the chordal average measurements at two positions at right angles to each other. An assessment can then be made whether the assumption of axisymmetry is appropriate and if so a cross-sectional mean using AAbel inversion can be obtained.

The important advantage of X-ray or γ-ray based techniques is that it can be adopted for studying a wide range of systems including high pressure and high temperature systems. The type of radiation that can be used can be X-rays or γ rays, β rays (applicable only for small test sections) or neutron beams. However, due to their higher penetrating capabilities X-rays and γ rays are the preferred types of radiation. The method lends itself to a certain degree of automation and consequently can be used to provide local information to supplement the global information provided by the bed expansion and the pressure drop method.

The use of densitometry or tomography as described above is not sufficient for three-phase systems for which the pseudohomogeneous approximation for the mixture of solid and liquid phases cannot be made. This is because in this case there are three unknowns viz., the holdups of the three phases, while the attenuation measurement provides only one equation. This along with the overall mass balance is not sufficient to discriminate between all three phases. If the linear attenuation coefficients for the gas, liquid and solid phases in a three-phase system are denoted by μ_g, μ_l and μ_s, respectively, and the corresponding void fractions are denoted as ϵ_g, , ϵ_l and ϵ_s respectively, then the transmission ratio for a three phase system can be expressed as :

$$l\, ln\frac{I_o}{I} = \int (\mu_g\, \epsilon_g + \mu_l\, \epsilon_l + \mu_s\, \epsilon_s)\, dl \tag{13}$$

where overall continuity requires

$$\epsilon_g + \epsilon_l + \epsilon_s = 1 \tag{14}$$

All the three quantities ϵ_g, ϵ_l, ϵ_s cannot be obtained by a conventional single energy CT. If measurements taken at two different photon energy levels are available, it is possible to resolve the holdup of these individual phases. This technique, known as dual energy CT, takes advantage of the functitional dependence of the attenuation coefficient of a material on the energy of the photons. The solution of the simultaneous equations resulting from the two transmission measurements described by Eq. 13 and Eq. 14 is best accomplished when the radiation at one energy level is primarily attenuated by one phase, and the radiation at the other energy level is attenuated mainly by the other phase. Consequently, the photon energy of the second source needs to be different from the first one by a significant amount in order to provide a unique second measurement for the accurate distinction of the third

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

Table 2: Linear Attenuaiatien 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 s	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 s 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 e is not very large and would not be the most ideal setup for dual energy tomography. Duual beam densitometry has been used by Daly and Bukur et al. (1995) for obtaining radial a and axial void fraction distribution in a slurry bubble column under Fischer-Tropsch synthaesis conditions. The densitometer consisted of a 35 mCi Cobalt-60 (1.17, 1.33 MeV) and a 50 0 mCi Cesium-137 (0.661 MeV) collimated sources each of which is associated with a NaI detetector. The system of sources and detectors are mounted on a movable assembly mechanisrm, which allows the positioning of the gauges both axially and laterally with respect to the e 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 beeen 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 5000 mCi Americium - 241 source and a set of 85 detectors. The capacitance tomographic sys'stem makes use of 8 electrodes each 10 cm long providing for a total of 28 capacitance measurements.

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

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

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

For the holdup measuremment based on the time of flight of ultrasound the transmittance time through the pure phasess and through the two-phase dispersion needs to be determined. The fraction of the voids alonng 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 trravel 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 hhigh temperature (300° C) and pressure. The specific arrival times of a pulse of ultrasoundd at a transducer along with the arrival times in a test section with only the fluid is used inn the reconstruction process.

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

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

More recently electrical i impedance measurements coupled with tomographic principles have been introduced for voiaid fraction measurements (Dickin et. al. 1993, Xie et. al. 1992). The method is based on meeasuring the electrical resistance or the dielectric permittivity in the flow between pairs ofof electrodes, a number of which are evenly spaced around the test section. The hardware fcfor the system is basically similar to the impedance void meters discussed in the section on glglobal measurement techniques. The procedure for measurement involves pulsing an alternatiring 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 differencees in electrical resistivity (or permittivity) between the phases is used to map the momentaryy distribution of the phases in the cross-section. Although they have the advantage of being ς capable of fine time resolution, the measurements made are not just a function of the voidagee but also of a number of other parameters such as the electrical properties and temperature c of the medium, the flow distribution, etc. All of this limits the spatial resolution compared t 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 c concentrations is yet to be demonstrated. In addition, imaging different sections of the flow ı is quite cumbersome because the electrodes are integrated into the wall of the test section.

Recommendation : *Thhe ideal system for obtaining the chordal averaged void fractions in systems as large as the Laaporte reactor is a γ-ray densitometer. The basis for this claim is the higher penetration cappabilities of γ-rays in comparison to say neutron beams or ultrasound. Unfortunately thee reactor is essentially operated as a three-phase system, and interpretation of densitometrtry results is only possible if one can consider the slurry as a pseudo-homogeneous phase a and treat the system as a two-phase system. The vertical scanning capabilities of the densiitometer 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 conductitivity 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

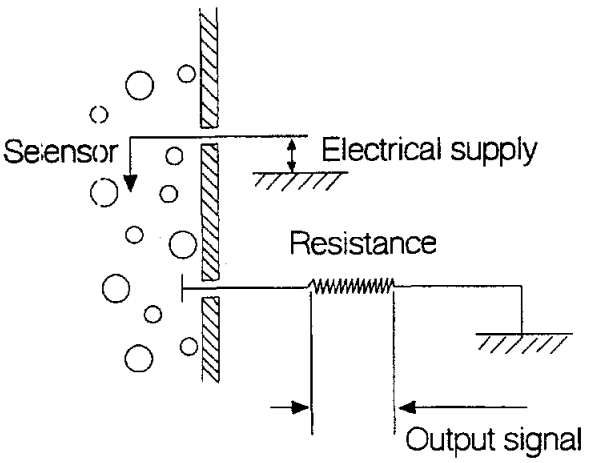


Figure 5: Operating schematic of the conductivity probe.

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-

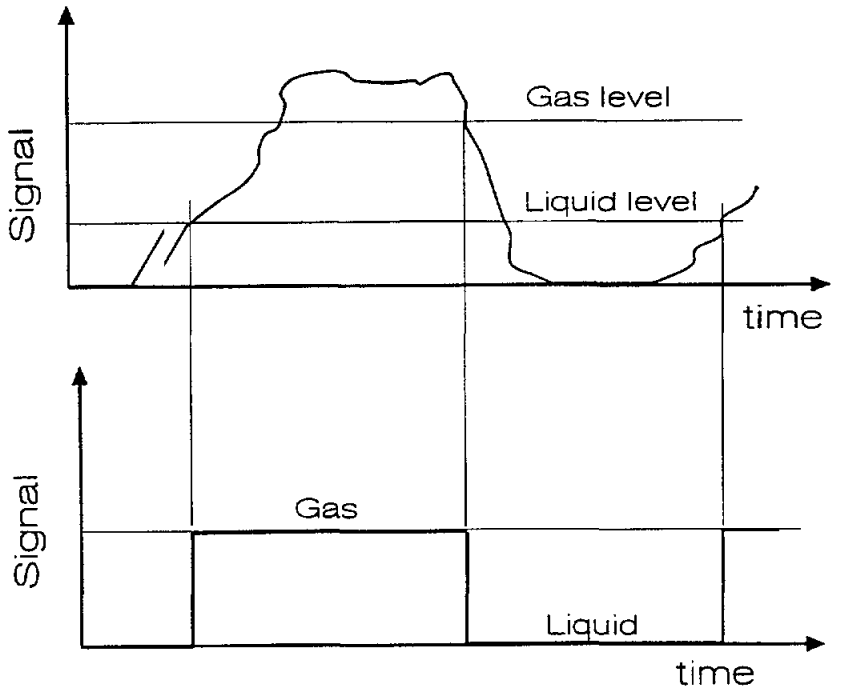


Figure 6: Output signal from a probe.

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

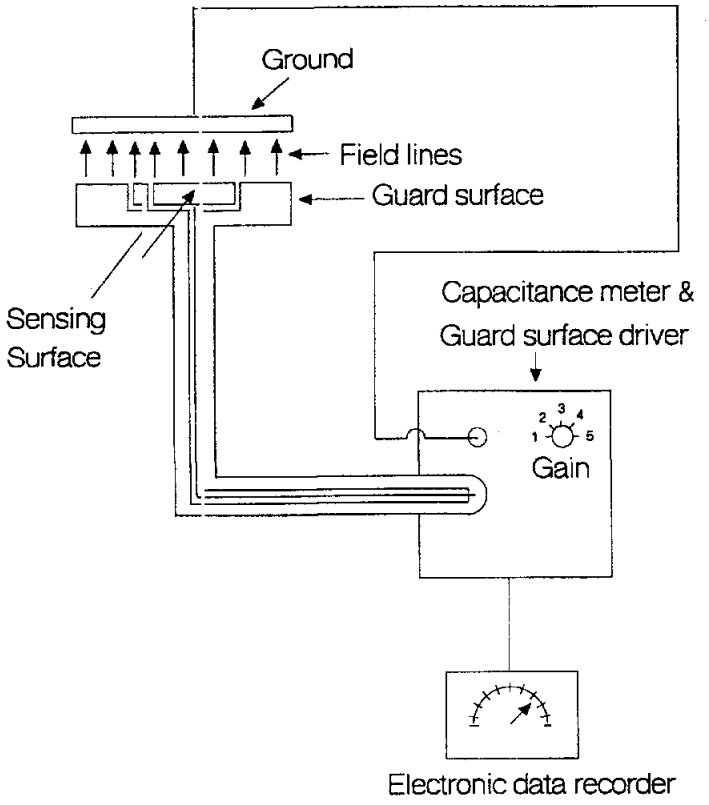


Figure 7: Schematic of the capacitance probe of Louge and Opie.

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 the U is large enough for the angle of incidence at the turning point to be larger than the angle 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 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 corresponding to gas and liquid. This principle is illustrated in Fig. 8.

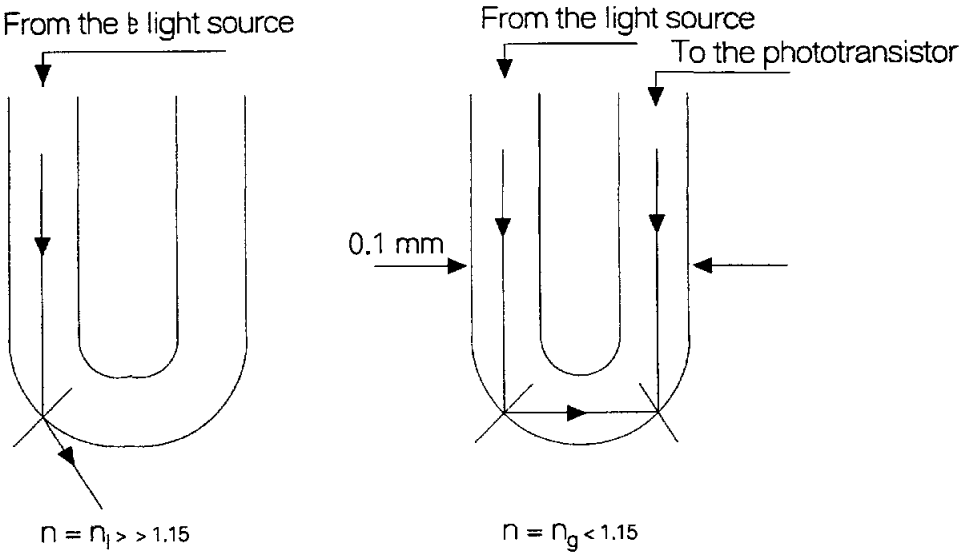


Figure 8: : Principle of operation of the optical probe

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

2.3.3 Other Probes

The electrochemical probe originally developed by Mitchell and Hanratty (1966), primarily for measuring the wall shear stress has been adopted by Nakaryakov et. al. (1984) for the measurement of liquid velocity and the void fraction in two phase flows. The probe consists of a small cathode and a larger anode, with the latter mounted flush with the wall. The

flowing liquid has to be an e electrolyte of special composition. With the application of a voltage betweén the electrodeles a chemical reaction leads to polarization of the cathode with the concentration of active icions on it going to zero. As a result active ions from the bulk diffuse to the cathode settingg up the flow of an electric current in the circuit. The anode, being much larger, does not inínfluence 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 solutioon of the diffusion equation along with a known profile for the velocity is used to relate the c curr:ent to the velocity. Since the probe is alternatively exposed to the gas and liquid phase, t the signal is correspondingly at two different levels so that the void fraction can be estimateed f:om the residence time of the probe in the gas phase.

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

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

Recommendation : *Thee choice of probe to be used depends to some extent on the physical properties of the liquid phhase in the reactor. For liquids such as alcohols, the conductivity probe is more suitable since tithese liquids are polar in nature and, as such, use of capacitive probes is problematic. On thee other hand if the liquid phase consists of paraffins and olefins the conductivity is much loweer and these liquids are not as polar as alcohols. Consequently, a capacitance probe would be ɛ a better choice. Also, the liquids should have as low a viscosity as possible so that the dewettiting time of the probe is small. For the Fischer-Tropsch wax at* 250° *this should not be a causse of problems. If only the local gas holdup is of interest, either the conductivity or the resistiiivity probe (depending on the liquid properties) is the best choice. If, however, the solids concenntration is also desired, then either the multi-sensor resistivity*

probe or the capacitance probbe can be used. However, despite all the claims that have been made about the capabilities ofpf these latter probes, one would still need to test the probes in simulated conditions to determmine their appropriateness for the specific application. Table 3 provides a comparison of the s characteristics of the available methods for local void fraction measurement.

3 Measurement of Bubble Sizes and Velocity

Unlike techniques for measureement of the local void fraction, the techniques that are available for measurement of bubble sizizes and velocity are few in number. The simplest method that can be used for measurement t of bubble sizes and their velocity is the photographic method. Pictures of the dispersion are e taken through plane parallel windows installed in the bubble column. Using computerized i image analysis the bubble sizes as well as their velocities can be estimated. The technique is lilimited in that the measured bubble sizes are not representative of the true bubble size distribbution since the large bubbles rise in the center of the column and most often the image acququired is of the bubbles in the flow closer to the wall. In addition, the system needs to be transpparent, 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 d method for bubble size measurement is a two point resistivity probe. Such a probe consiststs of two needles which are fixed at a small vertical distance apart. Each of the sensors haas a binary output signal depending on which of the phases is in contact with the tip. As a a bubble passes over each of the tips there is a mutual time delay t_{dly} between the signals s from the two sensors due to the time needed for the bubble to proceed from one probe to thhe other (ref. Fig. 9). The distance d between the probe tips being known, the component t of the bubble velocity along the direction defined by the line joining the probe tips can be e estimated as :

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

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

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

With this method there aare 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

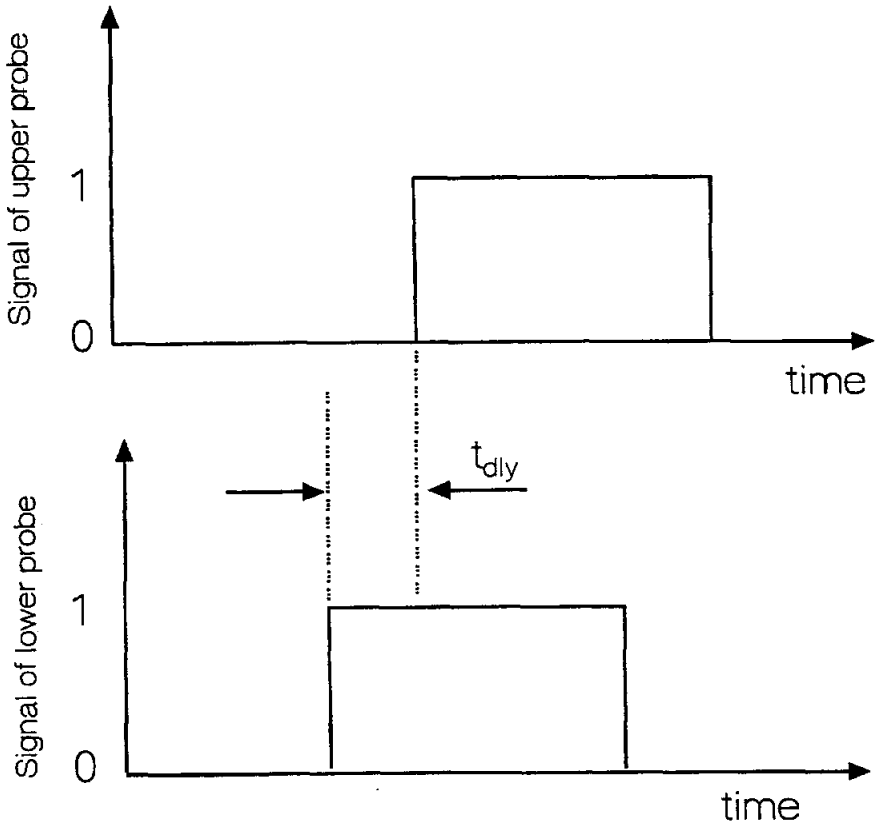


Figure 9: : The signals from a two point bubble probe

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

There are many potentialal problems in applying this method to operating slurry bubble column reactors. Bubbles thaat are rising in a direction not aligned with the two probes lead to major errors, since then it is p possible that there is no delay in the signal from the two sensors. This seriously limits their usisage in turbulent flow fields. To overcome this difficulty some researchers (Burgess and Calalderbank, 1975) have developed multi-point probes. However, these probes can be utilized oonly in flows where the bubble size is at least 6 mm (Buchholz et. al. 1981). The velocity of risese, as calculated above by Eq. 16, is applicable only if the bubble is centrally pierced. Steinemnann and Buchholz (1984) provide an alternative procedure for calculating the rise velocity y 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 is also has to be noted that the technique only provides bubble

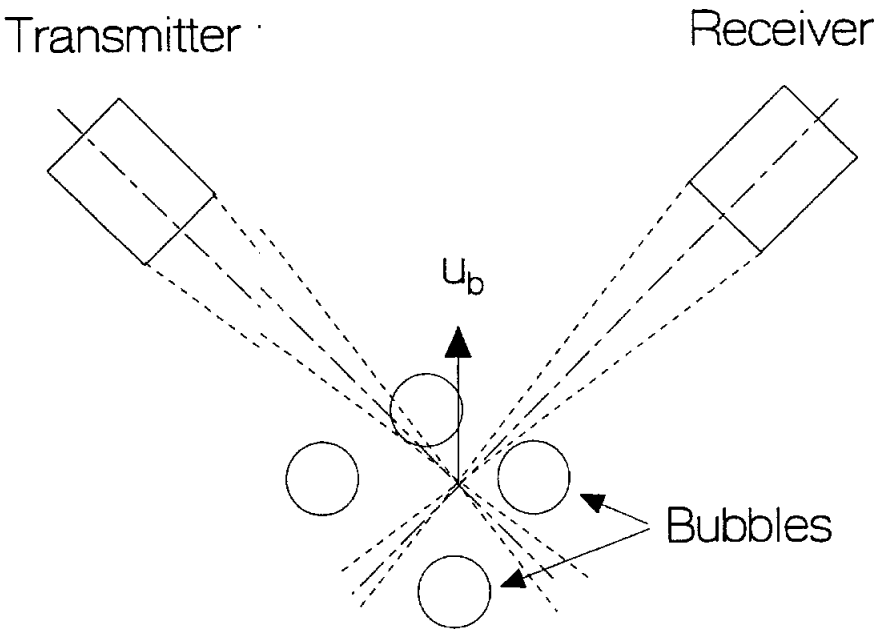
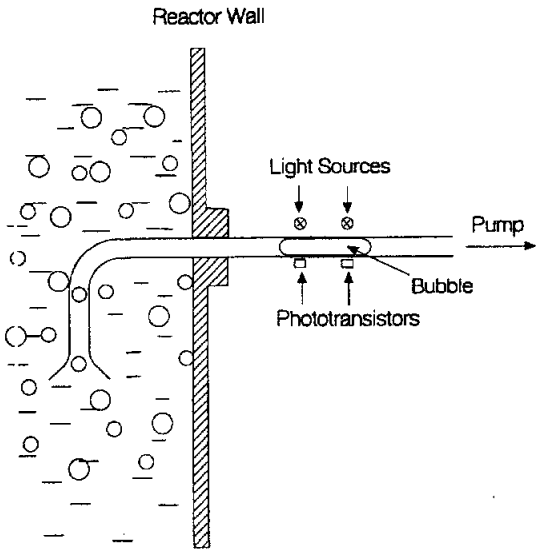


Figure 10: Measurement principle of the Ultrasound Doppler technique

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



Figuure 11: The isokinetic sampling probe

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

A rather simple method ı that has found wide acceptance for measurement of bubble velocities, and in turn their sizizes, is the dynamic gas disengagement technique. The method requires an accurate recordinng 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 existedd just before gas shut off. In its simplest form the technique assumes one or two dominantıt bubble sizes. The initial part of the disengagement profile is considered to be dictated solelely by large bubbles. The small bubbles disengage only after all of the large bubbles have l left the system. The disengagement profile (the height of the two phase dispersion as a funnction of time) has two distinct regions, corresponding to the two bubble sizes, which are fifitted with straight lines. A typical disengagement profile for a bimodal distribution is shovown in Fig. 12. The slope and intercepts of the straight lines are related to the holdup andd the rise velocities of the corresponding bubble sizes. If some relation (correlation) can be aassumed 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 annd the holdup corresponding to the large (transported holdup) and small bubbles (entrained l holdup) are estimated from :

Average gas holdup :

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

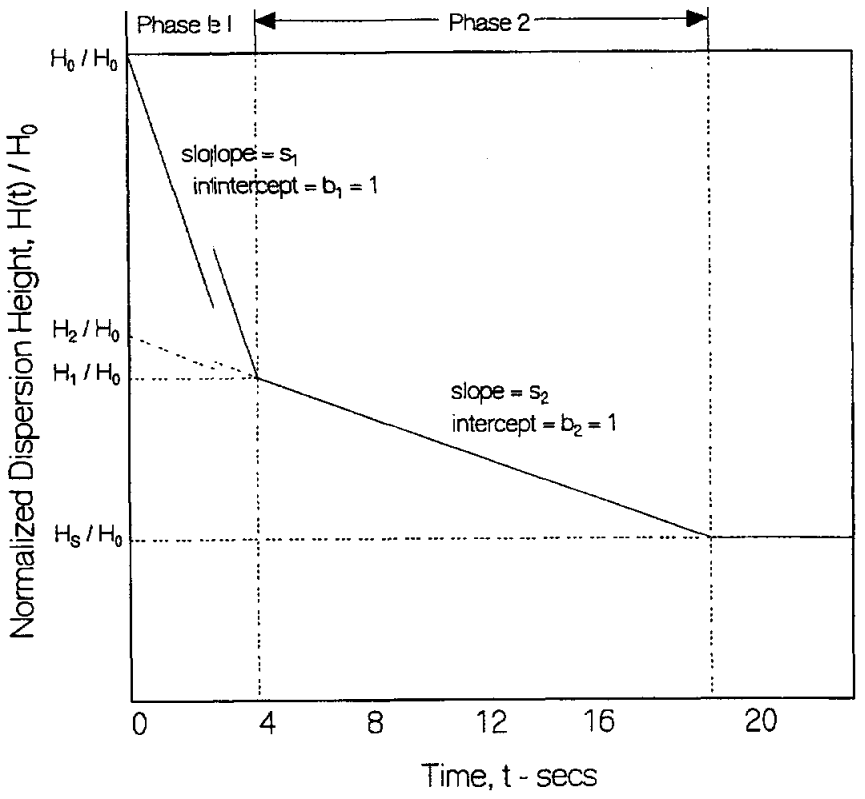


Figure 12: Typical disengagement profile for a bimodal distribution

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. 12.1. 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 nmethod after Sriram and Mann (1977) introduced it. Sasaki et. al (1986) have extended the ₂ technique to multi-modal bubble size distributions.

Recommendation : *It h has to be accepted that presently there are no techniques available for measurement of bubble chharacteristics in a reactor operating in the churn turbulent regime at high temperatures and prressure. The two point conductivity probe is not applicable under turbulent flow conditions. ₂ Although a multi-point probe can be used in a turbulent, two phase flow field, the bubble ₂ sizes need to be large. In a Fischer-Tropsch system the bubble sizes are expected to be smaall. Optical probes are not suitable either when the bubble sizes are small. Pulsed Ultrasounnd Doppler technique cannot be used at high voidages as well as at temperatures higher than about* $150^{\circ}C$. *The only method that can be adopted with ease for the Laporte reactor appeears to be the dynamic gas disengagement technique. Since the reactor walls are opaque reccording the drop rate of the free surface of the dispersion can be recorded using pressure tdaps provided along the reactor height or an automated movable* γ*-ray densitometer can be usused. Table 4 provides a comparison of the characteristics of the available methods for bubble ₂ size and velocity measurement.*

4 Measurementt of Liquid and Solid Velocities

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

The principle of the pitoot tube is very well known and is based on measuring the differences in the pressure at t the point of interest and the static pressure at the wall. The tube is inserted close to the ₚ point of interest in the flow such that its opening faces the flow. The velocity at the point is s 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 ₚ phase flow. For two phase flow situations the above relation is modified as (Euzen et. al. 1993) :

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

Table 4: Utility of Different Techniques for Bubble Size and Velocity Measurement

	Dual Resistivity Probe	Optical Probe	Ultrasound Doppler Method	Dynamic Gas Disengagement Method
Intrusiveness	4	4	5	1
Applicability in Aqueous Systems	Yes	Yes	Yes	Yes
Applicability in Hydrocarbon Systems	No	Yes	Yes	Yes
Applicability in 3-Phase systems	Yes	No	Yes	Yes
Applicability in corrosive, high pres./temp. systems	4	5	3	1
Accuracy	3	3	2	2
Ease of Use & Adaptability	3	3	4	1
Cost of System	2	3	4	1
Limitation	restricted to low flow rates	$\epsilon < 0.15$-0.20, small bubbles may not be detected	$\epsilon < 0.20$	global measurement

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.

where J is the phase coupling factor. If the two phase mixture can be considered as pseudohomogeneous, with the velocities of the two phases approximately equal, then J can be set to 1. Otherwise one needs to calculate J based on assumptions concerning the relative velocity between the phases. It is also necessary to know the local holdup at the same point measured at the same instant as the dynamic pressure ΔP. The complexity of data interpretation increases further in gas-liquid-solid systems. Nevertheless, the method has found wide acceptance in industrial circles, inspite of its limitations, but the interpretation is based on simplified treatment of Eq. 22 using assumptions that may not be justified in churn turbulent flows.

The turbine flow meter and its variants, the vane probe and the flywheel anemometer, are all based on measuring the rotational speed induced by the fluid in motion. The implicit assumption is that the momentum of the flowing liquid on the flow meter significantly exceeds that of the flowing gas. Similar to the pitot tube, the use of the method would be limited to low gas flow rates and complexity in the interpretation of measurement increases with the presence of a solid phase. Nottenkamper et. al (1983) have used the flywheel anemometer for liquid velocity measurements in an air-water bubble column.

In hot wire anemometry a small electrical resistance wire or film (supported on some base) is heated and exposed to the flow stream. Due to the removal of heat by the flowing fluid, the resistance changes. This change is a function of the flow velocity and the physical properties of the fluid. Thus, in single-phase flow, the heat flux is directly related to the velocity. The method can be implemented in one of two ways - either the constant resistance (or temperature) mode, or the variable resistance mode. In the constant resistance mode the resistance of the wire or film is held constant, so that the changes in the heat flux due to flow velocity are reflected as voltage changes in the anemometer circuit. In the variable resistance mode, the changes in the current in the circuit are measured. The main problem in using hot wire/film anemometry in two phase flows is the inability to recognize a phase change directly. This calls for some very intelligent signal processing. For example Resch and Leutheusser (1972) identified the phase change by comparing the peak to peak variation of the signal with a given threshold level. The difficulty here is in setting the correct threshold for identifying the phases and consequently there is some arbitrariness involved. The signal delivered by a hot film probe is very spiky owing to the abrupt change in the heat transfer coefficient at the crossing of the phases (Delhaye, 1969). This has been exploited by Michiyoshi and Serizawa (1986) who have used a method that is analogous to differential thresholding. The differentiated output signal indicates two distinct peaks corresponding to a bubble coming in contact with the sensor and leaving it. The entire period of time in between the two peaks (probe is in gas phase) is considered as a dead time and is eliminated from the liquid signal.