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IDENTIFICATION OF FLOW REGIMES IN VERTICAL GAS–LIQUID TWO-PHASE FLOW USING DIFFERENTIAL PRESSURE FLUCTUATIONS

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Abstract—Differential pressure fluctuations are used to estimate flow regimes of nitrogen gas–water mixtures in a vertical pipe because the fluctuations seem to be closely connected with the flow configuration. The regimes of vertical two-phase flow are classified by the peculiar features of statistical properties of the fluctuations, which are calculated from the data of static pressures measured at four locations along the flow direction. The results show that it is possible to identify the flow pattern from the configuration of probability density functions, the order of variance and the average value of differential pressures because these statistical properties depend on a flow pattern.

1. INTRODUCTION

In the design and operation of two-phase flow systems, it is essential to know the two-phase flow pattern because hydro- and thermo-dynamic data such as pressure drop, void fraction and quality depend on the flow pattern. It is therefore important to develop any technique to evaluate a flow pattern in an opaque pipe or duct. A number of experimental works have been made, which are concerned with statistical properties of void fraction or pressure in the two-phase flow. The results are available for the identification of flow pattern.

Nishikawa *et al.* (1969) investigated in detail statistical properties of static pressures and classified the features of properties that each flow pattern presents. This evaluation based on a static pressure signal, however, is not preferable because the static pressure signal includes pressure fluctuations occurring at not only the measured point but also another places outside of the measurement section. Akagawa *et al.* (1971) investigated the frequency distribution of differential pressure signal on a slug flow and showed that the distribution depends on the distance of differential pressure section. Jones & Zuber (1975) classified bubbly-, slug- and annular-like flows according to characteristics of probability density function of void fraction measured by X-ray absorption technique, but the instrumentation is not easy in practice, owing to difficulties of measurement.

In contrast, pressure signals are easily accessible to measurements and the instrumentation does not have such disadvantages. Moreover, pressure signals may contain sufficient information on peculiar features of flow pattern and flow condition for the two-phase flows. In this study we propose a technique of identifying the representative flow patterns of gas–liquid two-phase flow in a vertical pipe, based on the processing of measured data on four static pressure signals. Differential pressures, which fluctuations seem to be closely connected with flow patterns, are adopted in order to eliminate the influence of pressure fluctuations occurring outside of the measurement section. The differential pressure signals at both small and long intervals are examined at the same time. The small interval is chosen to the inside radius of pipe in order to discriminate a spherical cap bubble with a half length of the inside diameter of pipe. It is shown that the statistical properties (the probability density function [PDF], the cross-correlation [Φ_{ab}], the variance and the mean value) of differential pressure fluctuations demonstrate peculiar features for each regular flow pattern.

2. EXPERIMENTAL DEVICE AND INSTRUMENTATION

Figure 1 shows a schematic of the experimental apparatus. The channel system is a single closed loop as shown in figure 1(a) and consists of an upper level section, a downcomer section, a lower level section, a riser section and a gas–liquid separator along the flow direction. The riser section includes the vertical test section as shown in figure 1(b) which is constructed from a transparent plastic tube of 22 mm i.d. The nitrogen gas and water are used as working fluids.

The nitrogen gas is injected to the riser section filled with water through the nozzle section and separated in the gas–liquid separator at atmospheric pressure. The nozzle section has one or several nozzle-injectors with 0.4–22 mm i.d. The water flow rate is able to be chosen by a pump in the upper level section and a throttle valve placed at the downcomer. Experiments in three cases of non-, forced- and natural-circulations can be carried out.

In the case of mist flow the riser section is disconnected from the separator and the mist is formed by spray flow from the top to the bottom of riser section.

Static pressures p_1, p_2, p_3 and p_4 are detected at four locations 1, 2, 3 and 4 from the bottom along the flow direction by piezoresistive pressure transducers with the first resonance frequency of 600 Hz (see figure 1b). The intervals between locations 1 and 2 and between locations 3 and 4 are 11 mm, respectively, and the interval between locations 1 and 3 is 200 mm.

Four static pressure signals are sampled by a 12-bit A/D converter with the conversion time of 15 μs through a DC amplifier with the frequency response of 10 kHz and a 20 Hz low-pass filter, and fed into a minicomputer for data processing. A sampling time interval is 10 ms and the number of samplings is 3000 per each pressure signal. Statistical properties of differential pressures $\Delta p_a(=p_1-p_2)$, $\Delta p_b(=p_3-p_4)$, $\Delta p_c(=p_1-p_3)$ and $\Delta p_d(=p_2-p_4)$ are computed.

In order to confirm the results of the identification method based upon differential

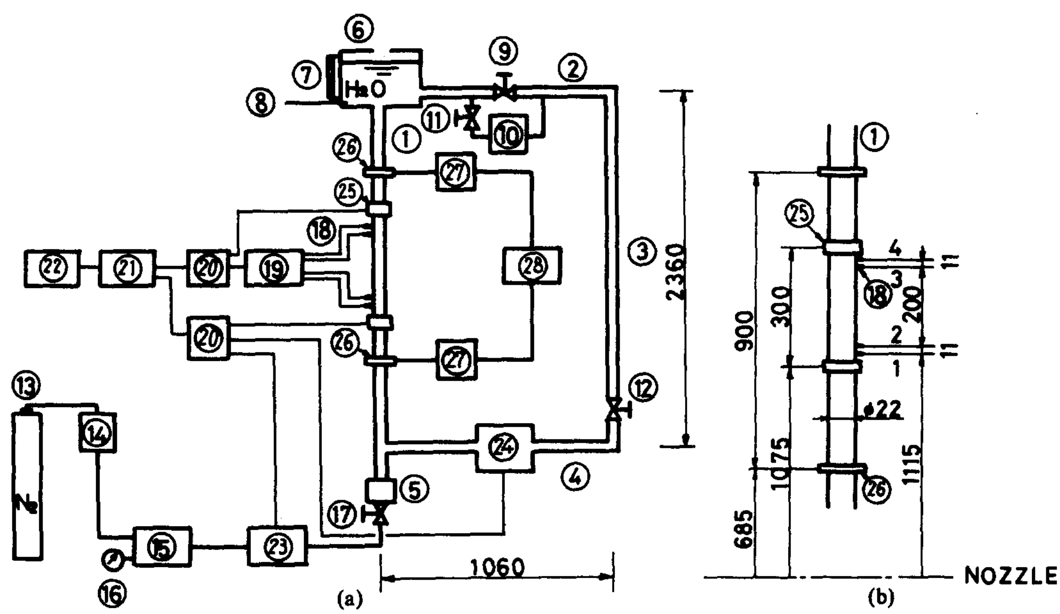

Figure 1. Schematic of experimental device (unit of dimension: mm). (a) Single experimental loop. (b) Test section. (1) Riser section; (2) upper level section, (3) downcomer, (4) lower level section, (5) nozzle section, (6) gas–liquid separator, (7) level, (8) mercury thermometer, (9, 11, 12, 17) throttle valves, (10) pump, (13) bomb, (14) pressure regulator, (15) accumulator, (16) pressure gauge, (18) diffusion-type piezoresistive pressure transducers, (19) amplifier, (20) low-pass filter, (21) A/D converter, (22) minicomputer, (23) float-type flow meter, (24) turbine-type flow meter, (25) electric capacitance-type void meter, (26) quick closing valves, (27) solenoid controlled valves, (28) air compressor.

pressure fluctuations, the gas flow rate and the water flow rate are measured by a float-type flow meter and a turbine-type flow meter, respectively, and the mean void fraction is measured by two cutoff valves. Furthermore, the flow pattern, bubble rise velocity and characteristic slug frequency are observed by sight and serial photographs.

3. CONCEPTION OF IDENTIFICATION METHOD

The static pressure at a time and a cross-section may be expressed by the sum of its time average component and time varying component. Moreover the latter appears to consist of two kinds of fluctuation, one of which prevails over a fairly wide range of the piping system, and the other arises locally owing to the moving of bubbles in the measuring section. Then the differential pressure between two cross-sections is expressed by the sum of the time average component and the local time varying component of the differential pressure and the effect of the various system disturbances disappear. The effect of high frequency disturbance is removed by use of a low pass filter. The pressure fluctuations due to a two-phase flow in the measuring section are obtainable. Thus the differential pressure may be used in order to estimate a flow pattern of two-phase flow in a vertical pipe.

The test section has four pressure taps which compose two kinds of observation scales, that is, short and long ones. The former, which is called R-scale, is chosen to the inside radius of pipe in order to discriminate a spherical cap bubble or a cluster of small bubbles with the size of the radius. The latter, which is called L-scale, is chosen to nearly ten times of the diameter of pipe in order to discriminate a developed gas-slug. The observation by both scales are made to identify a flow regime in a vertical two-phase flow.

The differential pressure $\Delta p_i (i = a, b, c, d)$ is normalized by the differential pressure Δp_{i0} of static fluid column in the corresponding measured section. Thus the normalized differential pressure

$$\Delta P_i = \Delta p_i / \Delta p_{i0} \quad (i = a, b, c, d). \qquad [1]$$

In the case that the acceleration and friction losses are very small compared with $(\Delta p_{i0} - \overline{\Delta p_i})$, the quantity $(1 - \overline{\Delta P_i})$ represents approximately the average void fraction in the section i. Therefore it may be convenient that the quantity

$$\Delta P_i^* = 1 - \Delta P_i \qquad [2]$$

is used for the arrangement of data for PDF. As the differential pressure measured at the L-scale has relatively small fluctuations, it is possible to estimate the average void fraction from the time average of ΔP_c^* or ΔP_d^*.

Here ΔP and ΔP^* are the time series data measured at every equal time increment δt during the total time interval T. If the probability that ΔP^* lies in the jth increment $\delta(\Delta P^*)_j$ of equally divided ones of ΔP^* is given by $n_j\delta t/T$, then

$$\lim_{\delta(\Delta P^*)\to 0} \frac{1}{\delta(\Delta P^*)} \frac{n_j \delta t}{T} = \mathrm{PDF}(\Delta P^*)_j \qquad [3]$$

represents the probability density function of ΔP^*. If the PDF obtained from the measurement of another time interval for the same steady flow is too different results from the PDF given by [3], a number of measurements is made and the obtained PDF results are averaged.

As the differential pressure fluctuations are considered to depend on the void fraction fluctuations in the case of vertical two-phase flows, it may be expected that the PDF of

ΔP^* will exhibit the similar configuration to that reported by Jones *et al.* (1972); that is, slug-like flows will show a twin-peaked PDF and the another flows, a single-peaked one.

The variance of ΔP may be used for evaluating the order of pressure fluctuations and for knowing whether a flow is gentle or violent. It is reported that in most cases of slug and froth flows the variance of the pressure fluctuations becomes larger than that in another flows (Nishikawa *et al.* 1969).

The transit time of gas-phase in unhomogeneous flows (i.e. slug-like flows) for the long measurement interval is given by the time lag $\tau = \tau_m$ at the maximum cross-correlation between ΔP_a and ΔP_b. Hence, if the interval between two measurement sections is given by L, the rise velocity u_{GE} of gas-phase is estimated by

$$u_{GE} = L/\tau_m. \qquad [4]$$

Moreover, if the characteristic frequency in slug-like flows can be obtained from the power spectral density based on the sufficient data, the estimation of slug-length will be feasible.

Summarizing, it is expected that vertical two-phase flows will exhibit the following behavior:

(a) Bubble flows—single-peaked PDF and low variance at low $\overline{\Delta P^*}$.

(b) Slug-like flows (spherical cap bubble, slug and froth flows)—at the short observation scale, twin-peaked PDF at medium $\overline{\Delta P^*}$. The variance becomes large in order of spherical cap bubble, slug and froth flows. At the long observation scale, the PDF exhibits a single peak in spherical cap bubble and slug flows but twin peaks in froth flows. In the cases of these flows, the rise velocity of gas-phase is obtainable.

(c) Annular flows—single-peaked PDF and medium variance at high $\overline{\Delta P^*}$

(d) Mist flows—single-peaked PDF and low variance at higher $\overline{\Delta P^*}$ than that of annular flows

Thus it appears that representative flow patterns observed in vertical two-phase flows are determinatable conceptually at least based on the above mentioned classification of the features of differential pressure fluctuations.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

A typical example that static pressures do not fully represent the inherent features of flow is seen in figure 2. The static pressures p_1 and p_3 in the case of spherical cap bubble flow shown in figure 5 are presented. In this case, it is seen that the inherent features of flow at the measuring location disappear owing to strong fluctuations of pressure outside of the measuring location. Thus it is difficult to discriminate a flow pattern of spherical cap bubble flow from the spreading distributions of PDF shown in figure 2. In addition, we cannot find the transit time of bubbles from the cross-correlation data. On the contrary, we can find the inherent features of this flow in the statistical properties of differential pressures shown in figure 5.

The use of two PDFs of ΔP^*_a and ΔP^*_b has an advantage in checking the change of flow between the measurement sections $\overline{12}$ and $\overline{34}$. Figure 3 shows PDFs of ΔP^*_a and ΔP^*_b in the case of transition from the developing slug flow to the developed one. Here two PDFs at L-scale are similar. The PDF at L-scale may be available when the features of flow can not be grasped from the PDF at R-scale.

Experiments are conducted for representative vertical two-phase flows such as bubbly, spherical cap bubble, slug, froth, annular and mist flows and single-phase flows of water alone and gas alone in the steady state. The classification of each flow pattern is tried by using the data of mean values, variances and profiles of PDFs of ΔP^*_a, ΔP^*_b, ΔP^*_c and ΔP^*_d.

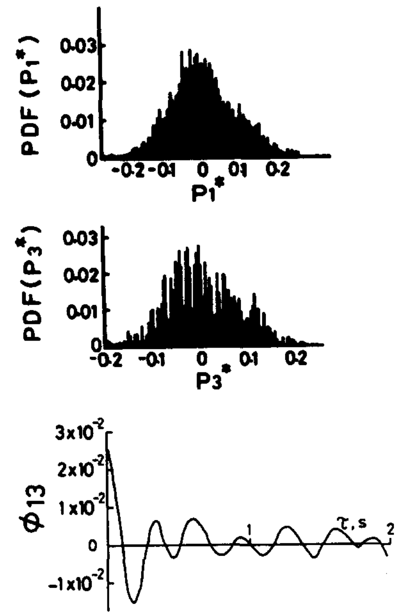

Figure 2. Typical example of statistical properties on static pressure signals in the case of spherical cap bubble flow shown in figure 5. Superficial gas velocity U_G = 0.0158 m/s, superficial water velocity U_L = 0.145 m/s and void fraction α = 0.056.

Typical results for each flow pattern are shown in figures 4–11. These examples are the cases that the PDF of ΔP_b^* exhibits the same configuration as that of ΔP_a^*. The normalized and modified differential pressure $\Delta P^* = 0$ corresponds to zero void fraction and $\Delta P^* = 1$ does to unity in void fraction, respectively, in the case that the friction loss is negligible comparing with the potential loss.

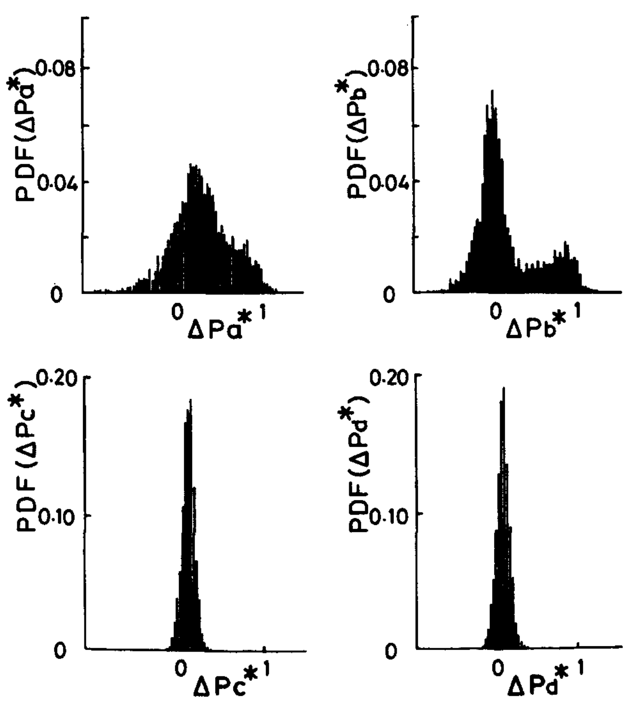

Figure 3. Typical distributions of PDF in the case of transition from developing slug flow to developed one. U_G = 0.122 m/s, U_L = 0.49 m/s and α = 0.105.

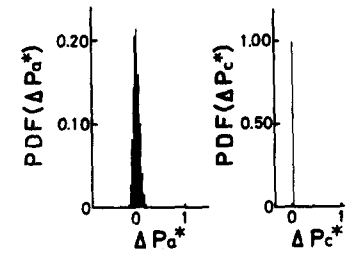

Figure 4. PDFs of differential pressure fluctuations in bubbly flow for $U_G = 0.009$ m/s, $U_L = 0.21$ m/s and $\alpha = 0.0335$.

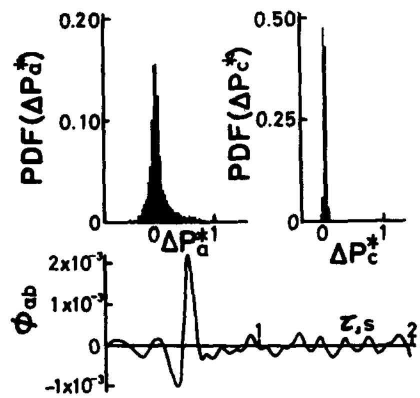

Figure 5. PDFs and cross-correlation of differential pressure fluctuations in spherical cap bubble flow for $U_G = 0.0158$ m/s, $U_L = 0.145$ m/s and $\alpha = 0.056$.

Bubbly flow (shown in figure 4)

This is a flow containing small bubbles dispersed uniformly in the liquid. The PDF of ΔP_a^* shows a normal type distribution with a single sharp peak at $\Delta P_a^* \doteqdot 0$. The variance of ΔP_a is very small. The coefficients of skewness and excess of ΔP_a^* are extremely small. Therefore this flow seems to be uniform in short (R −) observation scale. A flow with a normal type distribution of the PDF may be interpreted that it is a uniform one in the observation scale.

Spherical cap bubble flow (shown in figure 5)

This is a flow containing spherical cap-shaped bubbles and small bubbles in the liquid. The PDF of ΔP_c^* is similar to that of bubbly flow, but the PDF of ΔP_a^* is different from

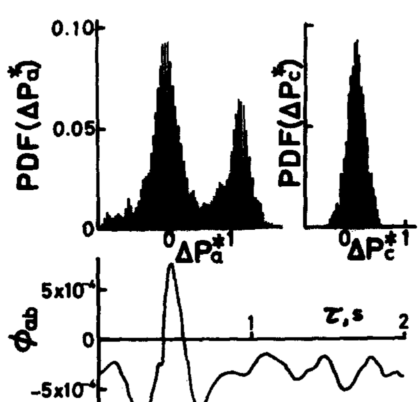

Figure 6. PDFs and cross-correlation of differential pressure fluctuations in slug flow for $U_G = 0.095$ m/s, $U_L = 0.13$ and $\alpha = 0.248$.

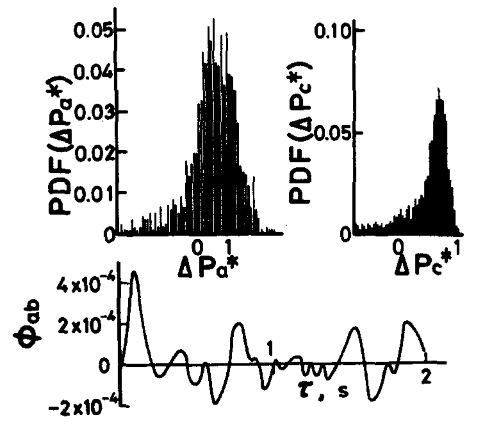

Figure 7. PDFs and cross-correlation of differential pressure fluctuations in froth flow for $U_G = 2.39$ m/s, $U_L = 0.12$ m/s and $\alpha = 0.645$.

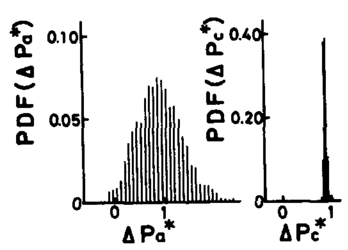

Figure 8. PDFs of differential pressure fluctuations in annular flow for $U_G = 12.5$ m/s, $U_L = 0$ m/s and $\alpha = 0.876$.

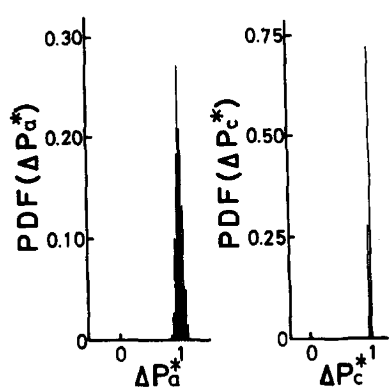

Figure 9. PDFs of differential pressure fluctuations in mist flow for $U_G = 4.06$ m/s, $U_L = 0.003$ m/s and $\alpha = 0.994$.

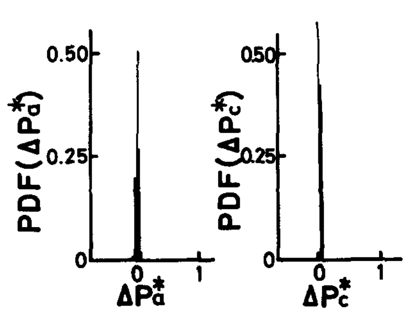

Figure 10. PDFs of differential pressure fluctuations in water flow for $U_G = 0$ m/s, $U_L = 0.2$ m/s and $\alpha = 0$.

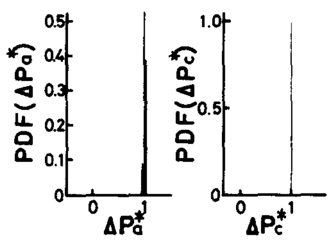

Figure 11. PDFs of differential pressure fluctuations in gas flow for $U_G = 1.83$ m/s, $U_L = 0$ m/s and $\alpha = 1$.

that of bubbly flow. The PDF of ΔP_a^* is slightly different from a normal type distribution and ranges to the right side (i.e. high void fraction side) as shown in figure 5. The flow is interpreted as a non-uniform one. The transit time of gas-phase is obtained from the cross-correlation Φ_{ab} and the rise velocity is estimated as $u_{GE} = 0.37$ m/s. The average rise velocity measured by serial photographs is $\bar{u}_G = 0.367$ m/s. The PDF of ΔP_c^* presents a normal type distribution, that is, the flow appears to be uniform in the long observation scale. The variance of ΔP_a is the order of ten times as large as that in the case of bubbly flow.

Slug flow (shown in figure 6)

This is a flow in which bullet-shaped large bubbles and dispersed bubbly flow portions appear alternately. The PDF of ΔP_a^* shows a peculiar distribution with twin peaks. The flow seems to be a periodic combination of a bubbly flow with low void fraction and an annular flow with high void fraction (Jones & Zuber 1975). It appears that the peak at the side of $\Delta P_a^* = 0$ is higher than the other when a liquid-dominant portion is longer than gas-dominant portion, and that the peak at the side of $\Delta P_a^* = 1$ is higher when otherwise. Therefore the ratio of two peaks indicates the ratio of liquid- and gas-dominant portion lengths as mentioned by Jones & Zuber (1975). In the long observation scale, the flow seems to be uniform. The variance of ΔP_a is the order of ten times as large as that in the case of spherical cap bubble flow. The PDF of ΔP_c^* may be different from a normal type distribution if the length of gas-dominant portion becomes longer than that of the long observation scale. In the case of figure 6, $\bar{u}_G = 0.438$ m/s and $u_{GE} = 0.425$ m/s.

Froth flow (shown in figure 7)

This is a flow in which gas-slugs develop and liquid-slugs shorten and the boundary of both slugs are complicated and vague. The PDF of ΔP_a^* shows a wider normal type distribution with a lower single peak comparing with that in the case of bubbly flow. The flow seems to be uniform in the short observation scale but pressure fluctuations are stronger than that of bubbly flow. The variance of ΔP_a is the order of one thousand times as large as that of bubbly flow. Therefore the flow is interpreted as a violent one. The PDF of ΔP_c^* is different from a normal type distribution and ranges to the left side (i.e. low void fraction side) as shown in figure 7. The length of gas-dominant portion may be evaluated to be longer than that of long observation scale. In this case, $\bar{u}_G = 2.17$ m/s and $u_{GE} = 2.1$ m/s.

Annular flow (shown in figure 8)

This is a flow that the liquid flows on the wall of pipe and the gas-phase containing small liquid droplets flows in the center. The PDF of ΔP_a^* resembles that of froth flow but the variance of ΔP_a reduces to the order of one-tenth of that of froth flow. The flow appears to be uniform because the PDF of ΔP_c^* shows a normal type distribution.

Mist flow (shown in figure 9)

This is a flow of small liquid droplets and the liquid doesn't flow on the wall of pipe. The PDF of ΔP_a^* presents a narrow normal type distribution with a high single peak at $\Delta P_a^* \doteqdot 1$, comparing with that of annular flow. The variance of ΔP_a is the same order as that of bubbly flow.

Comparison of two-phase flows with single-phase flows (shown in figures 10 and 11)

The PDF of ΔP_a^* in the cases of both single-phase flows of water alone and nitrogen gas alone show a higher and more pointed peak than that of two-phase flows and the variance of ΔP_a reduces to the order of one-tenth of that of bubbly or mist flow.

The test experiments of estimating the flow patterns by the identification method based on the above results are carried out for about 60 different flow rates in the ranges of the superficial water velocity $U_L = 0 - 1.5$ m/s and the superficial gas velocity $U_G = 0 - 10$ m/s. In these experimental conditions, we can encounter bubbly, spherical cap bubble, slug and annular flows. The results of identification agree well with that visual observations except for the cases of flows in the flow pattern transition boundaries. As the flow pattern of flows near the transition boundaries may change during the measurement, the determination of flow pattern is difficult. Even if the results of identification for these flows are different from that of visual observations, this is not always due to misjudgement. In such cases, it may be advisable to indicate the results of identification in terms of probabilities. As the range of spherical cap bubble flow is very narrow, it may be recommended to regard the appearance of spherical cap bubble flow as the transition from a bubbly flow to a slug flow.

5. CONCLUSION

It has been shown that the flow regimes in vertical gas–liquid two-phase flow exhibit the peculiar features of the statistical properties of differential pressure fluctuations, which are calculated from the static pressures measured at four locations arranged rationally along the flow direction. The experimental results for nitrogen gas-water two-phase flows show that the flow patterns are determinable by the identification method based on the classification of the features of differential pressure fluctuations in both short and long measurement sections.

The flow of liquid alone exhibits the distribution of PDF with the narrowest band and a sharp peak at about the value of differential pressure in the stationary state, the bubbly flow with a single peak, shperical cap bubble flow with a single peak ranging to the high void fraction side, the slug flow with twin peaks, froth flow with a single peak at the short observation scale but twin peaks at the long one and highest order of variance, the annular flow with a single peak at the high void fraction side, the mist flow with a single peak and a narrower band, and the flow of gas alone with the narrowest band a pointed peak at unity in void fraction. The single-phase flows have the variance of considerably lower order than the two-phase flows.

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