

Size Measurements of Droplets Entrained in a Stagnant Bubbling Liquid Column

Hae Yong Jeong and Hee Cheon NO
Korea Advanced Institute of Science and Technology

Chul Hwa Song and Moon Ki Chung
Korea Atomic Energy Research Institute

Abstract

Phase Doppler particle analyzer (PDPA) is a instrument which can be used to obtain simultaneous size and velocity measurements in a multiphase flow. In this study, the size of the water droplets entrained from a bubbling surface of a stagnant liquid column is measured by PDPA with a specially designed transmitter of long focal length and large beam diameter. The test section tube is made of acryle with 18 mm I.D. and 900 mm length. The experimental data are obtained for the air superficial velocity between 0.7 m/s to 3.4 m/s at atmospheric pressure. The experimental results show that there exists large difference in the entrainment mechanism between the churn-turbulent flow and annular flow. Through the present study, the phase Doppler analyzer system is shown to be successfully applied to measure particle sizes larger than 2,000 μm if a transmitter of long focal length is utilized.

1. Introduction

The determination of droplet size generated from two phase flow is very difficult because the direct measurement is impeded by the existence of other droplets or by the existence of continuous liquid phase. In most earlier studies, the droplet sizes were measured by photographic records obtained from video tape or camera with high-speed flash. In some experiments, the probing methods utilizing film coating or bacteria coating technique were also adopted. However, these methods take too much time and it is very tedious to do the data processing procedure. In addition, probing methods disturb the flow field and the accuracy of the experiment can not be achieved. Therefore, other methods that can be used more conveniently have been developed.

Among the droplet size measurement technique, laser Doppler anemometer (LDA) technique is widely used in two-phase flow study, combustion engineering and spray flow analysis. This method has been successfully introduced to measure the drop size and velocity in annular flow (Lopes and Dukler, 1986; Azzopardi et al., 1991). The technique of laser Doppler anemometer is developed into phase Doppler particle analyzer (PDPA).

Bubbling condition at a stagnant liquid column can be encountered in closed two-phase thermosiphons or in a nuclear reactor core uncovered after a loss of coolant accident. This flow condition is also observed in bottom-closed flooding situations. The information on the flow regime and the size of the droplets entrained from the system is important since it is closely related to the cooling capability of the system. However, the various correlations used to predict the droplet size entrained from churn-turbulent flow result in quite different sizes. This is because the experimental conditions, from which the data used for the derivation of the correlations are

obtained, are different in each case. In other words, the ranges of main parameters which affects the entrained droplet size are different.

Therefore, it is meaningful to investigate the effects of main parameters to the resultant droplet size in a stagnant bubbling liquid column. This will be helpful to generate the correlation describing the droplet size entrained at this condition. To obtain the direct measurement of droplet sizes, PDPA is utilized.

2. Phase Doppler Particle Analyzer

2.1 Introduction to PDPA

PDPA is a sophisticated instrument which utilizes the light scattered by spherical particles (drops, bubbles, solid spheres, etc.) to obtain simultaneous size and velocity measurements. The principle of PDPA is closely related to the interference pattern produced by two coherent light beams. The interference pattern changes position as the two beam sources move, producing intensity variations. Photodetectors placed on the receiver detect these intensity variations and produce electrical signals with frequency related to the velocity and size of a particle. The velocity is measured by detecting the frequency of the Doppler shift of the light scattered from a moving particle. The diameter of the particle is determined by detecting the phase difference between the Doppler burst signals received from two or more photodetectors situated at different angular positions. These measurements can be made *in situ* and nonintrusively, which is important when measuring easily deformable particles or probing sensitive flow fields. The optical system consists of a transmitter and receiver. The transmitter and receiver may be positioned around the test section to take advantage of available optical access to the facility.

Droplets passing through the intersection of the two beams scatter light which produces a far field interface fringe pattern. The spacing between these projected fringes is directly proportional to the drop diameter but also depends on the light wavelength, beam intersection angle, drop refractive index and the location of the receiver. The PDPA obtains measurements of this fringe spacing or its image. As the fringes move past the detectors at the Doppler difference frequency, they produce identical signals but with a phase shift proportional to the fringe spacing. The phase shift between the Doppler burst signals from the different detectors is proportional to the size of the spherical particles.

PDPA uses a unique method to directly measure the sample volume simultaneously with respect to particle size and velocity. This enables an accurate determination of the particle number density and volume flux. The Phase Doppler method requires no calibration because the measured particle size and velocity are dependent only on the laser wave length and optical configuration. Other significant advantage is the relative insensitivity of the method to uncertainties in the scattered light intensity and fringe visibility. Consequently, PDPA measurements are not subject to errors from beam attenuation or deflection which occurs in dense particle and combustion environments.

2.2 Sizing Principle of PDPA

As the particle crosses the fringes created by the interference of the two laser beams, it refracts or reflects the fringes onto the receiver. The light pattern seen by the receiver is a Doppler burst signal. The frequency of the signal is directly related to the velocity of the particle.

$$v = f_d \delta. \quad (1)$$

The fringe spacing of the interference pattern is determined by the wavelength of the laser beam and the beam cross angle.

$$\delta = \frac{\lambda}{2 \sin(\gamma/2)}. \quad (2)$$

The particle magnifies the fringe pattern onto the receiver to different degrees relative to its size. The degree of magnification is measured by comparing the spacing of the resolved fringes on the receiver detectors (spatial wavelength, Δ) and the fringe spacing. The diameter of the particle is then determined using this relation along with the receiver focal length and a sizing slope factor.

$$d = \frac{F_r \delta}{s \Delta}, \quad (3)$$

where s = sizing slope factor.

The output of each detectors is a Doppler burst similar to that of conventional two-beam laser Doppler velocimeter (LDV). However, the phase differences ϕ_{1-2} and ϕ_{1-3} between the detector outputs provide a measure of the size of the moving particle. To relate the phase differences between the detector outputs to the diameter of the particle, it is necessary to perform spatial integration of the scattered light over the different collection areas of the three detectors.

3. Experiment

The experiments were performed at the vertical air-water loop. The experimental facility consists of a recirculation water loop, a bubble generator, an air supply system, exchangeable acrylic test section with special windows for size measurements. It is shown schematically in Fig. 1. The test section currently used is made of acryle tube with 18 mm I.D. and 900 mm length. The entrance of the test section is tapered to prevent the air agglomeration at the exit of the bubble generator. The exit of the test section tube is also tapered to prevent the water accumulation on the end side of the tube. The air flow rate is measured by Dwyer RMB-55 model rotameters.

The water is initially filled up to the top of the bubble generator. Then, air is drawn from a compressed air supplier and fed into the stagnant liquid column through the bubble generator nozzle. The air-water mixtures in the test section show highly oscillatory motions during the experiment, and a number of droplets are entrained during the oscillations through wall-impact motion and/or breakup of liquid slugs. The size of entrained droplets is measured using Aerometrics' two-dimensional PDPA system. This measurement system uses a Ar-ion laser source (5 W in maximum power) with two wavelengths of 488 nm and 514 nm. In the present experiment, the laser power of 3 W is supplied. The pressure at the measuring point is maintained to be atmospheric. The flow conditions in the test section are regulated so that the distance from the maximum two phase mixture level to the measurement point should be in the range of 10 ~ 20 cm. Air mass flux is varied in the range of 0.85 ~ 4 kg/m²s, which corresponds to the superficial velocity of 0.7 ~ 3.4 m/s.

To obtain reliable data with PDPA, it is very important to set up several optical parameters appropriate for given flow conditions and optical configurations. Since, in general, conventional laser beams with the diameter below 1.4 mm could not be used to measure particle size larger than 1 mm, a specially designed transmitter with 4,080 mm focal length and 2, 5, 10 mm in diameter was designed in this study to detect large droplets passing through the probe volume made by two pairs of laser beams. To get the signals from scattered lights, a receiver of 500 mm focal length was chosen to use. The angle between the transmitter and the receiver is set to be 60°. With these optical configurations, it is found appropriate to detect the water droplets in the range of 20 ~ 6,000 μm . In addition to these optical configurations, some additional parameters such as photodetector sensitivity and burst detection level are adjusted to obtain high validity and reasonable distributions of diameter and velocity during the experiment. Typical parameters used in the experiment are summarized in Table 1.

4. Results and Discussions

The present study extends the range of measurements up to $j_g = 3.4$, exceeding the range of superficial gas velocity ($j_g \leq 1 \text{ m/s}$) in the previous works (Cheng and Teller, 1961; Teller and Rood, 1961). The measured droplet sizes for the given superficial air velocity are shown in Fig. 2. In the figure, the droplet sizes measured by Cheng and Teller (1961) and the results obtained by Teller and Rood (1961) are also given for the comparison with the present results. In the previous two experiments, entrainment occurred at higher velocities of the air through the liquid than the air velocities which cause separated bubbles to be formed. When air is forced into the liquid, the bubbles of air are intercepted by each other and tend to coalesce forming larger bubble as they rise to the surface of the liquid. Under these conditions the surface of the liquid is very turbulent and the mechanism of the formation of drops is somewhat obscured.

The results of Teller and Rood are larger than the results of the present study because they used film-coated probe to measure the droplets size entrained from the turbulent surface. When this type of probe is used, it is very difficult to estimate tiny droplets caught by probe. However, small droplets below 100 μm also can be measured if the drop sizes are measured with PDPA. Therefore, it can be said that the drop size estimated by the probe method results in larger size than the drop size measured with PDPA.

The experimental results of present study indicate that the entrained droplet size becomes large as the superficial air velocity increases in case that the flow is churn-turbulent. However, the size of droplet experiences a sudden decrease as the flow becomes annular-like. This results imply that the entrainment mechanism in churn-turbulent flow is quite different from that of annular flow. In annular flow, the shearing-off from the wave peak is the dominant entrainment mechanism.

Through the observations in the experiments, it can be said that the transition from churn to annular in a stagnant bubbling liquid column occurs at much lower gas velocity when it is compared with the transition criterion in a forced flow system. Some other researchers, including Ueda and Koizumi (1993), also found that the flow regime transitions appeared at much lower superficial gas velocity than the conventional two-phase flow transition criteria. This difference can be explained by the difference of the interfacial shape between the two cases. In a stagnant bubbling liquid column, there exists a severe oscillatory motion of liquid in the tube. It is

presumed that this oscillatory motion becomes a motive force for the early appearances of the flow regime transition.

In Fig. 3, the measured droplet sizes are compared with the prediction results obtained by the correlations suggested for the prediction of droplet size entrained from churn-turbulent surface or pool boiling surface. The results obtained in the present study are smaller than the results predicted by the correlations because the flow condition of the present study is different from the condition required for the simulation of reflooding core or pool boiling surface. If the wall is heated, the sputtering would be very active. As a result of the sputtering at the dryout point, larger droplets can be entrained.

The differences in flow characteristics between the stagnant liquid column and the reflooding conditions can be another source of the discrepancy between the present experimental results and the prediction results. In stagnant liquid column bubbling, there is no continuous liquid supply. However, in core reflooding conditions the water is supplied continuously. Therefore, the transition region can exist through a wide range of gas superficial velocity.

5. Conclusions

From the results of this experiment, following conclusions are obtained:

1. The entrained droplet sizes increase as the superficial air velocity increases in churn-turbulent flow. While the size of entrained droplets decreases with the increase of air superficial velocity.
2. The phase Doppler particle analyzer system can be applied to measure particle sizes larger than $2,000\ \mu\text{m}$ if a transmitter of long focal length and large beam diameter is utilized.

It is also suggested that the flow regime transition in a stagnant bubbling liquid column can be determined by measuring the droplet sizes entrained from the surface of bubbling liquid column since the entrainment mechanism of churn-turbulent surface is quite different from that of annular flow.

References

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Table 1 Typical parameters used in the present experiment

Parameter	Description	
Velocity Setup	channel 1	channel 2
High Voltage (V)	699	699
Frequency Shift (MHz)	40	40
DC Offset (mV)	14.4	40.3
Mixer Frequency (MHz)	39.93	39.915
Low Pass (MHz)	0.5	0.5
Burst Filter	40 MHz BP	40 MHz BP
Threshold (mV)	10.0	3.0
Envel Filter (uS)	3	3
Peak Detection	On	On
# of Samples	128	128
Sampling Rate	1.25 MHz	2.5 MHz
Min S/N Ratio	0.3	0.3
Diameter Setup		
Slope 63	0.4310 Reflection	
Refractive Index	1.333	
Available Rang (Transmitter)	18.9 - 6217.4	
	(ch 1)	(ch 2)
Collimating Lens	2	2
Beam Separations	35.00	35.00
Transmitting Lens (Receiver)	4080	4080
Coll. Lens	500 mm	
Focus Lens	175 mm	
Aperture	150 um	
DetSep A-B	10.88 mm	
DetSep A-C	30.69 mm	

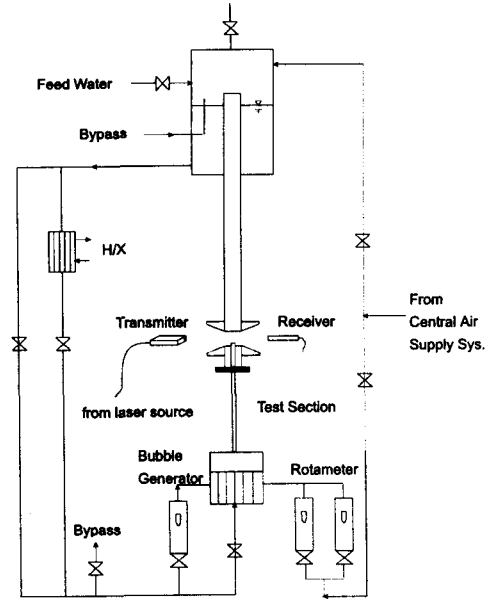


Fig. 1 Schematics of the experimental facility

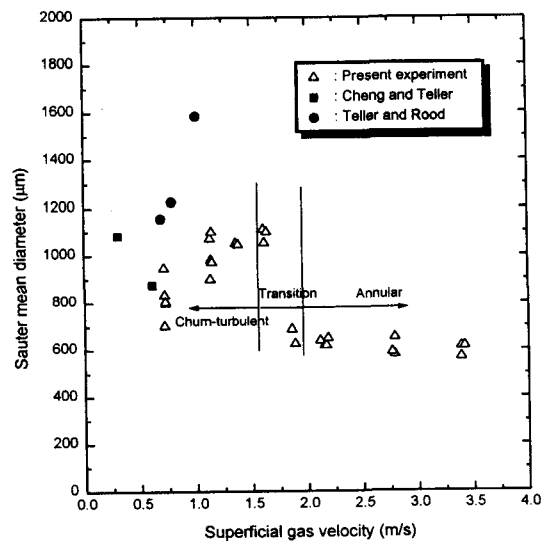


Fig. 2 Variation of droplet size with superficial gas velocity

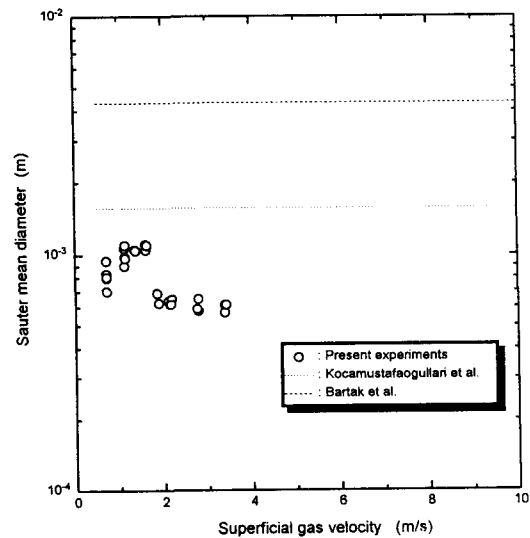


Fig. 3 Measurements results compared with the prediction results by other correlations