void fraction and superficial velocity. In this paper, measuring IAC parameter by five-sensor conductivity is also presented. The parameter such as void fraction, superficial velocity, number of bubbles and Sauter diameter of bubbles can be calculated at local flow positions though processing IAC parameter [6].

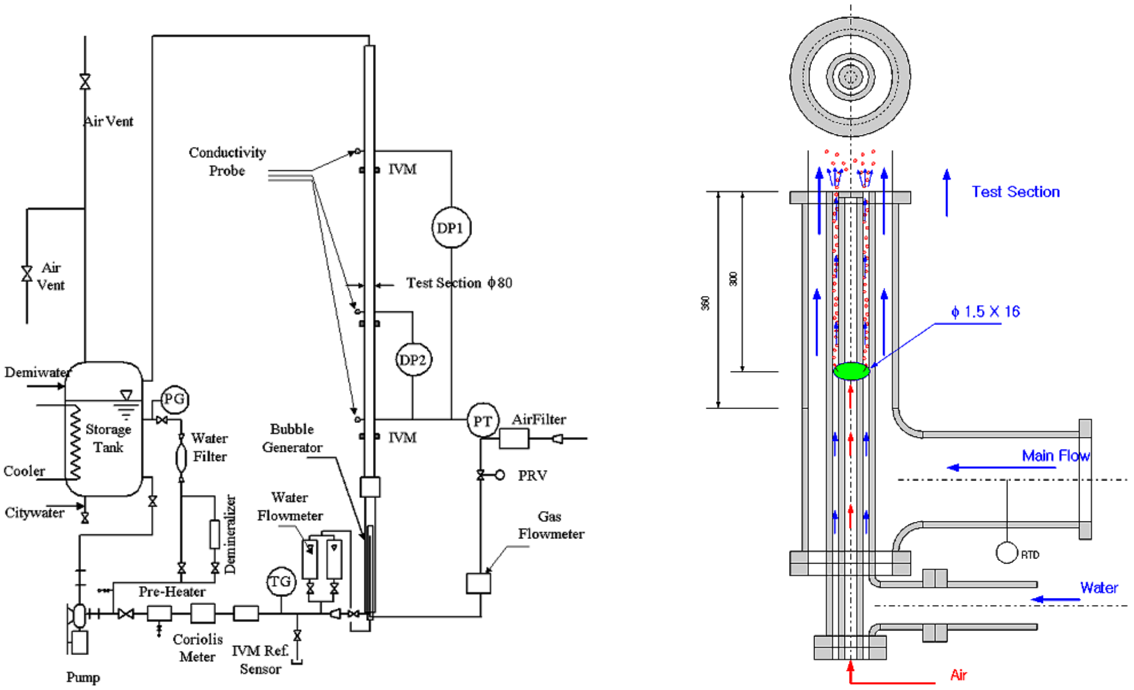
2. THE VAWL FACILITY AND MEASURING EQUIPMENTS

2.1. The VAWL facility

The facility consists of a test section, a bubble generator, systems supplying water, air, and control and data acquisition unit (Fig 2a). The test section is a transparent acrylic pipe with 0.08m of diameter (D) and 10m of height (L). The bubble generator is a cylinder pipe connected with test section (Fig 2b). Air is injected into the center of bubble generator and water is injected into the annular of bubble generator. Air and water are mixed together, and bubbles is generated by nozzle inside of the bubble generator. Water is pumped from a storage tank though a heater, the bubble generator, the test section, and turn back the storage tank. Temperature and pressure of the system are maintained constant about 46^{0}C and 2bar correspondingly. Temperature is controlled by the heater, the cooler inside the tank and a RTD installed at entrance of test section. Pressure is controlled by an auto valve and a relief valve. Three five-sensor conductivity probes are installed axially at three positions of the test section (L/D = 10.2, 42.2 and 100.7). Pressure is measured by one pressure transmitter (PT) at L/D =12.2 and two difference pressure transmitters (DPT) at L/D = 42.2 and 100.7. Three IVMs is placed at three positions L/D = 41.33, 42.2 and 42.95. The water and air flow rates are measured by a Coriolis and a Rotameter, correspondingly. [4]

2.2. The impedance void meter

IVM used to measure void fraction is a multi-channel conductance void meter. Their principle is the difference in electrical conductance of a two-phase mixture due to the variation of void fraction around a sensor, and variation of flow conductance with void fraction. IVM is consists of a main sensor, a reference sensor and a signal processing unit. The each sensor has a couple of measuring electrodes and two couples of guard electrodes electrically shielded to avoid polarization of fluid molecules. These electrodes are flush-mounted to the inner wall of test section to avoid flow disturbances. The reference sensor is placed upstream of bubble generator where only water flow in order to eliminate the drift in void signals caused by the changes in electrical properties of the flow medium. The signal of the main sensors is calibrated by the signal of the reference sensor in order to compensate the conductance changes depending on time of the flow medium. [4]



(a) (b)

Fig 2. Diagram of VAWL facility (a) and bubble generator (b)

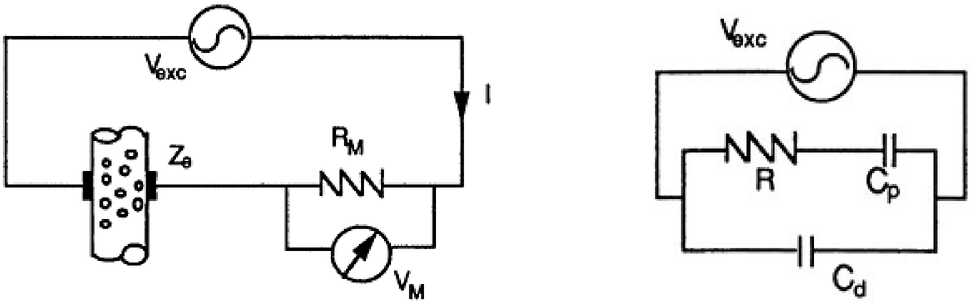


Fig 3. The principle scheme of IVM

The principle scheme of IVM is showed in Fig 3 [4,7]. The electrical conductance of two-phase mixture includes the electrical resistance of two-phase mixture (R), the capacity due to polarization of the fluid molecules near the electrodes (C_p), and the capacity due to the dielectric constant of conductive phase (C_d). An exciting source with potential V_{exc} and frequency *f* is used to determinate output potential signal (V_M) and the conductance (Z) as following:

$$V_M = \left|V_{exc}\right| R_M / \left(R_M + Z\right) \tag{1}$$

$$Z(f) = \frac{1}{\left[\dfrac{1}{R + 1/i2\pi fC_p} + i2\pi fC_d\right]} \tag{2}$$

Where, R_M is the resistant of the measuring meter. To determine resistant of the two-flow mixture, it need eliminate contribution of these capacities by choosing the frequency *f* so that they can be neglected. In this experiment, we choose f is 20 kHz and set V_M is 8V for water and 0V for air.

2.3. The five-sensor conductivity probe

The five-sensor conductivity probe is useful in measuring the two-phase flow parameters such as IAC, void fraction and superficial velocity. Its principle is the difference in electricity between two phases and dependence of conductivity on void faction. IAC is determinate follow the formula given by Ishii (1975) for a multi-sensor conductivity probe [8] as following:

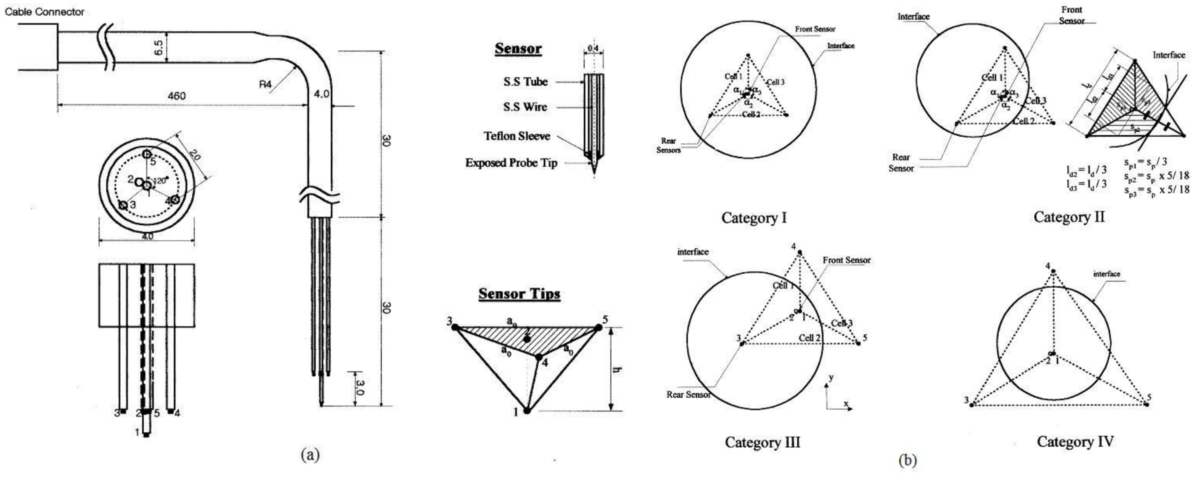


Fig 4. (a) Configure of the five-sensor conductivity probe
and (b) position of missing interface

$$\bar{a}_i^t\left(x_0, y_0, z_0\right)=\frac{1}{\Omega}\sum_j\frac{1}{\left|\vec{v}_{ij}\right|\cos\phi_j} \tag{3}$$

Where, Ω is total measuring time, ϕ_j is angle between velocity vector of interface j (v_{ij}) and normal vector at (x_0, y_0, z_0). The number of sensor depends on flow regime. The five-sensor conductivity probe is developed upon the four-sensor one in order to minimize effect of the missing interfaces and use for flow regimes without any assumptions. IAC is calculated by averaging of three cells on vertical projected plane of the probe. Dr. Euh calculates the cell-IAC for cases of missing interface position. Fig 4 shows configure of the five-sensor conductivity probe and positions of missing interface. [9,10]

3. EXPERIMENTAL RESULTS

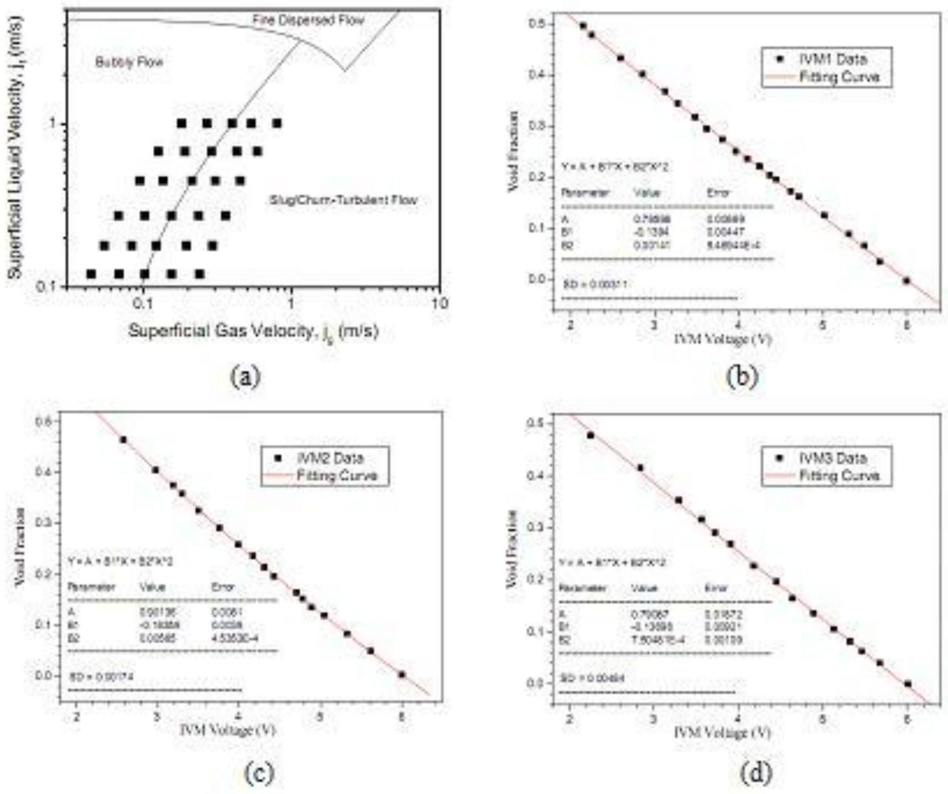
The experiment is performed with bubble-slug flow regimes in adiabatic condition (Fig 5a). System pressure and temperature are 46 ^{0}C and 2 bar correspondingly. The water flow rate changes in range 0.18 to 1(m/s), and the gas flow rate is in range 0.15 to 0.76 (m/s).

3.1. IVM Calibrating

The calibration of IVM is performed by measuring pressure drop of two-phase flow ΔP along the pipe. The experiment conditions are chosen so that the acceleration pressure drop and friction pressure drop can be neglected. The different potential values are applied to electrodes of IVM and void fraction values calculated (α) are plotted as a function of the potential signals (V) in equation (4) as shown in figures 5b, 5c and 5d.

$$\alpha=\frac{\Delta P}{g\rho_f\Delta z}=C_0+C_1V+C_2V_2^2 \tag{4}$$

Where, C_0, C_1 and C_2 are calibration coefficients, ρ_f is water density, and Δz is elevation.



(a) (b) (c) (d)

Fig 5. (a) Experimental condition, (b,c,d) calibration curves of IVM, IVM2 and IVM3

3.2. The averaged two-phase flow parameter

In the experiment, pressure is measured by PT and two DPTs, water/gas flow rate is measured by a Coriolis and Rotameter, and void fraction is calculated by the celebrating curves of IVMs. Figure (6) shows the pressure drops along the axial of test section. When the flow goes upward, pressure decreases strongly owing to effects of gravity, acceleration, and friction. However, the two components contained acceleration pressure drop and friction pressure drop are small and ignored under the experimental conditions. Therefore, total pressure drop depends on the measuring point and void fraction as shown in equation (4). At the middle measuring point, pressure drop increases when void fraction increase under the same interfacial liquid velocity. The pressure drop at the low end of pipe is not change because pressure is control constantly at here. The pressure drop at the upper end of pipe is irregular because of developing of the flow pattern along the pipe. However, the pressure drops at two end of pipe is not important.

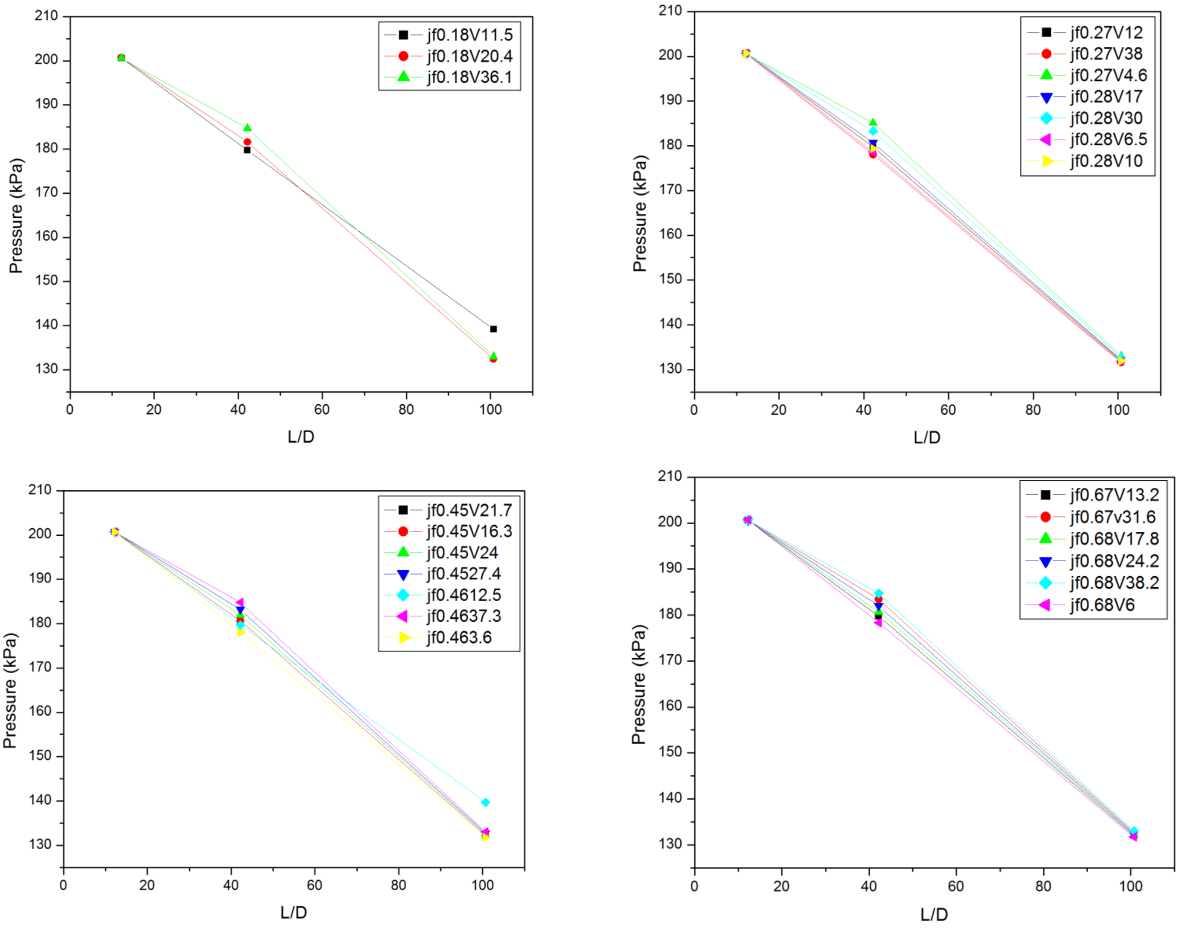


Fig 6. Pressure drop along the test section

The change of gas flow rate at three measuring points along the axial of test section is shown in figure (7). At higher void fraction, the gas density decreases because of pressure drop, bubble becomes larger, and effect of drag force dominates one of buoyancy. Therefore, gas flow rate is higher at upper and at higher void fraction. Figure (8) shows the change of void fraction along the length of pipe. At higher region, bubbles expanding due to pressure drop can coalesce easily into larger bubbles. Therefore, void fraction will be higher at upper. The experimental observation shows the change of flow pattern along the pipe. The transition from bubbly flow to slug flow occur at upper of pipe. Bubbles are longer and bigger at higher position. The observation is suitable to the measuring results of void fraction and gas flow velocity. However, if the gas flow velocity is increased highly to a certain value, the effect of wake entrainment region is enough strong to breakup larger bubbles into more small bubbles and the bubbly flow is remained.

The uncertainties of the parameters at 95% of confidence level are determined by uncertainties of the equipments and the calculations. The uncertainty of water/gas flow rate is very high because water/gas source are unstable, sometime not enough to supply. It is reason for error of void fraction is very high, up to 18%. The uncertainty of pressure is small, below 0.3%.

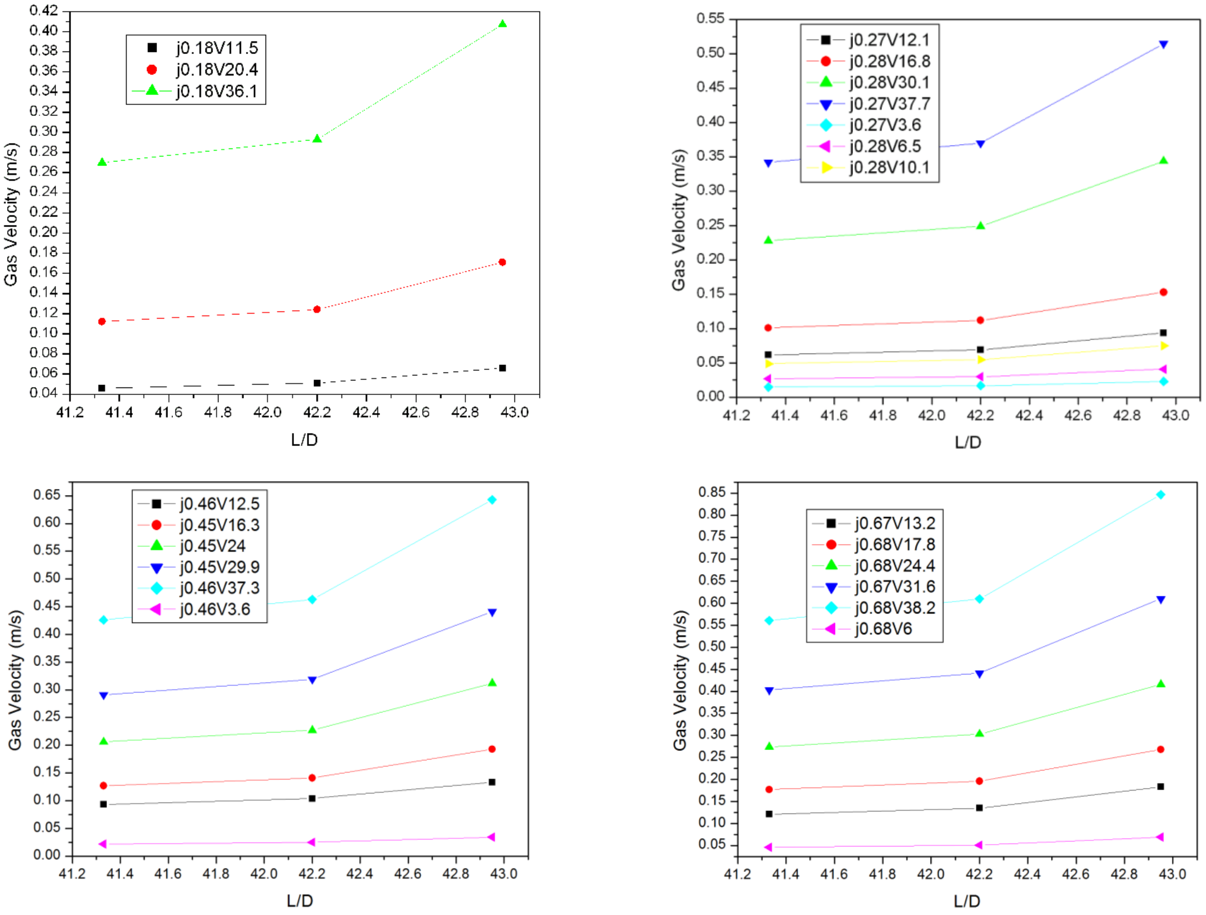


Fig 7. The change of gas velocity along the length of pipe

3.3. Signal processing of five-sensor conductivity probe

There are 16 measuring points from center to the wall of pipe with 2.5mm of displacement each step, at each measuring point along the axial. The conductivity signal of the mixture pass though conditioner to rectify and eliminate high frequency noises. The signal is discrete into binary values by ADC with sampling frequency is 20 kHz. The signal is converted into pulse form to define bubble/liquid signals to calculate the following flow parameters: [11]

Bubble velocity: $v_b = d_{tip,v} / t_{delay}$

Void fraction: $\alpha = \sum \tau_b / \Omega$

IAC: $a_i \sim f\left(N_b, v_i, \tau_b, d_{tip,v}, l_d\right)$

Sauter Diameter: $D_{sm} = 6\alpha / a_i$

Where, $d_{tip.v}$, t_{delay}, τ_b and Ω are distance between tips, delay time, residual time, and total time correspondingly. The process is programmed in C++ language. The program is built in VEE Pro 5.0 allow observation of the IAC signal form, and display calculated results. Fig 9 shows the signal forms obtained by the probes.

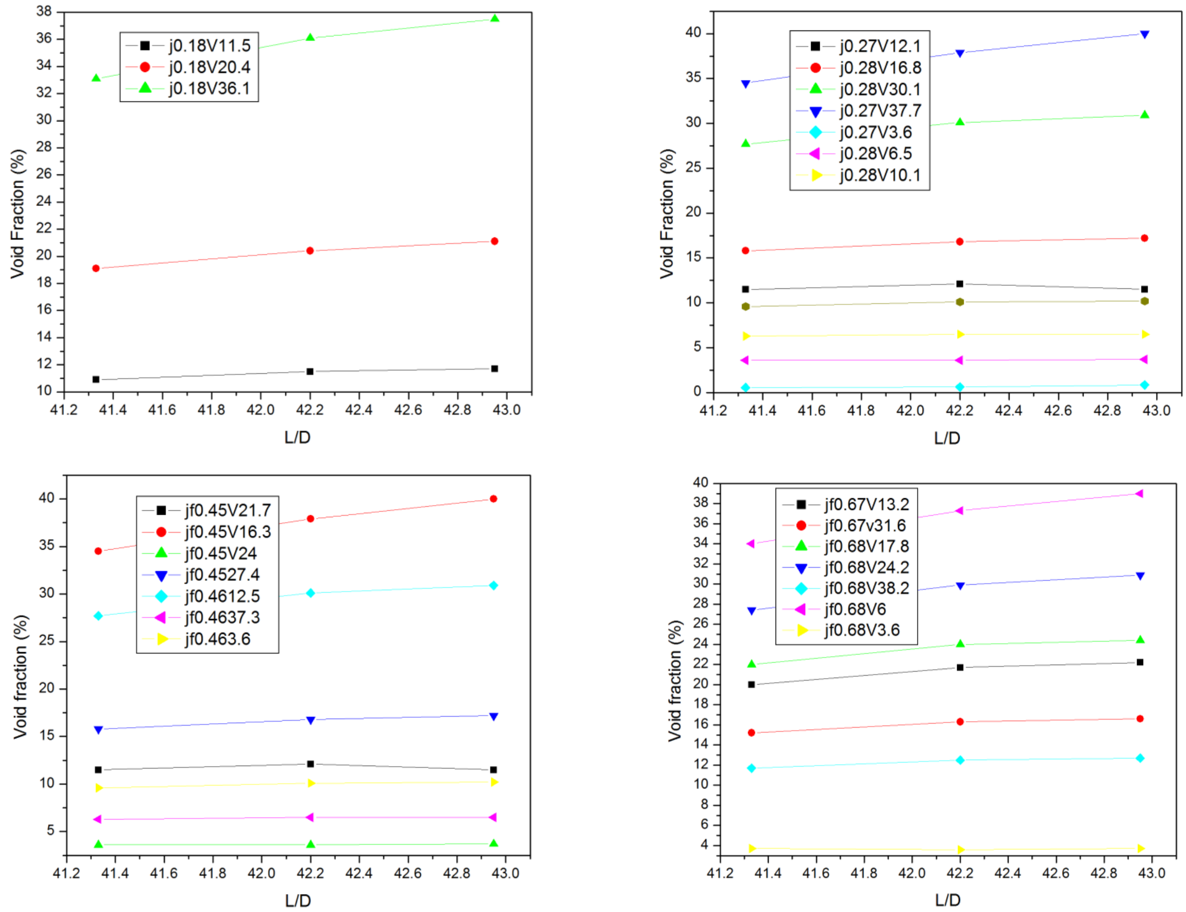


Fig 8. The variation of void fraction along the length of pipe

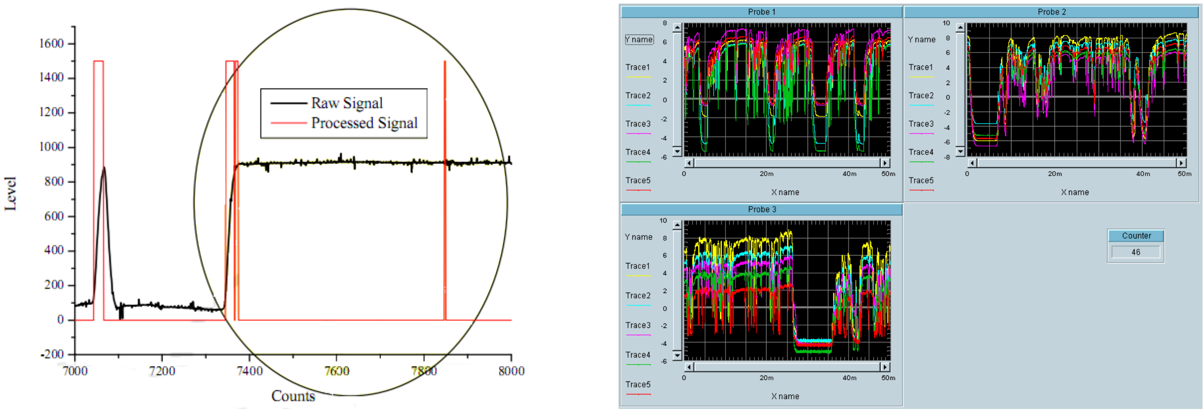


Fig 9. The signal forms of five-sensor conductivity probe

4. CONCLUSION

The most important issue in nuclear reactor safety researches is two-phase flow. The behavior of the two-phase flow is characterized by the flow patterns and the regime transition criteria between the flow patterns. In this paper, the two-phase flow patterns in a vertical pipe included bubbly, slug, churn and annular flows are presented. The characteristics of these flow pattern is described by shape and size of bubbles.

For the mixing of air and water in vertical channel with the VAWL facility, the parameters such as pressure, gas flow rate and void fraction is measured by IVM and the five-sensor conductivity probe. Structure and principle of the facility and the measuring equipments is presented in this paper. The obtained results show that the pressure decreases along the axial of test section mainly due to gravity. The gas flow rate and void fraction increase with pressure drop. At higher measuring positions, the gas flow rate and void fraction are higher The issues relate to coalescence and breakup of bubbles, and effect of buoyancy and drag forces. The principle of determination of the IAC parameter obtained by five sensor conductivity probe is also presented. The signal processing is consist of converting data, creating pulse shaped signal, finding and defining the bubble signals, and then calculating parameters such as void fractions, superficial velocity, Sauter diameter, etc. All the signal processing is performed by the C++ program integrated with VEE Pro 5.0.

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