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.

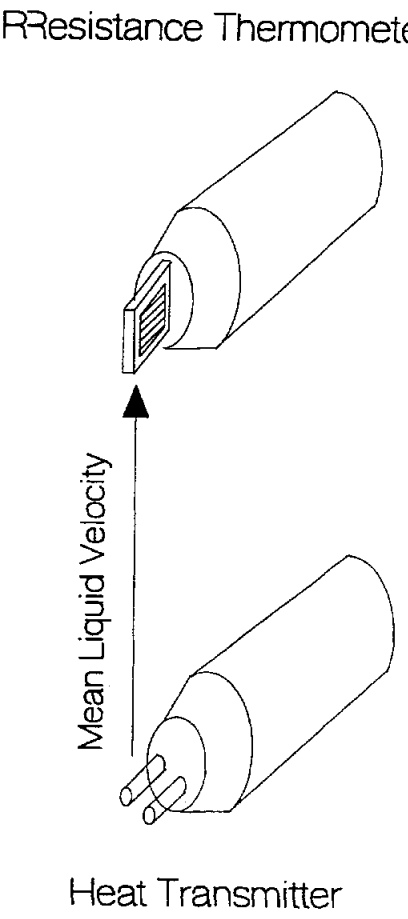

Figure 13: Arrrangement of probes for the heat pulse technique

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 measurnred 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 uuse 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 imagged 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 dessscribed 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 intensityy relation for the detectors. This in turn is dependent on the accurate positioning of the ttracer at known locations within the reactor. The requirement of an accurate calibration is aa 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 withinin 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 aabsorption 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 measurements 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 velocityy 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 Nomenclaturee

c	constant ;
C	cross-corrrelation
d	distance
D_c	column didiam.eter
f	friction fafactcr
f_D	Doppler s shift frequency
g	acceleratition due to gravity, m/s^2
h	axial coorrdir.ate
H_o	static heipight of the single (liquid) or
	two phasese (l:quid + solid) system
H_g	height of f two or three phase dispersion in the column
I	transmittted intensity of radiation
I_o	intensity r of radiation at source
J	two phasese flow coupling parameter
k	dielectric c constant
l	total pathh length of radiation in a mixture of phases, m
l_g	chord lenngth of bubble
m	power laww exponent in equation for radial variation of holdup
P	pressure
r	radial position
R	radius of f test section
t	time
U_l	liquid supperficial velocity
U	particle vvelocity
x	position
z	height of f liquid in manometer

Greek Symbols

ϵ	gas holduup, volume fraction of the column occupied by gas
ϵ_s	solids holdldup
$\overline{\epsilon}$	cross-sectctional mean holdup
ϵ_c	void fractction at the center of the test section
κ	di-electricic constant
λ	wavelengtgth

μ	mass atteenuation coefficient
ξ	dimensionhless position
ρ_l	liquid or slslurry density
rho_g	gas densitty
τ	time delayy
τ_w	shear stresess
θ	angle

Subscripts

g	gas phase e
l	liquid phaase
mt	empty testst section
tp	two phase e

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