(ii) The Optical Probe Methods

Procedures based on principles of optics have been developed and applied from time to time for the measurement of size and velocity of bubbles in two and three phase systems. In general, in such techniques a suitable light source (laser or tungsten filament lamp) sends a collimated beam of light through the dispersion and the transmitted and/or scattered light is analysed by a photocell or camera [51] or some electronic detector [52,53]. In another variant of this principle pioneered by Todtenhaupt [54] and further developed by Pilhofer and coworkers [55,56] a constant small sample stream is sucked from the gas-liquid dispersion through a glass capillary. In this process, the bubbles are therefore, transformed into slugs and are detected by two light barriers with the help of photoelectric cells. The two time intervals enable the determination of both the velocity and size of the bubbles. The former is calculated from the time interval between the corresponding signals of the two probe sensors while the latter is computed from the product of bubble rise velocity and the contact time of the bubble with one of the sensors. This method has been successfully employed by Weiland et al. [57], Keitel and Onken [58,59], and Greaves and Kobbacy [60].

An optical probe is sensitive to the changes in the refractive index of the surrounding medium and is very successfully employed to sense changes in the refractive index at its extremity. The latter is brought about as a result of the passage of an interface and consequently, the presence of a bubble is easily detected. By incorporating two or more probes in a compound-probe and in conjunction with logic circuitry, it is possible to measure bubble shapes, sizes and velocities. A distinct advantage of the optical probe lies in the fact that its operation is independent of the electrical properties of the medium surrounding the probe. Delhaye and

Jones [16] have reviewed the principle of operation and the various designs of optical probes which have been developed in relation to the analysis of two-phase gas-liquid flows. Three different configurations for the optical probes have been proposed and these are: glass-rod, fiber-bundle, and U-shaped-fiber systems. The operating principles of all these three different optical probe systems are described briefly in the following after Delhaye and Jones [16].

A glass-rod probe is typically made out of a 2mm diameter glass rod whose one end is reduced to about 0.3mm as shown in Figure 1. The tip of the glass rod is ground and polished to the shape of a right-angled cone. The other end of the glass rod is glued to a Y-shaped light guide. At one end of this guide, light is focused from an appropriate source while at the other end a light detector is placed such as a phototransistor and an amplifier circuit. The intensity of the light beam at the detector end of the light guide depends on the refractive index of the medium surrounding the glass rod tip and is governed by Snell's law. In relation to Figure 2, light traveling in a medium of refractive index n_o and incident on the interface at an angle i_o will be refracted in the medium of refractive index n, at an angle i such that

$$n \sin i = n_o \sin i_o$$

For a glass rod probe (n_o=1.62) with a total probe tip angle of 90° and light rays parallel to the axis (i_o=45°), light rays will be reflected back along the glass rod if $n<1.15$ and will be refracted and hence will exit from the glass rod if $n>1.15$. Several liquid-gas systems are possible for such a glass rod probe and probe tip configuration where the light beam will be refracted for $n=n_l>1.15$ and will be reflected back for $n=n_g<1.15$. n_l and n_g are the refractive index values of the liquid and gas phases of the two-phase system respectively.

A fiber-bundle optical probe is obtained by tying together several hundred of coated glass fibers in a bundle. A coated glass fiber, typical size of a 30μm diameter glass fiber, consists of a central core and an outer cladding, Figure 3. Due to the difference in the refractive indices between the core material (glass,n=1.62) and the cladding (n=1.52), total internal reflection takes place at the core-cladding interface for an angle of incidence greater than 69.7° instead of 38.1° if there is no cladding. As a result, the light loss for a coated glass fiber is considerably reduced. A typical design of such a probe is shown in Figure 4. One end of this bundle (0.5mm in diameter) is glued to a 0.5mm diameter 1mm long small glass rod coated with a glass of lower refractive index. The end of the glass rod is ground and polished. The two other ends of the fiber bundle are connected to a light source and a light detector respectively. The probe operates on the same principle as the glass-rod as shown in Figure 5. Depending on the value of the refractive index of the medium surrounding the glass rod, light will either emerge form the probe or will be reflected back as in the case of a glass rod probe.

The physical dimensions of the glass-rod and fiber bundle probes are of some concern being typically 0.3 and 0.5mm respectively as these can perturb the bubble movement and size. To overcome this shortcoming a relatively smaller U-shaped fiber probe is developed as shown in Figure 6. The probe consists of a single coated optical fiber, 40μm in diameter, and bent to a U-shaped structure. The entire fiber, except for the U-shaped bend, is enclosed in a protected 2mm diameter stainless steel tube. The so-called active tip of the probe has a characteristic size of about 0.1mm.

One end of the fiber receives focussed light from a suitable light source while at the other end is located a suitable sensitive light detector such as a phototransistor. Figure 7 shows the enlarged view of the probe tip and the light-beam transmission. As in the previous two types of probes, here also the phase detection at the probe tip is based on the principle of light refraction according to Snell's law. We will now review the individual efforts which have been undertaken from time to time to determine bubble sizes, size distribution and their velocities.

Calderbank and Pereira [61] developed a "dip-stick" of the glass-rod probe type mentioned above to detect changes in refractive index at its extremity. A minaturized version of this probe is shown in Figure 8, and was successfully used to detect the presence of a liquid or a gas phase at its tip. From one limb of its Y-shaped fiber optics light guide, light is conveyed to its extremity which is internally reflected back up the guide and sensed when its tip is in a medium of low refractive index (gas) or is lost in the medium if it is of high refractive index (liquid). This "dip-stick" was made by taking a rigid light guide of glass, typically 3mm in diameter, and drawing it out to produce a smaller rod of typically 0.2mm in diameter. The latter was about 12cm in length and its tip was ground to a point. If the tip was in a gas, light was strongly reflected back and was detected by a photo-detector at the end of the other leg of the Y-form guide. In liquids no light was reflected back from the probe tip. Transistor photo diodes were employed as detectors in which detector and amplifier were contained on a single chip. A standard comparator circuit was used to give an output of 4V on reflection and 0V in the dark. A light emitting diode gave visual indication of pulses and was very useful for trimming the comparator circuit. A step change in the reflected light was obtained on changing from gas to liquid or vice-versa and as a result the pulse duration on passage of a bubble was accurately measured. The direct analogue photocell output for a typical encounter between the probe and a bubble was first stored in computer memory and was then displayed. The signal rise-time was of the order of 0.5ms in a signal duration of about 100 times this period. The response time was found to be much sharper than that obtained for an electrical conductivity probe described later in this review.

A compound probe comprising of a set of five optical probes was used to sense the passage of those selected bubbles which strike the array coaxially. This enabled unambiguous measurement of the maximum bubble height, bubble shape and bubble velocity by means of an external discrimination circuit and accurate time base. The compound probe was an array of five sensors in which a leading probe was symmetrically surrounded by three identical probes as shown in Figure 9. A bubble was regarded as coaxial with the leading probe when it was later coincidentally sensed by the three upper probes. The time gap between "making" the leading and upper contacts and breaking the lower contact enabled determination of the bubble velocity and bubble height. The fifth probe was introduced to measure the position and height of a vertical cord at a known distance from the center line. This was then interpreted to establish the bubble shape, whenever required.

Pulses from the five channels were recorded on a transistor logic circuit which could discard noise from multiple bubble encounters with the compound probe through a series of discriminatory programmed operations of the data processing logic using a series of "gates". The make or break events at the five channels corresponding to five probes were continuously monitored and delay times measured on a high speed paper punch only for the desired correct sequence. The punched tape was interfaced to a regional

PDP/8 computer programmed to calculate the desired constants.

Abuaf et al. [62] developed a miniaturized optical probe with controlled tip geometry to determine unsteady local void fraction and interface velocities in liquid-vapor two-phase flows. The miniaturization of the probe is claimed to have minimized the disturbances caused by its presence to the flow field. Some pertinent probe construction details are being reproduced here. Two 125μm fibers were inserted into a 500μm outer diameter stainless steel tube. The two fibers were fused together at one end by means of a minitorch, forming a spherical bead. The fused end of the fibers was then pulled into the tube and epoxied in place. The fibers were separated at the opposite end and encased in two pieces of 250μm outer diameter stainless steel tubing as shown in Figure 10. For mechanical strength, the ends of the fibers and the bifurcation were epoxied. The fused tip of the probe containing the two fibers was ground and polished at a 45° angle with the fiber axes and this yielded an included angle of 90° at the finished probe tip. The two other ends of the fibers were ground and polished flat. One of them was placed in front of an incandescent light source and the other in front of a photodiode and an amplifier circuit with a design rise time of 20μs. The same was checked by placing a light-emitting diode in front of the probe tip. The hydrodynamic response of the probe to the passage of a bubble was investigated by means of a specially designed experimental arrangement. Oscillograms of the probe output during the passage of the bubble were analysed and it was found that the signal amplitude decreased with increasing bubble velocity for bubbles which were of the same size and hence void fraction. Probe response was examined in detail as a function of bubble velocity and it was concluded that the probe is capable of measuring the local interface velocity as well as the local void fraction.

Ishida and Tanaka [63] developed a probe design capable of detecting both bubbles and solid particles in three-phase systems. The designs of their probes are shown in Figure 11. Probes A and B consist of two fibers each, one of these two was used to send the light beam and the other for bringing out the reflected beam. For probe A this reflected light originates by reflection on the particle surface around the tip of the probe, while for probe B it constituted of the light reflected twice on the conical interface between the fiber glass and the fluid phase at the extremity of the probe as in the case of Abuaf et al. [62]. For probe A they used 180μm quartz fiber and the signals received were rather weak since the particles were quite dilutely distributed in the gas and liquid phases. This probe was also regarded as not being very appropriate for the detection of bubbles in a dispersed zone. Probes C and D were made from a single 350μm quartz fiber and were considered simple to fabricate in view of their simple shape. In these probes, the single fibers did both the functions of carrying in light and bringing out the reflected light. The end of probe C was cut flat and therefore only a part of the light sent through the fiber would reflect on this flat interface and returned through the fiber. The degree of reflection also depended significantly on the refractive index of the phase present around this flat end. Further, the light transmitted through this flat interface would be reflected back from the surface of the suspended solid particles. Hence single probes of type C could detect not only bubbles but also particles suspended in the liquid phase. The end of the single fiber probe D was made conical like in earlier investigations [62] to achieve total reflection. Both probes C and D were found adequate for detecting bubbles, but probe C only gave particle signals. This experimental effort also established that brittle optical fibers have enough mechanical strengh to maintain their integrity when exposed to the violent movement of solid particles.

Ishida et al. [64] developed a special probe design to measure the particle velocities, bubble sizes and bubble velocities at high temperatures in a three-dimensional gas fluidized bed. The cross-correlation method was used to establish the velociteis of particles in unsteady-state motion at a point in the bed. Quartz optic fibers were used and the probe design is shown in Figure 12 and is comprised of two parts A and B. The probe A was made of bundle of seven and probe B of three quartz optic fibers of 0.2mm diameter. A cross-sectional view of the two probes is also shown in this figure. In probe A. light was sent from the central fiber, 0, was reflected from the particle surface and was received by the peripheral fibers shown in the figure as 1 through 6. The velocity and direction of the particle flow were obtained by comparing the light signal received by fiber 1 with those received by fibers 2 through 6. The probe B was used to detect bubbles and sometimes particle velocity in the vertical direction. The bubble rise velocity was obtained by comparing the signals of the two probes A and B. Three kinds of particles, glass beads, alumina catalyst and sand particles were used in the experiments. The bubble diameter was computed from the knowledge of bubble velocity and the dwell time of the bubble being defined as the time period for which the bubble remained in contact with the tip of the optic probe. The probe design as well as the analysis techniques are directly applicable to slurry bubble columns.

Ishida and Hatano [65] employed a linear array of multifiber reflective probes to investigate the behavior of gas and solid particles around a single bubble rising in a three-dimensional incipiently fluidized bed as shown in

Figure 13. The linear array consisted of eight bundles, A1 through A7 and B. A3 was the main bundle and consisted of seven optical fibers of 0.2mm in diameter. As in the earlier design [64], its central fiber designated as 0 in the figure was the light projector and the peripheral fibers designated as 1 through 6 were receivers of light reflected from the surface of particles. This particular bundle, A3, was used continuously to determine the velocity and direction of the particle flow at its tip. The other six bundles arranged on the same plane were used to obtain bubble diameter and to judge the position of the bundle A3 relative to the center of the bubble. Bundle B was located at 20mm above the A3, and the signals from these two bundles were used to determine the bubble rise velocity and bubble height.

Bergougnou and coworkers developed a single U-shaped fiber probe to characterize bubble motion in three-phase fluidized beds. De Lasa et al. [66] employed a single core silica optical fiber of 400μm in diameter and bent it in a U-shape with a radius of approximately 0.5mm at the tip of the probe. For such a configuration the angle of incidence at the turning point has to be larger than the angle of total reflection for the fiber exposed to air and as such the source light would be conserved in the fiber. Further, the U bend must be curved in such a way that the radius is small enough to secure an angle of incidence at the turning point smaller than the angle of total reflection for the same fiber dipped in water. Thus, light will be totally or partially lost in water depending on the specific probe design and will be conserved when exposed to air. As a result, a significant difference in light intensity would occur at the detection end of the fiber each time that a gas bubble contacts the U-probe. The fiber was encased in a stainless steel tube so that only the tip of the U-bend was exposed to the bed. Four fiber probes were used, two of the probes were located vertically one above the other with a separation of 1.27cm. Two other probes were located at the same level as the upper one in a horizontal plane, one on either side with a separation distance of 1.27cm. A helium-neon laser beam was used as light source and it was focussed on one end of the fiber and was guided through the probe tip to the other end. The light variations at this point were monitored by a photo-detector. The analog signal from the photodector was first sent to an operational amplifier for impedance matching, to a high speed A/D convertor for digitizing and finally to a HP9826 microprocessor for storage and data analysis. The device successfully measured the bubble length, central bubble cord and bubble velocity in a two-dimensional three-phase fluidized bed using water, air and 335μm glass beads.

In another effort, Lee at al. [67] employed the same U-shaped fiber optic probes to examine bubble characteristics in a three-phase cylindrical fluidized bed. Five probe assembly was used, two of them were placed vertically with a separation distance of 0.95cm. Three probes were placed in the same horizontal plane as the upper probe in a symmetrical fashion so as to have a 120^0 circumferential separation. Each one of the U-shaped probes was specially designed to appropriately balance the light reflected and refracted when bubbles contacted the probes or when the probes were surrounded by the liquid-solid suspension. The probe assembly successfully measured the bubble characteristics.

In recentyears, considerable development at a rapid pace has taken place which will enable continuous monitoring on a TV screen, direct viewing and video recording of the bubble dynamics and particle motion in a multiphase reactor. A.O. Scientific Instruments Division of Warner Lambert

Technologies Inc., have introduced a new type of rigid fiber borescope, Models FB250 and FB550, adaptable to 35mm SLR or CCTV cameras for gas-solid systems. Brilliant illumination is provided by a battery operated halogen lamp and the unit is completely portable. The borescope has durable optics with flexible fiber optic image bundle in stainless steel shaft flexes to resist breakage. On the same lines, Diaguide Inc., of Orangeburg, New York, have come out with a quartz fiberscope which can record particles or bubbles in a three-phase reactor at temperatures up to about 1000K. Thus, the Diaguide high temperature fiberscope can record successfully the bubble and particle motion in a slurry column on a CCTV system comprising of a B and W camera, B and W monitor, proper lens mount and adaptor, and a VCR system. For illumination a 300W metal halide light source will be adequate even for optically opaque slurries.

(iii) The Electrical Conductivity Probe Methods

In connection with the determination of the local void fraction in two-phase flow systems, electrical conductivity probes or more commonly referred to as the electrical resistivity probes have been developed from time to time and an historical account may be found in a report by Nassos [68]. Here we will include only those works which have reported electrical conductivity probes which have been used in the determination of bubbles sizes in two or three phase systems. A general incentive to the development and adoption of electrical probes result from the fact that most liquid-solid dispersions are opaque to visible light, and even a beam of x-rays penetrates only to modest thickness and this fact has led to the wide spread use of such probes. Nassos [68] design of the probe is based on the probe developed by Neal [69] for the measurement of local void fractions in mercury-nitrogen flow. The difficulties arise because of the wetting of the probe by water and various refinements involving probe shapes, filming agents and a triggering circuit did not solve the problem and experimental values were found to be lower than those obtained by the use of gamma-ray-attenuation technique. This is attributed to the finite response time of the probe associated with the wetting of the tip.

The probe developed by Nassos [68] is sketched in Figure 14. It is made out of a 15.24cm long steel wire of 0.787mm in diameter bent at right angles at a distance of 31.75mm from one end. The tip of the shorter segment of the wire was filed to a point by means of an oil stone and emery paper. The longer wire segment was enclosed in a 10.16cm long stainless steel tubing of 3.175mm diameter but was insulated from it by Teflon spaghetti. The shorter wire segment was insulated by Krylon spray enamel. In order to ensure complete insulation, the bend was dipped in liquid paraffin and was then cooled. The probe tip was then carefully scratched to expose about 0.254mm of its length. In order to determine the fraction of time the probe tip was exposed to a gas, the probe signal was electronically integrated. Nassos and Bankoff [69] investigated an air-water flow system with such a probe. A battery and a resister in series with the probe were connected to the ground and a change in voltage was observed depending upon the nature of the interface (air or water) in contact with the probe.

Neal and Bankoff [70] designed an electrical resistivity probe, shown in Figure 15, and employed it to measure the local values of void fraction, bubble frequencies and local bubble size spectra in a mercury-nitrogen system. Analysis of the random output square wave signals in terms of autocorrelation functions and power density spectra [70-72] was developed to gain information about the structure of two-phase flows. The probe consisted of a 31.75mm long steel sewing needle welded to the end of a steel wire, 15.24cm long and 0.838mm in diameter. The steel wire was enclosed in a 7.62cm long stainless tube having a diameter of 3.175mm but insulated from it by means of a plastic sleeve. The short arm of the needle including the bend was insulated with a resi varnish. Only the tip of the needle was exposed. The probe was grounded through a 1.5V battery and a 10,000ohm resistor, as also the conducting liquid. This arrangement ensured that the circuit was closed when the needle tip was exposed t liquid but was open when gas was in contact with it. Such probes are, therefore, appropriate only for systems where the continuous phase has a high electrical conductivity and high surface energy. The latter causes only a poor wetting of the steel probe so that only a fast circuit is obtained.

Park et al. [73] employed an electroresistivity probe to investigate bubble frequency, volume fraction, size and size distribution, and velocity in an air-fluidized bed of conducting coke particles. The sketch of the probe is shown in Figure 16. It is comprised of two 1mm diameter Kovar (Co -Ni-Fe alloy) wires contained in a glass tube, 6mm in outer diameter, and were 85cm long. The two wires were insulated from each other except at the very tips which were aligned vertically one above the other and 9.5mm apart. The portions of the wires extending beyond the ends of the glass tube were insulated by spraying an insulating lacquer over them. The two wires of the probes were connected to two identical measuring circuits. A 4cm square sheet of silver shim material 0.5mm thick curved to fit snuggly against the lucite column wall acted as a common electrode for both the tips. A voltage drop fluctuating between 0V and a maximum value, adjusted to 6-7V, appeared across the sereis resistance of each circuit as the path between the tip and the wall electrode was opened and closed by bubble and dense phases respectively. These signals were recorded on an instrumentation tape recorder for later analysis on a hybrid computer.

Rigby et al. [74] employed an electroresistivity probe similar to that of Park et al. [73] to measure the local bubble properties in a three-phase fluidized bed comprised of air, water and solid particles (glass and sand). The probe design is shown in Figure 17. It consisted of two 0.5mm diameter chromel-alumel electrodes, aligned vertically with a separation of 8.5mm. These were positioned in a 6mm diameter glass tube assembly with a seal at one end of the glass tube. The electrodes were insulated except for a distance of 0.25mm from the tip where the insulation was scratched off. A separate measuring circuit was used for each electrode as in the previous work [73]. The wall electrode was comprised of strips of copper shim material 1.25cm wide and approximately 0.5mm thick cemented to the wall of the column. The output from each electrode was adjusted to give a voltage drop varying between 0 and IV as the gap between the tip and the wall electrode was opened and closed by the bubble and dense phase of the fluidized bed respectively. The output was recorded on a P.I. 6200 instrumentation tape recorder and was monitored continuously on a dual channel potentiometric recorder.

Darton and Harrison [75] have used the twin-probe technique to measure the bubble size and velocity in a three-phase fluidized bed. The schematic of the double-probe is shown in Figure 18. Tungsten wire of 0.5mm diameter was used as electrode and its tip was ground to a point and was insulated by a coat of an expoxy resin over its entire length except at the tip. They used two such double probes with tip separations of 8.6mm and 7.8mm. The tungsten wires were enclosed in an insulating glass sheath and were held rigidly in an epoxy resin mount. The electrodes were enclosed in a 3.2mm outer diameter stainless steel tube casing. A coaxial cable connected each tungsten electrode to a separate A. C. impedance bridge. The steel probe casing was earthed and acted as the common electrode. The bridges were powered by a single 16kHz oscillator. The output from each bridge was amplified and displayed on an oscilloscope which facilitated balancing the circuits with the probe located in the fluidized bed. Measurements revealed that the probe response time to the passage of an air-water interface was less than one period of the oscillator, or 62μs, and this was small compared to a typical pulse duration, 10ms. The output from each bridge was attenuated and recorded on 6mm magnetic tape at a speed of 7.62mm/s and was played back at a speed of 23.8mm/s. The play-back signal from each electrode was passed through a trigger circuit which suppressed any signal with an amplitude less than two-thirds of the off-balance voltage. This chopped off the noise caused by solid particles colliding on the electrode. The resultant rectangular wave activated a reed relay which opened and closed a 0-15V D.C. circuit. The D.C. signals were interfaced with an IBM 1620 digital computer which digitized and stored the probe signal. The estimated error in the measurement of bubble pulse duration was about 100μs.

The bubble velocity, U_b, and bubble cord length, l, were computed from signals such as shown in Figure 19. If t_1 and T_1 are the times at which the leading bubble surface strikes the lower and upper electrodes, and t_2 and T_2 are the times at which the trailing bubble surface strikes the lower and upper electrodes which are separated by a distance d. Then

$$U_b = d/\left(T_1 - t_1\right)$$

and

$$l = d\left(t_2 - t_1\right)/\left(T_1 - t_1\right)$$

Identification of the pulses on the two tracks which corresponded to the same bubble was accomplished by checks within the computer program analysing the digitized play-back record.

Burgess and Calderbank [76] developed a resistivity probe giving particular attention to the difficulty associated with the recording of the exact instant when the bubble arrives at the probe tip. In liquids the probe gets wet and the film drainage time could cause significant departure from a step voltage change. Further, they used an assembly of five probes and thereby could record only those bubbles where the bubble and probe axes of symmetry are coincident within fine limits. They refer to this probe assembly as a three-dimensional resistivity probe with five channels and used it successfully to send the bubble local interface approach angle as well as to measure bubble size and velocity. The discrimination logic allowed only those bubbles whose central axes were coincident with the probe axis to be analysed.

The engineering design features of the probe are shown in Figure 20. A nickel wire of diameter of 0.22mm and coated with polytetrafluoroethylene (PTFE) and enclosed in a hypodermic stainless steel tubing provided the basic element of the probe. The tip of the nickel wire was bared so as to enable the electrical contact to be made with the conducting liquid and PTFE coating being hydrophobic allowed rapid pulse fall times in liquids. The probe assembly was accomplished by symmetrically placing three probes (2,3 and 4) around the first probe (1) in a horizontal plane, a known distance d_p above the central plane and radially spaced from it a distance r_p apart. A fifth probe (5) was placed in the same horizontal plane as the central probe (1) but somewhat distant from it, x_p. The values of d_p and r_p were 3.57 ± 0.04mm and 1.52 ± 0.02mm respectively. The probe assembly or array was connected so that each probe formed part of an electrical resistivity circuit.

When the probe tip resided in a conducting liquid, the circuit was completed and current was drawn from an external D.C. power supply. A voltage was thus developed across a load resistor and was measured by the computer in digital form simultaneously for the five probes. An optical technique was used to align the probe elements initially and periodic checks were made during use with a travelling cathetometer. Further details of the measurements taken using this probe are given in a subsequent paper of Calderbank et al. [77].

Figure 21 is a sketch of the electrical resistivity probe employed by Serizawa et al. [78] to examine the turbulent structure of air-water bubbly flow. Its engineering design is shown in the figure and consisted of two stainless steel wire needles of 0.2mm diameter constituting the two sensors separated from each other by a distance of 5mm. The sensors were insulated from each other and from the sheath except for their tips by enamel coating and expoxy resin. The details of the stainless steel mount and casing are given in the figure together with the various dimensions. The bubble impaction rate was determined from the sensor located upstream of the probe. In determining the bubble velocity, the time lag between the two signals for the same bubble was established by two methods viz., the cross-correlation technique and the multichannel technique. The former method gives the average time lag of bubbles while the latter gives the spectrum of the time lag for each bubble. Herringe and Davis [79], used a somewhat similar probe made of stainless-steel needles with a 0.008mm tip radius. Epoxy insulation was applied to the entire needle and was allowed to run back during drying and thereby exposing a small tip area. As in other designs, the resistance between this insulated needle tip and the electrode from the supporting tube was used to detect the nature of the interface. Thang and Davis [80] used a similar probe as shown in Figure 22 to investigate air-water mixture flows through venturis. The needle tip had an average diameter of 12µm while the exposed sensing area had a diameter of about 50µm. The resistance between the needle tip and the stainless steel casing would indicate whether the probe tip is emmersed in air or in water phase. Lewis and Davidson [81] and Lewis et al. [82] also used a similar two electrode bubble detector in an air and water mixture flowing cocurrently upwards. They point out that the conductivity of tap water was enough for the probe to function. Their conductivity probe was made out of two stainless steel needles 315µm in diameter with their tips separated by a vertical distance of about 1.5mm. The needles were insulated with a PTFE-resin coating leaving exposed tips with a typical radius of 30µm and lengths of 25µm. The conductivity electrodes operated at a frequency of 10kHz.

Ueyama et al. [83] developed an electrical resistivity probe shown in Figure 23. It consisted of two platinum needles, 0.5mm in diameter, coated over their entire lengths except for the tips with an epoxy resin. The needle tips were positioned vertically one above the other with a separation of 4.3mm. A D.C. voltage was applied between the needles and a reference electrode made of a 3 x 3cm square platinum plate.

An electrical conductivity probe device has been developed by Smith and coworkers [84,85] and used extensively to measure local bubble size and velocity of the gas phase in a three-phase slurry column. The conductivity probe inserted into the slurry bubble column is shown in Figure 24. The twin-electrode conductivity probe consists of two Teflon-coated wires of 0.13mm diameter. The Teflon coating serves as a good moisture repellent, hydrophobic, surface for rapid shedding of the liquid by the bubbles and an electrical insulator. Chromel wire has proven to be a good compromise between strength and electrical conductivity in a slurry environment. A pair of wires are threaded through 3.2mm diameter tubing and a two-hole ceramic cylinder having an outside diameter of 1.6mm. The ceramic cylinder is bent perpendicular to the tubing and sealed to the tubing with epoxy to hold the wires in place and provide a water proof seal. One of the insulated wires extending from the epoxy seal is then bent in a J-shape such that the tip of the wire is perpendicular to the stainless steel tubing enclosing the insulated wires. In a similar manner, the other wire is bent approximately 1mm past the bend in the first wire and terminated approximately 3mm past the end of the first wire. The radial gap between wires avoids a liquid film buildup as a result of capillary attraction, and the vertical gap serves as a fixed reference for bubble travel after striking the upstream probe. The chromel wires are exposed at the tips of each wire with a scalpel to insure a minimal exposed area. A Conax fitting with Teflon seals is fitted over the tubing through a port in the column wall and facilitates the radial placement of the probe. The radial positioning of the probe is accomplished during the operation of the bubble column by loosening the Conax fitting and moving the probe to the desired position with the aid of a calibrated ruler and a reference point located outside of the column. The two chromel wires could be oriented in a horizontal configuration, if preferred, as against the vertical arrangement of Figure 24. The twin-electrode conductivity probes of the type shown in Figure 24, with thinner Teflon-coated chromel wires of diameter 0.076mm and with a vertical separation of 1mm have also been used by these authors [85-87] to examine the slurry bubble column operation.

The probe circuit consists of a power supply, probe, waveform recorder, Junction box, and double pole-double throw switch. The power supply (HARRISON 2102 A) is a variable D.C. supply nominally operated at 5V. Each electrode of the probe is in parallel with the power supply and waveform recorder. The waveform recorder (Biomation 2805M) measures and stores the electrical conductivity signals over a known time interval, and subsequently the stored information can be transferred to a computer, visual display, or chart. The junction box is used to select a particular probe from the multiple probes installed in the slurry bubble column. The double pole-double throw switch is used to reverse current occasionally to dispose of any charge that may be acquired on the probe tip.

The signal amplitude or intensity is obtained as a function of time from the probe measurements and can be related to the bubble characteristics. A computer program has been developed to read and interpret the data to obtain bubble velocity, bubble size and gas void fraction. In order to interpret the conductivity probe signals, the following computations are made. The slope of the signal intensity is computed continuously, and when the signal exceeds a threshold positive value, the start of a bubble signal is indicated and stored. The end of a bubble signal, corresponding to the bubble leaving the probe, is indicated and stored when the slope for two consecutive points changes from less than a threshold negative value to greater than a threshold negative value. The dwell time, τ, of a bubble corresponds to the duration of time in which the probe is immersed in the bubble. The lag time, Δt, between a pair of signals corresponding to the passage of a bubble is computed from the time interval during which the centroid of a pierced bubble travels from the upstream to the downstream probe. Let us indicate the coordinates associated with the downstream and upstream probes with the suffixes 1 and 2, respectively, and let us define the time, t, at which the signal intensity exceeds the slope threshold intensity as the instant at which a bubble is pierced by one of the two probes; then the following expression defines the lag time.

$$\Delta t = \left(t_2 - t_1\right) + \frac{1}{2}\left(\tau_2 - \tau_1\right)$$

The lag time, Δt, approaches the time interval for a bubble to be pierced by each probe as the dwell time of a bubble on each probe approaches the same value. The effect of taking the centroid of the pierced bubble as the reference frame for the computation of lag time is to average small deviations in dwell time due to the deflection or nonvertical travel of the bubble, and due to the offset of the top probe with respect to the bottom probe.

The matching of a signal pair representing a bubble passing through both probes requires several conditions to be satisfied. An error may result from the fact that a bubble pierced by the downstream probe is not always preceded by a bubble pierced by the upstream probe. A discussion of the scenarios for such an occurrence has been given by Serizawa et al. [78]. In one case, a bubble penetrated by the upstream probe may be deflected and not strike the downstream probe. In another case, a bubble pierced by the upstream probe may not be deflected, but before it can reach the downstream probe, another bubble that missed the upstream probe touches the downstream probe. In addition to the cases mentioned above, a slight deflection of a bubble striking the upstream probe may result in a different dwell time of the bubble on the downstream probe. Any combinations of the conditions mentioned above can occure simultaneously.

The ascending velocity, U_b, and length λ_b, of each bubble passing vertically upward through the column can then be calculated from the lag time, the dwell time, and the vertical gap (h) between the twin probes. Thus,

$$U_b = h/\Delta t$$

and

$\lambda_b = h\tau/\Delta t$

In order to avoid improper matching of a signal pair, three constraints are placed on the matching process. First, the dwell time of a pair of signal responses must be similar, less than 30% relative deviation. Secondly, the velocity of all bubbles must be greater than the bubble velocity associated with the smaller measured bubble length as calculated from Stokes Law. Finally, all the measured bubble velocities must be less than the velocity of a bubble slug bridging the column diameter.

Matsuura and Fan [88] designed a sturdy two-electrode resistivity probe to study the bubble properties of three-phase fluidized beds in which relatively large glass particles of diameter 3 and 6mm were used. Their probe design details are shown in Figure 25 and it consisted of two 0.4mm diameter stainless steel syringe needles coated with epoxy resin. The needle tips were exposed to the bed had a diameter of 0.2mm and the vertical separation between the two tips was 0.3mm. The needles were supported by glass and stainless steel tubings and the latter also served as the returning positive electrode.

The details of the analysis procedure to establish the various properties of bubbles from the probe records in regards to the equipment and the computer programs are not discussed in this report and may be found in some of the papers referenced above and in the works of Masson [89], Werther and Molerus [90], and Buchholz et al. [91]. In conclusion, we will point out to some of the investigations which have shed some light on the relative merits of these techniques discussed in this review for purposes of measuring bubble properties. Yamashita et al. [92], and Buchholz et al. [93] have compared the photographic and the two-electrode conductivity probe. Tsung [94] has presented the merits and demerits of the conductivity probe method in conjunction with the D.C., A.C. and R.F. power supply. Bergles [95] has presented a detailed examination of the various types of electrical probes used to investigate the two-phase flows.