

## A REVIEW ON ADVANCED TWO-PHASE GAS/LIQUID FLOW MEASUREMENT TECHNIQUES

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### ABSTRACT

Due to the existence of relative movement in the interfaces and variable interactions between two phases, two-phase two-component flow is a complex transport phenomenon compared to single-phase flow. Still there is no effective technique to identify the two-phase two-component flow regimes and it is even difficult to capture the accurate flow structures in the smaller conduits in turbulent flow cases. Lack of solid and comprehensive theories for predicting and calculating the pressure and void fraction variations in two-phase gas/liquid flow situations has left engineers without essential information for proper design of two-phase systems. This review is an effort to explore the state of the present advanced measurement techniques in this field of research. Subsequently some of the advanced photonics and pressure measurement techniques and correlations for identification of two-phase two-component flows, bubble sizes and droplet profiles are investigated.

**Keywords:** Two-phase flow, void fraction, pressure measurements, photonics measurement.

### 1. INTRODUCTION

Gas assisted atomization is becoming increasingly important in many industrial processes; such as physical, chemical and petroleum processes. It is crucial to have proper mixing of gas (air) and liquid (water) in the feeding conduit before entering into the nozzle for proper atomization. It is desirable to know exactly under what conditions there is a transition among the different flow regimes (dispersed, stratified, annular, annular-dispersed, slug, wavy-slug, mist-annular)

There are still fundamental aspects of two-phase flow; whose physical descriptions are still unknown and modeling results are questionable. Experimental observations are difficult in this case, as the migration of dispersed bubbles towards the top of the pipe, due to buoyancy, causes a highly non-symmetric volume distribution in the pipe cross-section. Often, existing measurement techniques cannot explain important physical properties and parameters needed to model the two-phase flow phenomena. There is an utmost need to explore the novel experimental techniques in order to obtain a better insight into fundamental phenomena associated with two-phase two-component fluid dynamics.

### 2. ADVANCED PRESSURE MEASUREMENTS TECHNIQUES

In two-phase gas-liquid flow, accurate pressure prediction assists to evaluate design criteria to prevent rupture [1] and pulsation. Since a slug flow is a periodic

phenomenon, if the frequency of the wave is near to the frequency of the structure, then it can lead to resonance and can increase damage risk to the conduit [2]. In two-phase gas-liquid flow, average density, flow velocity, and flow regime prediction, in combination with transient void fraction can be extracted from the pressure pulse data [2; 3]. Pressure fluctuations might be used to discover and locate leaks in long water tunnels and offshore pipelines [4]. In addition, studies show that the velocity and attenuation of the pressure waves were a function of the frequency and bubble radius [5]. Accurate prediction of the pressure drop in horizontal conduits is of great interest in many industries, especially in the oil industry.

### 3. ADVANCED VOID FRACTION MEASURE- MENT TECHNIQUES

Void fraction or volume fraction,  $\alpha$ , which is the portion of the pipe cross sectional area occupied by the gas phase, is an important parameter in the two-phase gas-liquid flows. It has been always a challenge to measure volume fraction of the phases, due to highly non-symmetric nature of two-phase gas-liquid horizontal flow, e.g. bubble can coalesce, break-up, interact with the conduit wall, which makes the flow extremely unstable. In literature different types of techniques were implemented to measure the void fraction in two-phase, gas-liquid closed flows. Several of them are described below:

### 3.1 Microwave Flow Sensor

One of the recent techniques is the microwave flow sensor [6]. Using radio frequency signals, the non-invasive meter will measure the mass-flow, quality and void fraction of any non-conducting vapor-liquid mixture. This method can identify the quality and void fraction. These sensors are good for cryogenics, refrigerants and low flow rate two-phase gas-liquid flow. Since these instruments are entirely data-driven, the results depend heavily on the amount and quality of the data that is acquired for a given application. The probe, however, cannot measure mixtures with significant water content.

### 3.2 Optical probe

Cartellier et al. and Serdula et al. [7; 8; 9] used a fibre optics method to measure the void fraction. It was found that the rise time of the signal pulses created when bubbles crossed the probe tip and were closely correlated with the bubble velocities. Therefore, bubble velocities and hence bubble sizes could be estimated using a single probe. It was observed that the correlation between the rise time and the bubble velocity varied significantly between probes but was only a weak function of water type (i.e., freshwater or seawater) and the bubble impaction angle. This method provided high accuracy and stable measurement. Size and velocity of each bubble were measured with this method. This method was also applicable for non-conductive fluid. However, the use of fibre-optic probes to measure very small void fractions was not recommended because of the large errors that were anticipated [9]. The effect of bubble deflection is expected to be more pronounced as the bubble radius and velocity decrease and as the liquid viscosity increases [8]. In this study the range of bubble diameters was from approximately 1 to 6 mm and bubble velocities from 5 to 120 cm/s, the water velocity was varied from 45 to 92 cm/s.

Changa et al. [10] used an optical signal derived from a diode laser driven by a constant current then launched into a single-mode optical fiber and transmitted, through a fiber coupler, to the signal fiber (125 μm in diameter) inserted into the test fluid. The diode laser used is a multilongitudinal mode device that has a low coherence length of about 200 mm. The coherently mixed signal propagates back to the signal fiber, through the fiber coupler, and is detected by a detector. By analyzing the signal, the velocity and fraction ratio of each phase can be obtained. However there is intrusion to the fluid by the tiny fiber probe.

Pettigrew et al. [11] developed a fiber-optic probe to measure local void fraction. Each probe has a conical tip and is made of an optical fiber of 170 μm diameter. It acts as a phase sensor based on the different level of light reflection between air and water. Two flow conditions were investigated in detail, i.e., 50 and 80% volumetric void fraction at a nominal pitch flow velocity of 5 m/s. For each measurement, the probe data was recorded for a period of 20 s at a  $2 \times 10^6$  Hz sampling rate. An experimental program was undertaken with a rotated-triangular array of cylinders subjected to

air/water flow to simulate two-phase gas-liquid mixtures. The array, which has a pitch-to-diameter ratio of 1.5, is made of relatively large diameter cylinders (38 mm). This results in larger gaps (19 mm) between cylinders to allow for detailed two-phase flow measurements.

Hamad et al. [12] describes the development and application of a dual optical probe for local volume fraction, drop velocity and drop size measurements in a kerosene-water, liquid-liquid, two-phase flow. Measurements were carried out in a large-scale vertical two-phase facility, mainly at the pipe center-line, to demonstrate the advantages of using optical fibers with normal cut ends in a kerosene-water, two-phase flow. High reliability of this measurement technique for detailed studies of the drop component of liquid-liquid, two-phase flow can be possible. A single probe is depicted in Fig. 1.

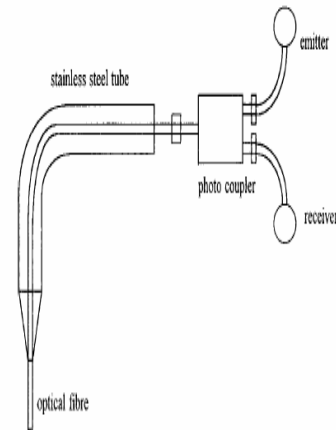


Fig 1: Single optical probe.

### 3.3 Gamma-ray Densitometers

Several studies on implementing gamma-ray densitometers showed that multi-beam gamma-ray densitometers with detector responses examined by neural networks can analyze a two-phase flow with high accuracy [13]. Void fraction and flow regime in oil/gas pipes could be measured with an error of 3% for all of the flow regimes. Oil-water two-phase flow experiments were conducted in a 15 m long, 8.28 cm diameter, inclinable steel pipe using mineral oil (density of  $830 \text{ kg/m}^3$  and viscosity of  $7.5 \text{ mPa}\cdot\text{s}$ ) and brine (density of  $1060 \text{ kg/m}^3$  and viscosity of  $0.8 \text{ mPa}\cdot\text{s}$ ) [14]. Two gamma-ray densitometers allowed for accurate measurement of the absolute in situ volumetric fraction (holdup) of each phase for all flow patterns. In addition, other researches showed that mixture densities obtained with gamma-ray densitometer agree well with the direct measurements made by using quick-closing valves [15]. One of the disadvantages of the gamma-ray densitometers is the shielding requirement of the gamma-ray.

### 3.4 Capacitance Sensor

Capacitance sensors for instantaneous void fraction in air-oil, two-phase flow was developed [16]. This method

could effectively identify the different flow regimes although this method was unable to provide accurate results over the entire range of flow regimes. This method is not effective while there is high water loading.

### 3.5 Quick-closing-valves (QCV)

Void fraction of two-phase flow often measured by isolating a section in the conduit; [17] named as the quick-closing-valves (QCV) technique. However, most of the studies conducted in vertical bubble column. A technique for synchronizing valves and determining bubble rise velocities in two-phase flow is presented in a study [18]. It is very crucial to commence the closing of both valves simultaneously. Error in void fraction measurements by the QCV due to asynchronization of the valves can be expressed as [18]:

$$\% \text{ Error} = \frac{100u_m t_{ac} (1 - \alpha)}{d_c} \quad (1)$$

here,  $u_m$  is the mixture velocity in the conduit,  $\alpha$  is the void fraction,  $t_{ac}$  is the asynchronization closing time,  $l_c$  is the closing length between the two valves. In our two-phase, horizontal experiments we used high-speed video camera to capture the asynchronization closing time,  $t_{ac}$ . In addition, we would examine the local pressure before and after closing the valves in the conduit through our static pressure transducers. Previous studies showed that for a two-phase bubble flow at low flow rates and a closing length of 5 m, for each millisecond of delay there would be 1% error.

In addition, synchrotron  $X$ -rays [19], pulsed neutron technique [20], conductance probe [21], ultrasonic technique [22], and ring impedance probe [23] have been used successfully to measure the void fraction in two-phase flow systems. Several other void fractions measuring techniques can also be found in literature. These are: electromagnetic flow meter, which utilizes the electrical conductivity of the continuous phase. Electric field perturbation void fraction probe, which is basically used for transient and time-averaged measurement of the void fraction under various thermal-hydraulic conditions [24]. The electric field perturbation (EFP) probe operates by measuring the electrical properties of a two-phase mixture which are related to the void fraction by a theoretical electromagnetic field model.

### 4. BUBBLE DIAMETER

Sotiriadis et al. [25] conducted experiments with air and water in a large circulating rig with a 0.105 m diameter test section. In their experiments the majority of the bubbles were ellipsoidal as shown in Figure 2.

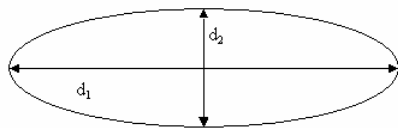


Fig 2: Major and minor axis lengths of an ellipsoidal bubble.

The bubble diameter,  $d_b$  can be expressed as [25]:

$$d_b = \sqrt[3]{d_1^2 \times d_2} \quad (2)$$

where  $d_1$  and  $d_2$  are the major and minor axis lengths of the ellipsoid, respectively, as shown in Figure 2 in a two-dimensional projection. The number average bubble diameter,  $(d_b)_{ave}$  and the mean volume surface diameter or Sauter mean bubble diameter,  $d_{32}$ , can be subsequently calculated as follows [25].

$$(d_b)_{ave} = \sum_{i=1}^{N_b} d_b / N_b \quad (3)$$

$$d_{32} = \frac{\sum_{i=1}^{N_b} d_b^3}{\sum_{i=1}^{N_b} d_b^2} \quad (4)$$

where,  $N_b$  is the number of bubbles. Marco et al. [26] conducted experiments by injecting gas (nitrogen) bubbles in a fluorine liquid (FC-72) at ambient temperature and pressure through an orifice (about 0.1 mm diameter) drilled on a generatrix of a horizontal tube. In this study, the equivalent diameter of the bubble was proposed as [26]:

$$d_{eq} = \sqrt[3]{\frac{6V_b}{\pi}} \quad (5)$$

where,  $V_b$  is the bubble volume. The maximum bubble size predicted by Hibiki et al. [27] is expressed as follows:

$$d_{max} = 4 \sqrt{\frac{\sigma}{g\Delta\rho}} \quad (6)$$

where  $\sigma$ ,  $g$ , and  $\Delta\rho$  are the surface tension, the gravitational acceleration, and the density difference, respectively.

### 5. CONCLUSIONS

In this paper, we examined several advanced two-phase, gas-liquid measurements techniques. We emphasized on two-phase void fraction, pressure, and bubble size distribution measurement techniques. Due to highly non-symmetric nature of two-phase gas-liquid horizontal flow system, it has always been a challenge to obtain accurate data in this type of flow. In addition, the success of void fraction and two-phase two-component flow measurements largely depends on the respective flow regime; whether it is dispersed, slug, or stratified flow. Most of the studies were conducted on vertical bubble columns and used different working fluids rather than air-water phases. In addition, measurement accuracy and characteristics depend on the phase velocity and air-to-liquid ratio. Based on pressure

measurements in two-phase, two-component flow, several empirical equations have been developed. In our air-water two-phase horizontal flow (6.35 mm ID diameter, 36.8 cm long pipe, air-to-liquid ratio 1-9%, operating pressure in the ranges of 300 kPa to 1.4 MPa) we would implement those empirical equations to explore the validity of those equations.

High performance dynamic and static pressure transducers would be reliable instruments in two-phase, two-component pressure measurements. Most of the void fraction measurements are intrusive in nature. Other methods have the safety issues and accuracy challenge. However, mechanical quick-closing-valve technique has been proved more reliable and easy-to-implement method if the synchronization of the two closing valves can be assured. High-speed video and photonics measurement are also very reliable non-intrusive volume fraction and flow patterns estimation techniques. Generally, there are three kinds of methods used to identify two-phase flow regimes. The first one is the direct method. This method includes the direct identification of the flow regimes as to flow forms, such as the high-speed photography method. The second one is the indirect method. This method includes the statistical analysis of measured signals, which reflect the fluctuant characteristic of two-phase flows, and the flow regimes. The third one is the intrusive method. This method includes the placement of a high performance sensing probes inserted inside of the conduit, which provide a time varying signal. This method disturbed the local flow field significantly and in some cases could provide erroneous information. By the author's knowledge, different types of photonics measurement (high-speed photography, shadowgraphy, stroboscopic back illumination, high power pulsed laser) would be able to accurately provide the flow structure of two-phase two-component flow. Information obtained from this photonics measurement could be coordinated with the flow transition maps and correlations provided by several researchers. However, most of the flow maps and correlations are designed for rectangular, vertical, and large diameter tubes. We should identify the applicability of this photonics measurement in our horizontal nozzle assembly (feeding conduit of 36.8 cm in length and 6.35 in ID). This would also assist us to accurately identify the flow transition region in this unique type of industrial nozzle assembly.

Two important phenomena, bubble coalescence and breakup, play an important role in atomization from a feeding nozzle in petrochemical processes. In the present investigation we will find out the correlation between the droplet profiles in the spray and bubble distributions in two-phase air-water flows in horizontal conduit. In this effort, we will measure the sauter mean diameter ( $SMD$  or  $D_{32}$ ) of the air bubbles in the feeding conduit and water droplet from the feeding nozzle. Subsequently we will verify our experimental results with the proposed correlations found in the literature. A non-intrusive high-speed video shadowgraphs and stroboscopic back illumination still images and subsequent image analysis technique would be an effective way to quantify the

bubble population in two-phase air-water horizontal flows in a very thin conduit. However, in the feeding conduit to quantify an effective air bubble diameter size is very critical.

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## 8. NOMENCLATURE

Symbol	Meaning	Unit
$\alpha$	void fraction	[-]
$u_m$	mixture velocity	(m/s)
$t_{ac}$	asynchronization closing time	(sec)
$l_c$	closing length between the two valves	(m)
$d_b$	bubble diameter	(m)
$d_1$	major axis length of the ellipsoid	(m)
$d_2$	minor axis length of the ellipsoid	(m)
$(d_b)_{ave}$	mean volume surface diameter	(m)
$d_{32}$	Sauter mean bubble diameter	(m)
$N_b$	number of bubbles	[-]
$V_b$	bubble volume	(m <sup>3</sup> )
$d_{max}$	maximum bubble size	(m)
$\sigma$	surface tension	(N/m)
$g$	gravitational acceleration	(m/s <sup>2</sup> )
$\Delta\rho$	density difference of the phases	(kg/m <sup>3</sup> )