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

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

$$U = \frac{f_D \lambda}{2\, sin 0.5\theta} \tag{23}$$

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

Tsuji and Morikawa (19992) have used LDV for the simultaneous measurement of the velocities of both phases in aan air-solid two phase flow in a horizontal pipe. Solid particle sizes were of the order of a mnillimeter to a hundred microns. The particles used for seeding the gaseous phase were muchh smaller. The intensity of the scattered signal from the large particles is stronger than fromn those used for seeding the air. The identification of the signals from these two kinds of particlcles was thus based on the amplitude of the signal. The difficulty is that the amplitude of the s signal obtained due to a particle that intersects the measuring volume partially is a source o of noise. However, most often the amplitudes for these partial

intersections are in between t the two extremes of the signal amplitudes corresponding to the solid phase particles and thee seed particles. Thus, only the signals corresponding to these two extremes are retained aand the rest are eliminated. This method is probably suitable for measuring the solids velclocity in a Fischer-Tropsch system with moderate (15 to 20 % by weight) solids loading. FFor larger particle sizes the Doppler burst drops out completely (at least in the forward scatttering mode) and hence LDV cannot be used to obtain the flow velocity of such solids.

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

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

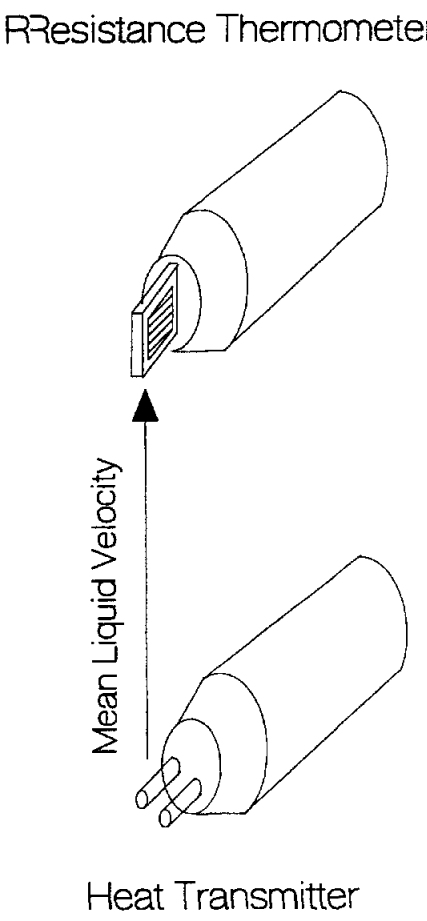

Figure 13: Arrarangement of probes for the heat pulse technique

The concentration of the partrticles used corresponds to volume fraction of the order of 10^{-8} to 10^{-5} and consequently doeoes not affect the fluid rheology. The velocity field in the plane of the imaged sheet is measurrred by recording a series of exposures and extracting the mean displacement of the particle i image between successive exposures. A problem arises if the first or second image of a paarticle is not recorded because its trajectory carries it out of the illuminated plane. Simililar to other optical techniques, PIV is restricted to relatively transparent media. Thus, thhe concentration of suspended solids (if one of the phases is a solid) has to be low. Even ifif one resorts to refractive index matching of the solid and the liquid phase, high concentratitions of the solids would mean a reduction in the transmission of the scattered light. The u use of PIV techniques to bubble columns and gas-liquid-solid fluidized beds has been advoocated by L. S. Fan and his group at the Ohio State University (Tzeng et. al. 1993).

A technique which is simililar to PIV is Laser Induced Photochemical Anemometry (LIPA)

in which the liquid and/or the solid phase is doped with photoexcitable chemicals which, upon excitation by a beam of laser, enables the identification of points in the flow. The laser highlighted regions are imaged at successive times, in a manner similar to PIV, and from their displacement by the flow, information concerning the velocity field can be inferred. Falco and Nocera (1991) contend that, unlike PIV, the technique does not have reflected light problems and is also relatively insensitive to refractive index mismatch. The system is applicable to studies of flows with suspended solids by using photoactive solid particles seeded into the flow. The LIFPA technique is rather new and is still undergoing development. It might be a method for measuring the solid phase velocities in very densely suspended flows. It has been demonstrated to measure the phase velocities in a liquid-solid flow with 33% solids loading by volume. However, it is a rather expensive method and also one needs to find specific chemicals for the flow velocities and fluids of interest. Very specific light sources are needed as well. Consequently, one cannot recommend it for use in a system such as the Laporte reactor. It is probably a good system to work with within the confines of a laboratory.

Finally, we review the technique that we work with in our Chemical Reaction Engineering Laboratory (CREL) at Washington University in St. Louis. Radioactive tracing has been used in industry for residence time distribution (RTD) measurements in reactors. The Computer Automated Radioactive Particle Tracking (CARPT) facility in our laboratory is an extension of that principle. A single radioactive particle of size and density designed to match the properties of the phase to be traced (solids in gas or liquid fluidized beds, liquid in gas-liquid bubble columns) is introduced into the flow. Instantaneous particle position is identified by the simultaneous monitoring of the radiation intensities received at a set of NaI detectors located strategically around the column. For a given operating condition of the flow, the particle motion is continuously tracked for long periods of time. Pre-established calibration curves for radiation intensity versus distance for each detector are then used in a linear regression scheme to determine the position of the particle at each sampling instant. Time differentiation of this position data yields instantaneous velocities and accelerations of the particle. To infer the flow field from this, the flow domain is divided into a set of compartments and the calculated instantaneous velocities are assigned to the compartment in which the particle resides at that instant of time. Each compartment ultimately has a large number of such assignments corresponding to the data collected over the period of investigation during which the system is operated at steady state. Invoking the ergodic hypothesis, an ensemble average of all such velocities in a compartment yields the average velocity for each of the compartments in the flow. The instantaneous and time averaged velocities can then be used to determine various turbulence parameters of interest. The hardware and software

developed for CARPT is desscribed by Devanathan (1991), Moslemian et. al. (1992) and Yang (1992). The accuracy c of the system is dependent on the accuracy of the calibration in the distance and intensity y relation for the detectors. This in turn is dependent on the accurate positioning of the trtracer at known locations within the reactor. The requirement of an accurate calibration is a a major drawback of the technique. In addition, it also appears that one needs to match the p particle density to the dynamic density of the dispersion rather than that of the fluid itself. LLike the LIPA it is also a method that can be implemented and used conveniently only withiin a laboratory or a pilot plant.

Some of the techniques mmentioned above for the measurement of liquid phase velocities can also be adopted for the nmeasurement of solid particle velocities. The laser velocimetry and particle image velocimetstry methods are applicable for solids velocity measurements in system with relatively small s solids loading, generally about 15 to 20 %. With higher solids concentration the attenuationn and scattering of the light beam or sheet leads to problems in the interpretation of the signaal. The radioactive particle tracking technique is ideally suited for the measurement of solidsls velocities.

Apart from these sophistiticated and powerful methods there few relatively simple techniques for measurement of soolids velocities. A technique that could possibly be used in an industrial system is the one baased on the intercorrelation of signals from two identical sensors that are placed a small distaance apart. The time delay in the measured quantity between the sensors represents the timme required for the information to propagate from one sensor to the other. If $s_1(t)$ is the meaasured signal at the first probe and $s_2(t + \tau)$ is the measured quantity at the downstream p probe at time $(t + \tau)$, the cross-correlation is defined as

$$C(\tau) = \frac{\int_0^T s_1(t)\, s_2(t + \tau)}{\int_0^T s_1^2(t)\, dt}$$

where the averaging is perforrmed over a sufficiently long period of time T. A plot of $C(\tau)$ with respect to τ provides the e most likely value of the transit time τ_m between the two probes. With the distance between thhe two sensors known the velocity can then be calculated.

For the application of thhis technique it is necessary that the sensors used are highly sensitive and rapid. Typicallyly used sensors are capacitance and optical probes, the principles of operation of both having beeen discussed earlier. With the capacitance probes the variation on the dielectric permittivity y is measured at two points slightly apart form each other, in the main flow direction. The signnals from the two probes are examined by a correlator. Optical fiber probes can similarly be e used but the application is limited to dilute systems, since in dense or opaque media the alabsorption of light disturbs the measurement and the light that

is reflected or backscattered l must be taken into account. In addition, these probes are very fragile. Most often the distaance between the sensors has to be optimized for a given range of velocities to be measured.l.

Recommendation : *OOnce again the choice of a method is rather difficult. It is our opinion that it is best to chaoose a couple of simple methods and obtain a measure of their performance in simpler laborratory conditions by comparing the results with those obtained by more accurate methods. Thisis would provide some estimate of the errors that might be involved when using a simpler techniique in the actual reactor. For example, we could compare the results from a pitot tube witith say that from hot wire anemometry in an air-water flow in the laboratory. Based on sonme theoretical assumptions for the flow conditions prevailing, it might be possible to estimatee the phase coupling factor required for the use of the pitot tube in three phase systems. Depeending on the flow conditions (such as solids loading, superficial gas velocity etc). it might eveen be possible to use hot film anemometry or the heat pulse probe of Lubbert. Considering the a difficulty involved in making velocity measurements in the actual system, it might be best to mnake measurements of the centerline velocities using a pitot tube that has been suitably calibraated for the presence of solids. Table 5 provides a comparison of the characteristics of the avvailaible methods for phase velocity measurement.*

5 Final Recommmendations and Remarks

The presently available instrtrumentation for measurement of the fluid dynamic parameters are by and large cumbersomne to be used in a slurry bubble column on the scale of a pilot plant. However, some gross l feaatures of the flow in such a system are still measurable. The measurement of the overall l gas holdup can be achieved by means of the bed expansion method and/or by pressure e drop measurement. The bed expansion can be conveniently measured by using the γ dennsitometer already in use at Laporte. It is also recommended to install a series of pressure tapps along the column height which would enable the measurement of the sectional holdup in thhe system. They can also be used in the estimation of bubble sizes by means of the dynammic gas disengagement technique. Installation of an Americium - 241 source in addition to t the Cesium - 137 source is also recommended to provide some chordal average measuremennts of the solids holdup by means of dual energy densitometry principles. Measurement of c centerline phase velocity can also be accomplished by means of a suitably calibrated pitot tuube. Tests on using the heat pulse probe of Lubbert to provide some measure of the velocity of the phases is also recommended.

Table 5: Utility of Different Techniques for Liquid Velocity Measurement

	Pitot Tube	Hot Wire/Film Anemometry	LDV	Heat Pulse Probe	PIV	CARPT
Intrusiveness	5	4	1	4	1	1
Applicability in Aqueous Systems	Yes	Yes	Yes	Yes	Yes	Yes
Applicability in Hydrocarbon Systems	Yes	Yes	Yes	Yes	Yes	Yes
Applicability in 3-Phase systems	4	2	3	3	3	4 (liquid phase) 1 (solid phase)
Applicability in corrosive, high pres./temp. systems	5	4	1	3	1	1
Accuracy	4	3	1	3	2	2
Ease of Use & Adaptability	1	2	2	2	5	5
Cost of System	1	2	3	2	5	5
Limitation	restricted to low flow rates	restricted to low flow rates	$\epsilon < 0.15$-0.20	indirect velocity measurement	$\epsilon < 0.2$ refractive index matching required	cumbersome procedure, but provides unique data

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.

6 Nomenclature

c	constant
C	cross-correlation
d	distance
D_c	column diameter
f	friction factor
f_D	Doppler shift frequency
g	acceleration due to gravity, m/s^2
h	axial coordinate
H_o	static height of the single (liquid) or two phase (liquid + solid) system
H_g	height of two or three phase dispersion in the column
I	transmitted intensity of radiation
I_o	intensity of radiation at source
J	two phase flow coupling parameter
k	dielectric constant
l	total path length of radiation in a mixture of phases, m
l_g	chord length of bubble
m	power law exponent in equation for radial variation of holdup
P	pressure
r	radial position
R	radius of test section
t	time
U_l	liquid superficial velocity
U	particle velocity
x	position
z	height of liquid in manometer

Greek Symbols

ϵ	gas holdup, volume fraction of the column occupied by gas
ϵ_s	solids holdup
$\bar{\epsilon}$	cross-sectional mean holdup
ϵ_c	void fraction at the center of the test section
κ	di-electric constant
λ	wavelength

μ	mass attenuation coefficient
ξ	dimensionless position
ρ_l	liquid or slurry density
rho_g	gas density
τ	time delay
τ_w	shear stress
θ	angle

Subscripts

g	gas phase
l	liquid phase
mt	empty test section
tp	two phase

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