phase. Otherwise the equations are ill conditioned. In practice such sources can be found (e.g. Cesium - 137 with a photon peak at 660 keV, and Americium - 241, with a photon peak at 60 keV). The attenuation coefficients of some materials at these photon energy levels are tabulated in Table 2. The draw back with the Americium - 241 source is that its photon energy is low requiring a large sampling time for counting with good statistics. Consequently, the time required for a complete scan with Americium - 241 as a second source would amount to more than a day. One can, however, use dual energy methods for densitometry purposes and obtain a few chordal average measurements for the holdup of the three phases.

Table 2: Linear Attenuation Coefficient of some materials as a function of energy

Material	$\mu - cm^{-1}$ at 60 keV	$\mu - cm^{-1}$ at 660 keV
Air	2.14E-4	9.29E-5
Water	0.197	0.0857
Glass beads	0.5625	0.184

Another possibility is to use X-rays instead of γ-rays for the dual beam measurement. The advantage with X-rays is that by changing the voltage of the cathode of an X-ray generator the energy of the emitted radiation can be changed. However, the difference in the energy levels obtainable is not very large and would not be the most ideal setup for dual energy tomography. Dual beam densitometry has been used by Daly and Bukur et al. (1995) for obtaining radial and axial void fraction distribution in a slurry bubble column under Fischer-Tropsch synthesis conditions. The densitometer consisted of a 35 mCi Cobalt-60 (1.17, 1.33 MeV) and a 500 mCi Cesium-137 (0.661 MeV) collimated sources each of which is associated with a NaI detector. The system of sources and detectors are mounted on a movable assembly mechanism, which allows the positioning of the gauges both axially and laterally with respect to the column. This allowed measurements to be made at different axial locations. The two densitometers were separated by an axial distance of 0.25 m. Dual beam tomography has also been accomplished with the combination of γ-ray and capacitance tomography by Johansen et. al. (1995) at the University of Bergen in Norway. The system is designed for imaging horizontal multiphase flow in a pipe of 82 mm in diameter. The gamma ray system uses a 500 mCi Americium - 241 source and a set of 85 detectors. The capacitance tomographic system makes use of 8 electrodes each 10 cm long providing for a total of 28 capacitance measurements.

Another experimental technique for measuring gas holdup and solids concentration relies on ultrasound. The measurement can be based on either the transmission, or the time of flight of a beam of ultrasound. The principle for the transmission method is identical to that of the radiation absorption described earlier. For a gas-liquid system the attenuation or the absorption coefficient is a function of the bubble size distribution, the projected area of the bubbles, and the wave number of the ultrasonic beam. The constraints that need to be met for using attenuation of ultrasound for holdup measurements in three phase systems are as follows:

1. Particles and bubbles should be of uniform size and belong to a unimodal distribution.
2. Particle sizes should be much larger than the wavelength of the radiation but smaller than the beam diameter and the particles should be approximately spherical.
3. Multiple scattering effects should be negligible. In practice this means that the holdup of the dispersed phase should be small, usually less than 10%. An additional factor limiting the holdup of the dispersed phase is that the governing relations are extended from those corresponding to single particle interaction with the beam and hence the inter particle distances have to be large.

Thus, this technique works well for systems with low void fraction (10 to 15 %) and for small test sections. For larger test sections one would have to introduce the transmitter and receiver of ultrasound inside the reactor to get the information on a local scale. Stravs and Stockar (1985) have used this method for obtaining holdups in gas-liquid flows with low holdup (3 to 4 %).

For the holdup measurement based on the time of flight of ultrasound the transmittance time through the pure phases and through the two-phase dispersion needs to be determined. The fraction of the voids along the path of the sound wave propagation is computed from :

$$\epsilon = \frac{t^* - t_1}{t_2 - t_1} \tag{15}$$

where t_1, t_2 and t^* are the travel times in the pure phases and the dispersion, respectively and ϵ would be the holdup of phase 2. Tsouris et al. (1990) have used this method for real-time holdup monitoring in control of extraction columns.

Recently Soong et al. (1996) have attempted to measure solids concentration in a three phase reactor using transmitted ultrasonic waves. They developed a probe which shows potential for operating at high temperature (300° C) and pressure. The specific arrival times of a pulse of ultrasound at a transducer along with the arrival times in a test section with only the fluid is used in the reconstruction process.

Okamura et. al. (1989) have devised a novel indirect method for measuring solids holdup by analyzing the shape and phase lag or lead of an ultrasonic wave transmitted through a three phase system. The phase lag or lead is only a function of the solids concentration and is unaffected by the presence of bubbles. This provides an average value of the solids holdup along the ultrasound beam path. The requirement, however, is that the temperature of the medium remains constant.

Tomography based on transmission of ultrasound has been used for bubbly flow conditions by Wolf (1988). The argument in favor of the use of ultrasonic techniques as opposed to the ones based on nuclear radiation is safety consideration. However, ultrasonic techniques are not applicable for flows with high gas holdups since then effects of multiple scattering become high, and allowable distance between the transducers cannot be too large.

More recently electrical impedance measurements coupled with tomographic principles have been introduced for void fraction measurements (Dickin et. al. 1993, Xie et. al. 1992). The method is based on measuring the electrical resistance or the dielectric permittivity in the flow between pairs of electrodes, a number of which are evenly spaced around the test section. The hardware for the system is basically similar to the impedance void meters discussed in the section on global measurement techniques. The procedure for measurement involves pulsing an alternating current via one pair of electrodes and measuring the voltage at other pairs of electrodes. The procedure is repeated for all possible combinations of pairs of electrodes. The differences in electrical resistivity (or permittivity) between the phases is used to map the momentary distribution of the phases in the cross-section. Although they have the advantage of being capable of fine time resolution, the measurements made are not just a function of the voidage but also of a number of other parameters such as the electrical properties and temperature of the medium, the flow distribution, etc. All of this limits the spatial resolution compared to X-ray or γ-ray tomography. Current techniques do not yield resolution better than a centimeter (Xie et. al., 1995). Applicability in flows with high void fractions or high solids concentrations is yet to be demonstrated. In addition, imaging different sections of the flow is quite cumbersome because the electrodes are integrated into the wall of the test section.

Recommendation : *The ideal system for obtaining the chordal averaged void fractions in systems as large as the Laporte reactor is a* γ*-ray densitometer. The basis for this claim is the higher penetration capabilities of* γ*-rays in comparison to say neutron beams or ultrasound. Unfortunately the reactor is essentially operated as a three-phase system, and interpretation of densitometry results is only possible if one can consider the slurry as a pseudo-homogeneous phase and treat the system as a two-phase system. The vertical scanning capabilities of the densitometer can be utilized for obtaining an axial density profile. If* *another radiation source such as Am 241 can be obtained, the axial variation of the solids concentration can also be obtained. These measurements would complement the overall phase holdups obtained by the global measurement methods recommended earlier.*

2.3 Probes for Local Gas Holdup and Solids Concentration Measurement

One way of measuring the local void fraction is by means of probes. These probes can be based on electrical impedance or optical principles.

2.3.1 Impedance Probes

The electrical impedance probes can be further based on either conductive or resistive or capacitive effects. A conductivity probe makes use of the difference in conductivity of the gas and liquid phase and is quite suitable for aqueous gas-liquid systems. Resistivity probes sense the variation in resistance between two electrodes with the passage of bubbles through the gap between them. They are more suitable for measurement of solids concentration. Similarly, a capacitance probe uses the difference in the dielectric constant associated with each phase for phasic discrimination. They can be used in non-polar media and have been used more often for solids concentration measurements in fluidized beds and three phase systems.

A possible choice for the measurement of gas holdup in a three phase reactor would be a conductivity probe. The electrical conductivity probe essentially consists of a stainless steel insulated needle exposed only at the tip and a larger electrode mounted on the wall. With the liquid in contact with the probe tip the electrical circuit between the needle and the wall electrode is closed and if the tip is immersed in a bubble the circuit gets broken. The electrical operating schematic is shown in Fig. 5. The probe therefore acts like a switch and the signal therefore is binary. The typical output signal from the probe (including the capacitance and optical probes, to be discussed later) is shown in Fig. 6. In practice there is a delay in response to a bubble due to the dewetting time required. The response time depends on how fast the liquid film is sheared off from the probe allowing the signal to rise from the voltage corresponding to the gas phase to that of the liquid phase and vice-versa. Consequently, the signal is not exactly binary with the rise and fall times depending on the tip geometry, bubble size and rise velocity as well as on the surface tension of the liquid. Minimization of the rise and fall time is possible with proper probe design and appropriate signal processing. The void fraction is obtained from the ratio of the integral of the time the probe spends in the gas phase and the total time. Two such needle probes have been

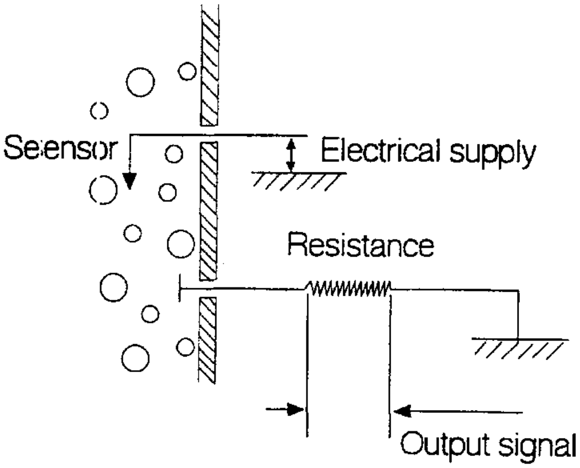

Figure 5: Operating schematic of the conductivity probe.

integrated together such that their tips are vertically aligned and a small distance apart so that from the measurement of the time of flight of a bubble between the two tips the bubble rise velocity can be estimated (Ueyama et al., 1980; Yasunishi et al., 1986; Matsura and Fan 1984, Ikeda et al., 1986). In general, the measurements from such a conductivity probe are also sensitive to the temperature of the medium, the orientation of the probe with respect to the flow, the flow velocity and changes in the ionic strength (conductivity) of the medium. Thus, one needs either to ensure that the temperature and the conductivity in the flow media are constant or to monitor them constantly and account for the changes. The sensitivity to the direction of the flow is probably of critical importance in situations where the flow velocity in the direction normal to the probe axis is not small in comparison to the velocity along the probe axis, as in stirred tanks. For a bubble column this effect may not be so critical. One would, however, have to orient the probe in the reverse direction for measurement in the downflow region. The effect of the orientation of the probe with respect to the flow direction has been clearly demonstrated by Groen et al. (1995).

For the measurement of the solids concentration in a slurry system a modified form of the conductivity probe can be used (Nasr-El-Din et al., 1987). Their probe consists of two sensor electrodes which are completely insulated from each other and are surrounded by two field electrodes. When the probe is immersed in a conducting fluid such as water, the application of a potential across the field electrodes results in the flow of a small current between the field electrodes. The magnitude of this current depends on the total resistivity of the surrounding medium. With increasing solids concentration the resistivity increases and the current decreases. Relating this change in current provides a measure of the solids concentration. However, the current depends on both the slurry resistivity and the polarization resistance developed on the surfaces of the field electrodes, and the latter is a function of velocity. Measuring the voltage across the sensor electrodes removes the effects of polar-

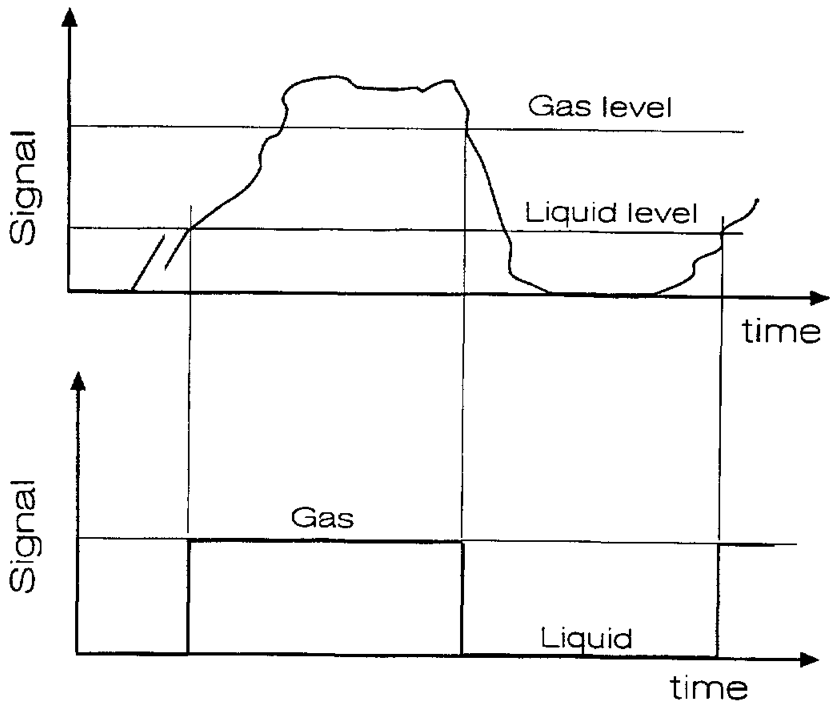

Figure 6: Output signal from a probe.

ization. This is because the sensor electrode circuitry has a very large impedance and hence no current flows through them. Thus, the effects of flow velocity on the solids concentration measurement is circumvented. The conductivity probe has been used for solids up to 1 mm in diameter (or characteristic size) and solids concentrations up to 25 to 30 %. An important advantage of this probe appears to be that for non-conducting solids, the solids concentration can be obtained directly from the sensor voltage using the Maxwell equation (5) for mixture conductivity. This eliminates any need for calibration.

Another means of measuring the local solids concentration is a capacitance probe (Riley and Louge, 1989), which senses the variation of the effective dielectric permittivity of the suspension between the two electrodes. The magnitude of the variation in the capacitance due to the variation in solids concentration is of the order of picofarads. This small capacitance is overwhelmed by the cable capacitance and any stray capacitances. The design of Louge and Opie (1990) overcomes this problem by the use of a guard circuit that eliminates all stray capacitances and measures only that between the sensing electrode and the ground. The schematic of their design is shown in Fig. 7. The most important advantage of this system is that one can adapt it to work in high temperature environments. Like the conductivity probe the capacitance probe is also sensitive to its orientation with respect to the flow.

All the above probes in general can also be used in three phase systems. If the size

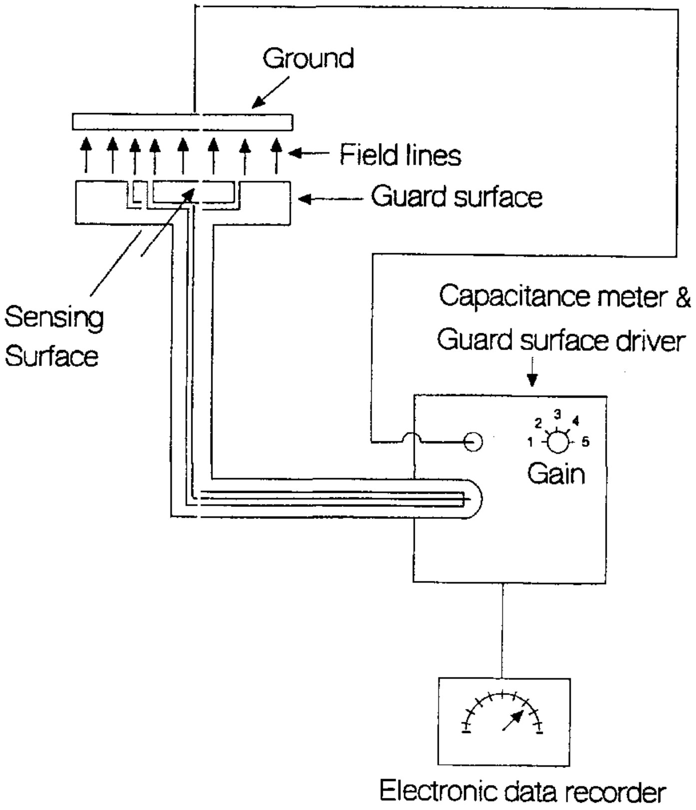

Figure 7: Schematic of the capacitance probe of Louge and Opie.

of the solids is small (of the order of microns), the slurry can be considered as a pseudo homogeneous phase. The signal from a conductivity probe will be binary with the two levels corresponding to the gas and the slurry phase respectively. If the diameter (or the characteristic length) of the solids is quite large, again the signal from the probe is binary (the impact of a solid particle on the probe tip has no significant influence on the signal).

2.3.2 Optical Probes

Optical probes exploit the differences in the index of refraction of the two phases and rely on the application of Snell's law at the probe-fluid interface. Depending on which phase exists at the probe's tip the light from the tip is reflected or refracted. The most common optical probe consists of two optical fibers fused and ground to a 45° angle with respect to the probe axis. The other ends of the fibers are free with one of them serving as an emitter and the other as a receiver. Light detection can be achieved with a phototransistor. In a novel approach, De Lasa et. al. (1984). have the optic fiber bent into an U-shape such that the radius of curvature of thde U is large enough for the angle of incidence at the turning point to be larger than the anpgle of total reflection when the fiber is exposed to air (gas). At the same time the radius is too be small enough to secure an angle of incidence at the turning point smaller than the angle ϵ of total reflection when the tip is in water (liquid). With this, the light will be conserved in a gas and lost in liquid resulting in a significant difference in the detected signals correspondinpg to gas and liquid. This principle is illustrated in Fig. 8.

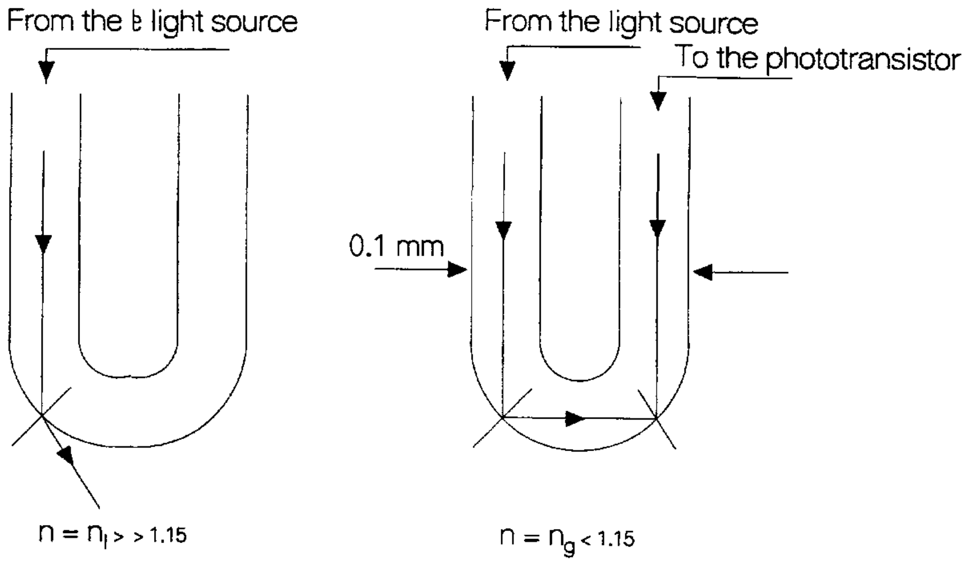

Figure 8: : Principle of operation of the optical probe

Optical probes for void frfraction measurements have been made by Lance and Bataille (1991), Abuaf et. al. (1979), l Moujaes and Dougall (1987) . In general, an optical probe can be used only in transparent s systems, at low void fractions and at moderate temperatures. The success of the probe in ι discriminating between the phases depends on good contact between the probe tip and theae bubble. Thus, if the bubble size is very small the probe would be unable to detect the channges in voids. The use of the optical probe in a three phase system is considered problemnatic by Euzen et. al. (1993) mainly because of the difficulties in differentiating between the.e signals from the solids and the bubbles.

2.3.3 Other Probes

The electrochemical probe oririginally developed by Mitchell and Hanratty (1966), primarily for measuring the wall shear c stress has been adopted by Nakaryakov et. al. (1984) for the measurement of liquid velocitity and the void fraction in two phase flows. The probe consists of a small cathode and a larrger anode, with the latter mounted flush with the wall. The flowing liquid has to be an electrolyte of special composition. With the application of a voltage between the electrodes a chemical reaction leads to polarization of the cathode with the concentration of active ions on it going to zero. As a result active ions from the bulk diffuse to the cathode setting up the flow of an electric current in the circuit. The anode, being much larger, does not influence the process, and the current is entirely governed by the diffusion of the active ions to the cathode. If this condition, known as the regime of limiting diffusion current, is satisfied, the current in the electrode will depend on the liquid velocity near the electrode. A solution of the diffusion equation along with a known profile for the velocity is used to relate the current to the velocity. Since the probe is alternatively exposed to the gas and liquid phase, the signal is correspondingly at two different levels so that the void fraction can be estimated from the residence time of the probe in the gas phase.

In addition to the impedance and optical probes, attempts have been made to utilize hot wire or film anemometry (Delhaye, 1969), and even a micro thermocouple (Delhaye and Semeria, 1973), for phasic discrimination and in turn for void fraction measurements. However, as noted by Delhaye (1969), the applicability of anemometery is limited to low flow rates and by the dimensions of the bubble.

As discussed for impedance probes these probes act essentially like a switch depending upon the medium surrounding the probe tip. The ideal signal from the probes should therefore be binary. In practice there is a delay in the response to a bubble due to the dewetting time required. The response time is related to how fast the liquid film is sheared off from the probe allowing the signal to rise from the voltage corresponding to the gas phase to that of the liquid phase and vice-versa. Consequently the signal is not exactly binary with the rise and fall times depending on the tip geometry, bubble size and rise velocity as well as surface tension effects of the liquid. Minimization of the rise and fall time is possible with proper probe design and appropriate signal processing. The void fraction is obtained from the ratio of the integral of the time the probe spends in the gas phase and the total time.

Recommendation : *The choice of probe to be used depends to some extent on the physical properties of the liquid phase in the reactor. For liquids such as alcohols, the conductivity probe is more suitable since these liquids are polar in nature and, as such, use of capacitive probes is problematic. On the other hand if the liquid phase consists of paraffins and olefins the conductivity is much lower and these liquids are not as polar as alcohols. Consequently, a capacitance probe would be a better choice. Also, the liquids should have as low a viscosity as possible so that the dewetting time of the probe is small. For the Fischer-Tropsch wax at* 250° *this should not be a cause of problems. If only the local gas holdup is of interest, either the conductivity or the resistivity probe (depending on the liquid properties) is the best choice. If, however, the solids concentration is also desired, then either the multi-sensor resistivity* *probe or the capacitance probe can be used. However, despite all the claims that have been made about the capabilities of these latter probes, one would still need to test the probes in simulated conditions to determine their appropriateness for the specific application. Table 3 provides a comparison of the characteristics of the available methods for local void fraction measurement.*

3 Measurement of Bubble Sizes and Velocity

Unlike techniques for measurement of the local void fraction, the techniques that are available for measurement of bubble sizes and velocity are few in number. The simplest method that can be used for measurement of bubble sizes and their velocity is the photographic method. Pictures of the dispersion are taken through plane parallel windows installed in the bubble column. Using computerized image analysis the bubble sizes as well as their velocities can be estimated. The technique is limited in that the measured bubble sizes are not representative of the true bubble size distribution since the large bubbles rise in the center of the column and most often the image acquired is of the bubbles in the flow closer to the wall. In addition, the system needs to be transparent, and it is also necessary to provide special plane parallel windows at the column wall. This is not a technique that can be used easily on an industrial scale reactor.

The other commonly used method for bubble size measurement is a two point resistivity probe. Such a probe consists of two needles which are fixed at a small vertical distance apart. Each of the sensors has a binary output signal depending on which of the phases is in contact with the tip. As a bubble passes over each of the tips there is a mutual time delay t_{dly} between the signals from the two sensors due to the time needed for the bubble to proceed from one probe to the other (ref. Fig. 9). The distance d between the probe tips being known, the component of the bubble velocity along the direction defined by the line joining the probe tips can be estimated as :

$$v_x = d/t_{dly} \tag{16}$$

This velocity along with the knowledge of the mean residence time of the bubble at one of the probe tips t_m can be used to estimate the pierced chord length of the bubble as :

$$l_g = v_x t_m \tag{17}$$

With this method there are variations in bubble frequency and the corresponding chord

Table 3: Utility of Different Techniques for Local Void Fraction Measurement

	Radiation Methods	Conductivity Probe	Capacitance Probe	Optical Probe	Hot Wire Anemometer
Intrusiveness	1	4	4	4	4
Applicability in Aqueous Systems	Yes	Yes	No	Yes	Yes
Applicability in Hydrocarbon Systems	Yes	No	Yes	Yes	Yes
Applicability in 3-Phase systems	Not sufficient*	Yes (Gas)	Yes (Solids)	No	No
Applicability in corrosive, high pres./temp. systems	1	4	4	5	5
Accuracy	1 (at $\epsilon > 0.05$)	3	3	3	4
Ease of Use & Adaptability	1	3	3	3	3
Cost of System	4	2	2	3	2
Limitation(s)	safety requirements	restricted to low flow rates	restricted to low flow rates	$\epsilon < 0.15$ - 0.2 small bubbles may go undetected	restricted to low flow rates

Numbers in table indicate a ranking on a scale of 1 to 5. Rank 1 indicates that the technique is most suitable and rank 5 signifies that the technique is not to be preferred. Ranking for the cost of the system is based on 1 representing the least expensive and 5 representing the most expensive system.

[@] an additional measurement by an independent technique is required

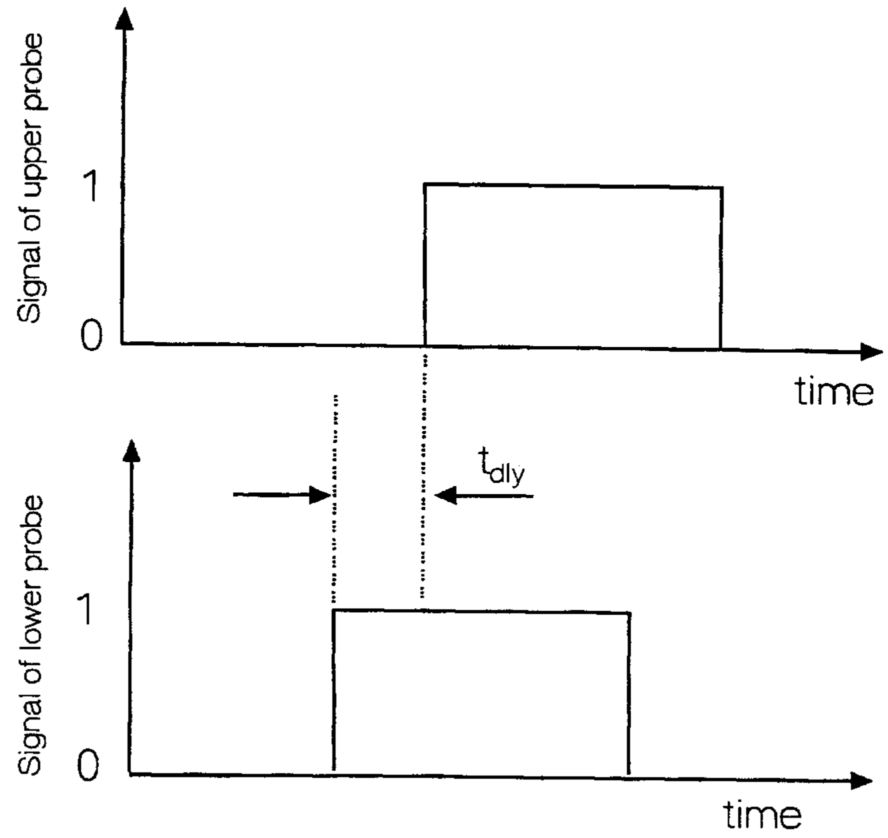

Figure 9: : The signals from a two point bubble probe

lengths obtained using the measurements from the upper and lower sensor. If such variations are statistically significant, this is indicative that there are problems of cross-talk and capacitive effects. This implies that the sensors are too closely spaced together. The optimum separation between the sensors is unfortunately a function of the bubble frequency, the range of bubble chord lengths intercepted by the sensors as well as the sensors size and geometry. Cheremisinoff (1986) recommends that the distance between the sensors should be set at a distance equal to the maximum anticipated bubble size.

There are many potential problems in applying this method to operating slurry bubble column reactors. Bubbles that are rising in a direction not aligned with the two probes lead to major errors, since then it is possible that there is no delay in the signal from the two sensors. This seriously limits their usage in turbulent flow fields. To overcome this difficulty some researchers (Burgess and Calderbank, 1975) have developed multi-point probes. However, these probes can be utilized only in flows where the bubble size is at least 6 mm (Buchholz et. al. 1981). The velocity of rise, as calculated above by Eq. 16, is applicable only if the bubble is centrally pierced. Steinemann and Buchholz (1984) provide an alternative procedure for calculating the rise velocity of bubbles that are not centrally pierced. This is based on assuming a probability density function for the bubble chord distribution, the parameters for which are fitted to the measured chord distribution. If the bubbles are small (less than a 1 mm), there is the possibility that a bubble never gets pierced but goes around the sensing probe tips. In order to eliminate the effects of cross-talk between two closely positioned sensors an alternative method of acquiring the mean time delay between the signals from the two tips is to obtain it from the cross-correlation function of both the signals (Zun and Saje, 1982). The two point probe, therefore, is an acceptable instrument for measuring bubble characteristics only if the bubbles are spherical, not too small and have a unimodal distribution.

For the two point optical probe the principle of detecting the bubble sizes and the velocities is identical to that of the two point resistivity probe described above. The limitations described for the void fraction probes based on the same principles apply in this case as well. Chabot (1993) has used the optical probe to study the bubble characteristics in a high temperature bubble column with some hydrocarbons as the liquid phase.

An interesting alternative to the intrusive kind of probes of the kind discussed above is the Ultrasound Doppler Technique (Hilgert and Hofmann, 1986; Lubbert et al., 1987; Broring et al. 1991). Since bubbles are good reflectors of ultrasound, some of the energy of a beam of ultrasound transmitted through the flow dispersion gets reflected into a detector. The measurement principle is illustrated in Fig. 10. Most often the transmitter itself can also serve as a detector. In accordance with the Doppler effect the pulse of ultrasound reflected from the surface of a moving bubble is shifted in frequency by an amount proportional to the bubble velocity. A spectral analysis of the Doppler shift provides a distribution of the bubble velocity components in a direction that bisects the incident and reflected beam. The measuring volume is typically a few centimeters away from the transmitter and, therefore, to obtain the spatial distribution of the measurements the device has to be moved around in the reactor like any other probe. The advantage of the system is that there is no direct interaction between the measuring device and the bubble, although there is some flow disturbance caused by the presence of the transmitter/receiver inside the reactor. It also appears that the technique is applicable only for flows with low holdups (less than 20%). A higher concentration of bubbles draws the measuring volume closer to the device, and if one persists with longer transmission time to increase that distance, then the error in measurement increases since the effects of transmission of ultrasound become significant. This then leads to errors in the measurement. In addition, one needs to obtain the bubble velocities in at least three directions at each measuring point. A further limitation of the technique is that the ultrasonic transducer cannot operate in environments with temperatures higher than about 150°C. It also has to be noted that the technique only provides bubble

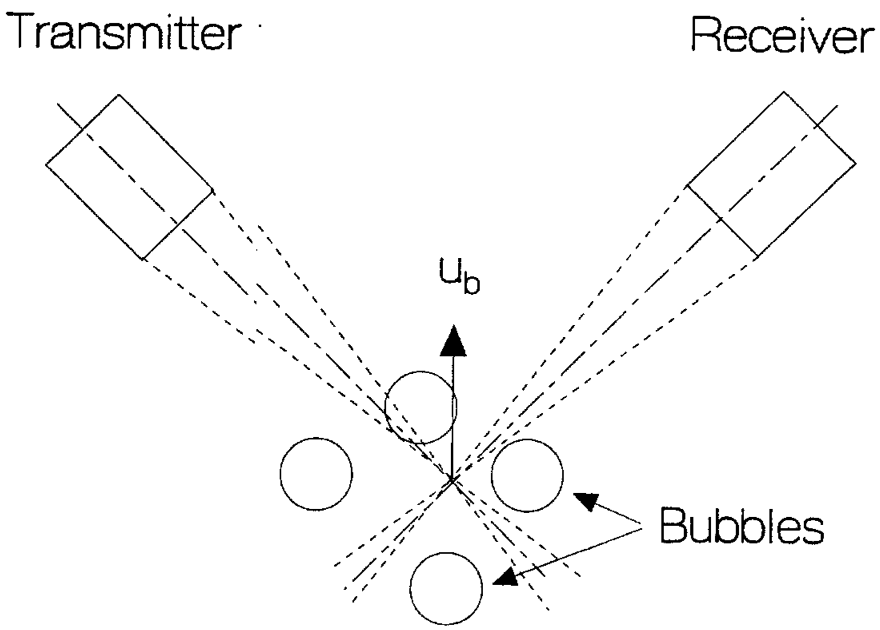

Figure 10: Measurement principle of the Ultrasound Doppler technique

velocities and no information on their sizes.

A technique that provides information only on the bubble sizes is the isokinetic sampling probe. This measurement principle is conceptually different and relies on physically sucking out a sample of the dispersion into a capillary tube. The sampling end of the capillary is funnel shaped with an expansion such that it provides a uniform acceleration as the bubbles get converted into a slug filling the capillary cross-section. A narrow collimated beam of light from an optical switch is directed through the glass wall of the capillary tube. The measured signal consists of the variation in intensity of the transmitted light due to the passage of gas or liquid slugs. These signals are similar to the signals of the conductivity or the optical probes (binary). The time elapsed between the detection of the two ends of a bubble is inferred from this signal. This, along with the known cross-sectional area of the capillary, can be used to estimate the bubble volume. With the assumption of a spherical bubble a diameter for the bubble can be computed. The schematic of the system is illustrated in Fig. 11. Greaves and Kobbacy (1984) and Pilhofer et. al.(1974) have used this method for bubble size estimation.

The principle of isokinetic sampling can also be used for the measurement of solids concentration. The key requirement is that the velocity of sample withdrawal and the process

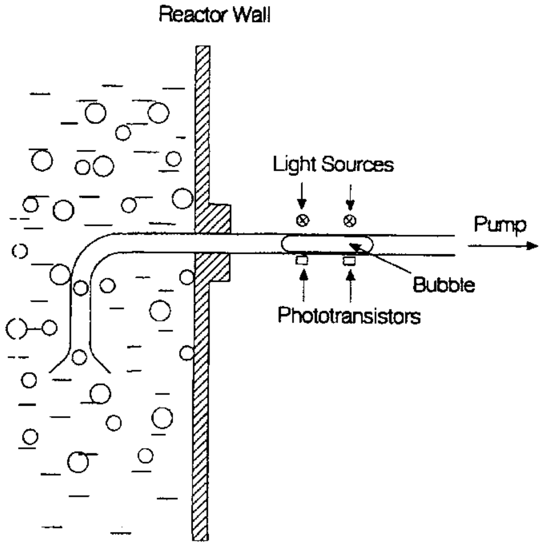

Figure 11: The isokinetic sampling probe

stream needs to be matched to prevent sample size differentiation. Since, the velocity of the flow is often not known complying with this requirement is not easy.

A rather simple method that has found wide acceptance for measurement of bubble velocities, and in turn their sizes, is the dynamic gas disengagement technique. The method requires an accurate recording of the rate at which the surface of the dispersion drops once the gas flow is interrupted. The measured disengagement profile is used to estimate the holdup structure that existed just before gas shut off. In its simplest form the technique assumes one or two dominant bubble sizes. The initial part of the disengagement profile is considered to be dictated solely by large bubbles. The small bubbles disengage only after all of the large bubbles have left the system. The disengagement profile (the height of the two phase dispersion as a function of time) has two distinct regions, corresponding to the two bubble sizes, which are fitted with straight lines. A typical disengagement profile for a bimodal distribution is shown in Fig. 12. The slope and intercepts of the straight lines are related to the holdup and the rise velocities of the corresponding bubble sizes. If some relation (correlation) can be assumed between bubble rise velocities and their sizes then, the latter can also be estimated. Assuming that there is no interaction between the two bubble classes the average holdup and the holdup corresponding to the large (transported holdup) and small bubbles (entrained holdup) are estimated from :

Average gas holdup :

$$\epsilon_{avg} = 1 - \frac{H_s}{H_o} \tag{18}$$

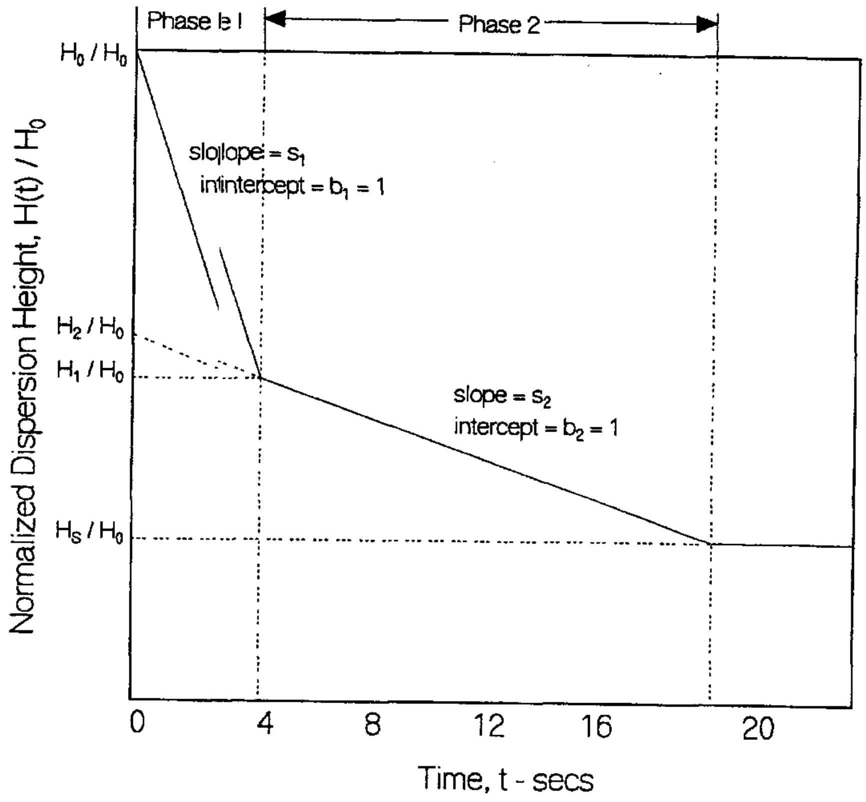

Figure 12: Typical disengagement profile for a bimodal distribution

Small Bubble Holdup :

$$\epsilon_s = 1 - \frac{H_s}{H_o b_2} \tag{19}$$

Large Bubble Holdup :

$$\epsilon_l = \frac{H_s}{H_o} \frac{1 - b_2}{b_2} \tag{20}$$

where H_o is the steady state dispersion height prior to gas shut off and the quantities H_s and b_2 are defined in Fig. 12. If one takes into account the interaction between the different classes of bubbles as they disengage, the above expressions for the holdup get modified (Patel et. al. 1989).

Most often in the use of the dynamic gas disengagement method it is assumed that there is no interaction between bubbles during gas disengagement and that the dispersion is axially homogeneous prior to gas flow interruption. Inspite of its simplicity the dynamic disengagement method provides very useful global information. Vermeer and Krishna (1981), Schumpe and Grund (1986), Patel et. al. (1989) are some of the researchers who have enhanced the utility of the method after Sriram and Mann (1977) introduced it. Sasaki et. al (1986) have extended the technique to multi-modal bubble size distributions.

Recommendation : *It has to be accepted that presently there are no techniques available for measurement of bubble characteristics in a reactor operating in the churn turbulent regime at high temperatures and pressure. The two point conductivity probe is not applicable under turbulent flow conditions. Although a multi-point probe can be used in a turbulent, two phase flow field, the bubble sizes need to be large. In a Fischer-Tropsch system the bubble sizes are expected to be small. Optical probes are not suitable either when the bubble sizes are small. Pulsed Ultrasound Doppler technique cannot be used at high voidages as well as at temperatures higher than about 150° C. The only method that can be adopted with ease for the Laporte reactor appears to be the dynamic gas disengagement technique. Since the reactor walls are opaque recording the drop rate of the free surface of the dispersion can be recorded using pressure taps provided along the reactor height or an automated movable* γ*-ray densitometer can be used. Table 4 provides a comparison of the characteristics of the available methods for bubble size and velocity measurement.*

4 Measurement of Liquid and Solid Velocities

Techniques that have been commonly used for the measurement of liquid velocities in multiphase systems are essentially the ones used in single phase flow with some modifications in the interpretation of the measured data. These methods include the simple pitot tube, devices based on the turbine flowmeter, hot wire or film anemometry, and Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), Laser Induced Photochemical Anemometry (LIPA), particle tracking and tracer techniques.

The principle of the pitot tube is very well known and is based on measuring the differences in the pressure at the point of interest and the static pressure at the wall. The tube is inserted close to the point of interest in the flow such that its opening faces the flow. The velocity at the point is calculated based on the dynamic pressure measurement. The relationship is

$$\Delta P = \frac{1}{2}\rho v^2 \tag{21}$$

and is applicable for single phase flow. For two phase flow situations the above relation is modified as (Euzen et. al. 1993) :

$$\Delta P = \frac{1}{2}(\epsilon_g \rho_g v_g^2 + J \epsilon_l \rho_l v_l^2) \tag{22}$$

Difficulties still exist due to smaller amplitude peaks corresponding to incomplete piercing or bubble sliding on the probe. In such situations it is difficult to identify whether the signal is due to a bubble or comes from the liquid phase. Despite all these complexities, the probe has found wide acceptance, since it is probably the most convenient and inexpensive method for the purpose of liquid velocity measurements.

Laser Doppler Velocimetry is considered to be an accurate and reliable method of measuring flow velocities in single phase flow. In a dual beam system two laser beams of equal intensity are focused to cross at a point of interest in the flow field. The measurement volume is a small ellipsoidal region at the intersection of the beams. The fluid is seeded with minute tracer particles which follow the motion of the fluid. When one such particle passes through the control volume, light from each of the beams get scattered and interfere in space. This is seen as a varying intensity fringe pattern by a detector. The electrical signal output from the detector is referred to as a Doppler burst. The particle velocity U is related to the Doppler shift frequency f_D, the intersection angle between the incident laser beams θ and the wavelength λ of the beams by :

$$U = \frac{f_D\,\lambda}{2\,sin0.5\theta} \tag{23}$$

Thus, for a given wavelength and angle of intersection of the laser beams, the Doppler shift is directly related to the velocity, and no calibration is required. When a bubble passes through the beam, a large amount of light is scattered, reflected and refracted, some of which reaches the photodetector. It is necessary to set up the LDV processor so that the light scattered by a bubble is not interpreted as the liquid phase velocity. The signal is rejected if it is above a certain amplitude. If the test section to be investigated is large, difficulties also arise due to the interruption of the laser beam outside the measuring volume. Satisfactory measurements of the instantaneous velocity components can be made for void fractions of less than 10 % provided that the signal is adequately processed to reject the noise due to reflection of the light by the bubbles (Lance and Bataille, 1991)

Tsuji and Morikawa (1992) have used LDV for the simultaneous measurement of the velocities of both phases in an air-solid two phase flow in a horizontal pipe. Solid particle sizes were of the order of a millimeter to a hundred microns. The particles used for seeding the gaseous phase were much smaller. The intensity of the scattered signal from the large particles is stronger than from those used for seeding the air. The identification of the signals from these two kinds of particles was thus based on the amplitude of the signal. The difficulty is that the amplitude of the signal obtained due to a particle that intersects the measuring volume partially is a source of noise. However, most often the amplitudes for these partial intersections are in between the two extremes of the signal amplitudes corresponding to the solid phase particles and the seed particles. Thus, only the signals corresponding to these two extremes are retained and the rest are eliminated. This method is probably suitable for measuring the solids velocity in a Fischer-Tropsch system with moderate (15 to 20 % by weight) solids loading. For larger particle sizes the Doppler burst drops out completely (at least in the forward scattering mode) and hence LDV cannot be used to obtain the flow velocity of such solids.

In analogy to tracer techniques used for measurement of the residence time distribution of a phase in a reactor, Lubbert and Larson (1990) have developed a tracer technique for measurement of not only the local liquid phase velocity but also the mixing behavior. The method relies on using heat instead of electrolytes or dyes as the tracer. Fluid elements are tagged by direct local ohmic heating using a high frequency alternating current between two small electrodes introduced inside the reactor. The dispersion of heat is measured at a small distance away from the source of heat using a hot-film anemometer switched as a temperature detector. The distance between the transmitter and receiver can be varied in an interval of 2 to 20 cm. The signal to noise ratio of the device is increased by using input signals in the form of a pseudo-random sequence rather than as a series of identical pulses. The information concerning the time of flow distribution is obtained from the cross-correlation between the input and output signals. A schematic of the probe is illustrated in Fig. 13. A probability density function (p.d.f.) is assumed for the number of tracer particles at a given distance from the source, at a given instant of time after injection. This distribution is assumed to be normal. A nonlinear fit of the measured time of flow data to the assumed p.d.f. provides the mean time of flow as well as certain other parameters related to the local dispersion. From the mean time of flow and the distance between the sensors the local liquid phase velocity can be estimated. Indeed the method is rather elegant for measuring local velocities with the added advantage of obtaining information on local dispersion as well. Unlike the other intrusive probes, it does not have the problems of signal processing associated with phase change and partial intersection of a bubble with the measuring device. It is however, not clear as to how the system would respond if the fluids involved are already at an elevated temperature. Its application to three phase system has not been tested.

In addition to the kind of techniques described above, there are methods for velocity measurements that can be grouped under flow visualization. Particle Image Velocimetry (PIV) (Adrian, 1991) in its simplest form uses a sheet of laser light to illuminate a section of the flow and images of small scattering (tracer) particles are photographed at right angles to the sheet. The scattering particles used are very small, of the order 10 to 20 microns, and consequently the laser source used must have high energy to ensure adequate scattering.