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**NOVEL TECHNIQUES FOR SLURRY BUBBLE COLUMN
HYDRODYNAMICS**

**Annual Technical Progress Report No. 1 for the
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Novel Techniques for Slurry Bubble Column Hydrodynamics

First Annual Report for
DE FG 22 95 PC 95212
July 1, 1995 - June 30, 1996

ABSTRACT

The objective of this cooperative research effort between Washington University, Ohio State University and Exxon Research and Engineering Company is to improve the basis for scale-up and operation of slurry bubble column reactors for syngas conversion and other coal conversion processes by increased reliance on experimentally verified hydrodynamic models. The first year of this three year program was spent on developing and tuning the experimental tools that can provide accurate measurement of pertinent hydrodynamic quantities, such as velocity field and holdup distribution, for validation of hydrodynamic models. Advances made in preparing the unique Computer Automated Radioactive Particle Tracking (CARPT) technique for use in high pressure systems are described in this report. The work done on developing a reliable heat transfer coefficient measurement probe at operating conditions of interest is also described. Finally, the work done in preparing the Exxon pilot plant facilities for high pressure runs and pertinent hydrodynamic measurements is outlined together with preliminary studies of matching the fluid dynamics program predictions and data in a two dimensional column.

NOVEL TECHNIQUES FOR SLURRY BUBBLE COLUMN

HYDRODYNAMICS

DE FG 22-95 PC 95212

JOINT UNIVERSITY/INDUSTRY PROJECT

July 1, 1995 - June 30, 1998

First Annual Report

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EXECUTIVE SUMMARY

The objective of this cooperative research effort between Washington University, Ohio State University and Exxon Research and Engineering Company is to improve the basis for scale-up and operation of slurry bubble column reactors for syngas conversion and other coal conversion processes by increased reliance on experimentally verified hydrodynamic models. The emphasis during this first year of this three year project was placed on developing the experimental techniques that are capable of providing accurate measurements of hydrodynamic quantities such as velocities and holdup distribution at operating conditions of interest. Research progress has been made in the following areas:

At Washington University (WU) the unique Computer Aided Radioactive Particle Tracking (CARPT) technique was modified and improved. The technique is capable of providing solids (or liquid) velocities at high gas or solids holdup where all other methods fail. Wavelet filtering of particle position versus time data was implemented, and this improved by an order of magnitude the accuracy of the turbulence parameters that the technique can provide. A Monte Carlo based simulation was implemented for calculation of detector responses for any position of the tracer particle. Three dimensional maps for the inversion problem will be completed during the next phase of the project. This will allow accurate calibration and use of CARPT in high pressure systems. Data obtained with CARPT were compared to other techniques.

At Ohio State University (OSU) the limitations of the most powerful Particle Image Velocimetry (PIV) technique were explored and it was found that the technique has the potential of providing the full velocity and holdup field up to a 4" diameter column at high gas superficial velocity and holdup. Experiments are currently underway to compare PIV results in such a column to the previously obtained CARPT data. A new and useful heat transfer coefficient probe was developed at OSU and its capabilities are described in this report.

At Exxon Research and Engineering preparations were made for making the high pressure 6" diameter bubble column available for CARPT and other measurements. Necessary modifications to the column are being made. Jointly with WU needed tracer particle strength was determined and a device for calibration was designed. In addition, CFDLIB codes for hydrodynamic modeling have been installed and a preliminary case study of a two dimensional column was conducted. It is shown that experimental time averaged velocity profiles can be matched by the model with proper selection of closure parameters.

NOVEL TECHNIQUES FOR SLURRY BUBBLE COLUMN HYDRODYNAMICS

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I. REVIEW OF OBJECTIVES

The overall objective of this cooperative university (Washington University and Ohio State University) - Industry (Exxon Research and Engineering) research is to improve the basis for scale-up and operation of slurry bubble column reactors (SBCRs) by an increased reliance on phenomenologically or fundamentally based hydrodynamic models which are experimentally verified. This research complements the work in progress related to the LaPorte Advanced Fuels Demonstration Unit (AFDU) operated by Air Products with Department of Energy funding. The research under the present grant focuses at providing experimental tools for measurement of important fluid dynamic quantities at high pressure, high temperature operation.

Specifically the following goals have been set for this three year project.

- Task 1. Develop computerized mathematical procedure (based on physics of radiation and Monte Carlo calculations) for calibration of the Computer Automated Radioactive Particle Tracking Technique (CARPT) that will eliminate the currently lengthy in-situ calibration and allow the technique to be used in the field on high pressure units. Specifically, plan the use of CARPT on a high pressure bubble column at Exxon Florham Park pilot plant facility.
- Task 2. Improve the accuracy of the CARPT technique and compare the velocities obtained by CARPT in certain region of the column to those determined by the Heat Transfer Probe and Particle Image Velocimetry (PIV).
- Task 3. Develop local probes for assessing velocities, holdups and heat transfer coefficients in commercial bubble column reactors.
- Task 4. Collect velocity and voidage profile data in gas-liquid and gas-liquid-solid systems at different solids loadings and at close to atmospheric pressure.
- Task 5. Use state-of-the-art hydrodynamic models and codes to predict velocity and holdup fields under conditions studied experimentally. Search for most suitable constitutive forms (e.g., lift, drag, turbulence closure models, etc.) to reach agreement between calculated and experimentally observed values. Try to assess the effect of elevated operating pressure on various constitutive forms.
- Task 6. Collect the data in a high pressure 6" diameter bubble column at Exxon Research and Engineering and compare to model predictions. Also collect high pressure PIV data in slurry systems at Ohio State University. Refine models if needed.

II. SUMMARY OF RESEARCH ACCOMPLISHMENTS

Here we briefly summarize the activities conducted as part of this project at Washington University, Ohio State University and Exxon Research and Engineering. In the subsequent sections a more detailed report is provided from each of the above three organizations, which are involved in this cooperative research effort, only for the work that has been completed. Work in progress will be reported on in detail upon completion.

The activities at Washington University were on improving the accuracy of the CARPT technique (Task 2) and developing a mathematical Monte Carlo method for CARPT calibration (Task 1). In Section III of this report we show that CARPT accuracy for obtaining turbulence data has been remarkably improved via wavelet filtering of the particle position - time data. Now CARPT provides not only accurate ensemble averaged quantities but also fluctuating quantities. Preliminary comparison of CARPT data with other techniques is also shown. Data has been collected in air-water system (Task 3) in different columns and 4" diameter column data has been selected for comparison with PIV. These PIV experiments are now in progress at OSU.

The activities at Ohio State University included making PIV operable in 3 dimensional columns and testing the upper limits on column diameter for which the technique is still reliable. A set of gas superficial velocities studied by CARPT in a 4" column are now being investigated by PIV at OSU. Section IV of this report is focused on the successful development of a heat transfer probe to be used in the pilot plant and commercial reactor.

The activities at Exxon Research and Engineering involved the preparations for high pressure measurements in a pilot plant 6" diameter column and computational fluid dynamics.

The 6" diameter, high pressure, slurry bubble column is being prepared at Exxon for the experimental program to obtain detailed hydrodynamic measurement. The unit is equipped with basic measurements, such as differential pressure along the column, sampling ports and optical windows. Additional measurements, such as, void fraction, liquid velocity, and tracer testing are planned along with the CARPT measurement to cross check all measurement techniques under representative pilot plant reactor conditions.

A heat-pulsed-anemometer manufactured by Professor Lubbert of Hannover University and purchased by Exxon was sent to the Ohio State University to test against PIV technique under low gas holdup ($< 15\%$) conditions for velocity and local mixing of the liquid phase. Three gas holdup measurement probes and one heat transfer probe which will be suitable for our 6" unit use are under construction by the Ohio State University. These probes will be tested against PIV measurements with or without the presence of solid. An Extrel MS250 mass spectrometry was purchased and will be used for both gas and liquid tracer experiment.

The mechanical drawing of the high pressure 6" diameter slurry bubble column was sent by Exxon to Washington University for review to prepare it for the CARPT experiment. The nozzles and flange on the unit could potentially affect the accuracy of the CARPT data. It will be evaluated by Washington University if any modifications are necessary.

Jointly with Washington University a device for calibrating the Exxon column for CARPT was designed, and source strength for the CARPT particle was estimated and radioactive safety procedures established (see Section V).

In the area of computational fluid dynamic modeling work was pursued jointly between Exxon and Washington University. The Los Alamos CFDLIB code was installed on the Exxon SGI server. A case study from two dimensional column (described in Section V) was computed.

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Section III: REPORT FROM WASHINGTON UNIVERSITY

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1 Introduction

The main goal of the study conducted at the Chemical Reaction Engineering Laboratory (CREL) at Washington University as part of this DOE grant is to improve the basis of scale-up and operation of slurry bubble column reactors (SBCR) by an increased reliance on phenomenologically or fundamentally based hydrodynamic models which are experimentally verified.

For the first year the envisioned objectives were :

- Complete the improvements in Computer Automated Radioactive Particle Tracking and Computed Tomography (CARPT/CT), and develop the Monte Carlo based calibration for the CARPT technique.
- Complete studies with air-water in a single diameter column and compare the results for velocity obtained by CARPT to those obtained by other techniques such as thermal probe and Particle Image velocimetry (PIV).

Improvements in CARPT technique encompasses two tasks. The first one involves the development of a filtering procedure to eliminate the fluctuating effects of the statistical nature of the emissions from the tracer particle. Although the mean quantities estimated from the CARPT measurements are unaffected by the fluctuations, accurate estimation of the turbulence and backmixing parameters requires that the intrinsic noise caused by the fluctuations in emissions from the tracer be removed by some filtering procedure.

The other improvement in the CARPT technique is associated with the calibration procedure required for locating the particle position from the intensity of radiation measured by several detectors. In the current calibration procedure it is necessary to position the tracer particle at a few hundred known locations inside the reactor and acquire the intensity data from several detectors strategically positioned around the reactor. These measurements are then used to develop an intensity versus distance relationship for all the detectors used. This is an extremely laborious process and often difficult to perform in reactors with opaque walls. Moreover, the calibration needs to be done in-situ. In addition, the accuracy of the calibration and the subsequent location of the tracer depends on the accuracy of positioning of the tracer at a given location. In order to avoid this extensive and cumbersome calibration process one of the objectives is to develop a phenomenological approach to account for geometry and the attenuation properties of the flowing phases on the radiation measurement process. The modeling of the emission of radiation, the attenuation by the flowing phases as well as the column wall and the subsequent detection by the scintillation detectors is accomplished by the Monte Carlo method.

In this report we first present a brief account of the progress made in each of the above mentioned research areas.

2 Filtering CARPT Data Using Wavelet Based Technique

Owing to the quantized nature of the γ photons, the intensity of radiation exhibits continuous fluctuations in time. The emission of γ rays follows a Gaussian distribution (with mean, n_c , and standard deviation, $\sqrt{n_c}$). This is manifested as white noise in the data and results in the generation of "spurious velocities", i.e., non-zero velocities for a physically stationary particle. Consequently, the instantaneous velocities measured have partial contribution from the fluctuations in the source particle emission. Time (ensemble) averaging of the instantaneous velocities in each compartment eliminates these source fluctuations (since the fluctuations have a Gaussian distribution with zero mean). This is reflected in the negligible mean spurious velocities calculated, which are in the order of 0.1 cm/sec (For comparison, the actual monitored velocities are 10 cm/sec to 50 cm/sec). However, the fluctuating velocities and root mean square fluctuating velocities measured, are resultant of the fluctuations due to the turbulent flow field and the spurious velocities. This causes an over-estimation of the turbulence quantities that are measured. Therefore it is necessary to eliminate or reduce to the best possible extent, the spurious fluctuations in the particle position data in order to obtain more accurate estimates of the turbulence parameters.

2.1 Objectives

Since the tracer particle is of finite size ($\sim 2\text{mm}$), it follows eddies only up to a certain frequency range corresponding to the length scale of the size of the particle. An estimate of this frequency limit can be calculated on the basis of single phase flow turbulence theory (Hinze 1959). It is found to be in the range $10 - 35 \text{ Hz}$, depending on the mean flow conditions, which vary within the column.

Fourier domain filtering was first attempted using a third order low pass Butterworth filter with a cut-off frequency of 10 Hz . It can be observed from Figure 1a (note the highlighted regions enclosed in boxes) that the resulting filtered signal is unable to capture the sharp peaks present in the original signal. As a result, these sharp changes that characterize the flow are removed as noise, as can be seen in the bottom part of Figure 1a. This shows strong peaks in the filtered noise which are not characteristic of the white noise that is known to cloud the data. If the cut-off frequency for the filter is increased, this results in residual

high frequency components of the white noise in the signal. This problem arises due to the inherent non-stationary nature of the signal obtained from CARPT measurements describing the turbulence in the system, which has localized frequency characteristics. This renders a low pass filter unsuitable for filtering CARPT data.

Wavelet analysis, which is a time-frequency based method is a suitable alternative and has the distinct advantage over Fourier transform techniques, as it can be used to analyze non-stationary data. This is illustrated in Figure 1b where the filtered noise, using a wavelet based technique resembles the white noise present in the intensity data.

Figure 1: Comparison of Fourier Transform and Wavelet Analysis Techniques for Filtering CARPT Data

The objective of this work is to apply the wavelet packet algorithm for filtering CARPT data. To demonstrate its suitability in this regard, an experiment is conducted with a controlled motion of the radioactive tracer particle. This enables *a priori* knowledge of the trajectory of the particle and provides a reference against which the results from CARPT experiments subject to wavelet packet filtering can be compared. A quantitative estimate of the errors involved in the estimation of the particle position, as well as the extent to which the intrinsic noise in the data is removed can therefore be arrived at. Thereafter the technique is applied to data from bubble column experiments.

2.2 Wavelet Analysis

The wavelet transform of a signal refers to the projection of the signal onto local, re-scalable functions called wavelets. These functions have prescribed smoothness, are well localized in time and frequency and form a well-behaved basis (Daubechies 1988). Wavelets, $\psi_{a,b}(t)$, of constant shape are generated by the dilation and translation of a prototype or mother wavelet $\psi(t)$. Therefore each wavelet has a specific time-frequency localization. Wavelets of high frequency are narrow (well localized) in time, while wavelets of low frequency are broad in time. As a result wavelets are able to capture both short lived high frequency phenomena as well as longlived low frequency phenomena. This enables them to work well for filtering non-stationary signals clouded with white noise.

In what follows we focus on those aspects of wavelet analysis that are used in this work, introducing with the underlying basic concepts, discrete wavelet transforms (DWT) and wavelet packet decomposition (WPD). DWT involve the projection of a data set, $f(t)$, onto discrete wavelets to give discrete wavelet coefficients. This is represented as :

$$\langle f, \psi_{m,n} \rangle = 2^{-m/2} \int_{-\infty}^{\infty} f(t) \psi(2^{-m}t - n) dt \quad (1)$$

where m and n represent the discretized dilation and translation parameters respectively. DWT is a special case of wavelet packet decomposition (WPD). In WPD, a library of wavelet packets are used, from which a variety of bases can be extracted to represent the signal. The construction of wavelet packets can be represented in a hierarchy as shown in Figure 2, where two filters, H , a low-pass filter and G , a high-pass filter, are used to generate the entire library of wavelet packets using a recursive scheme (Wickerhauser 1994). The nature of the wavelet packets generated depends on H and G . There are a variety of wavelets available, of which Daubechies' (1988) orthonormal, compactly supported wavelets are most popular.

The decomposition of the signal onto these wavelet packets constitutes WPD. As in the case of DWT, the wavelet packet coefficients are given by :

$$\lambda_{s,f,p} = \langle f, \psi_{s,f,p} \rangle = 2^{-s/2} \int_{-\infty}^{\infty} f(t) \psi_f(p - 2^{-s}t) dt \quad (2)$$

where λ is the wavelet packet coefficient. The resulting library of wavelet packet coefficients contains redundant information, from which a best basis is chosen by minimizing the entropy of the coefficients (Coifman and Wickerhauser, 1992). The more the randomness in the signal, the greater its entropy, and therefore the greater the number of coefficients required to represent the signal accurately which means larger information cost.

White noise has very poor time-frequency localization, or in other words is incoherent.

Figure 2: Hierarchy of Wavelet Packets

Therefore, as mentioned above, a large number of wavelet packet coefficients are needed to represent it. We are interested in the application of the best basis algorithm in denoising noisy signals. The idea here is to extract coherent parts present in the signal (signal features with good time-frequency localization), using the Matching Pursuit Algorithm (Mallat and Zhong 1992). In the Matching Pursuit Algorithm the signal is decomposed into a coherent part and an incoherent part. The coherent part is extracted by retaining a fraction of the signal energy in the form of a few large wavelet packet coefficients. The remaining incoherent part is decomposed several times to extract all the coherent parts remaining in it. All the individual coherent parts, thus extracted, are superimposed to give the filtered signal. The incoherent part remaining at the end is rejected as noise. The advantage of the algorithm is that exact characterization of the process is not required. In the present work, we essentially adopt a modification of the matching pursuit algorithm. If the signal to noise ratio is high, i.e., the energy level of the noise in the signal is low, a suitable threshold for the energy is set, by which a large number of coefficients with the lowest energy, which are known to represent the randomness due to the noise, are set to zero, thereby removing the noise.

2.3 Wavelet Packet Filtering of CARPT Experimental Data

The white noise present in the radiation intensity data, is transmitted to the estimated position of the particle in cartesian coordinates, $P(x, y, z)$. It is found that the noise in each coordinate is white noise uncorrelated with each other. Filtering of the radiation intensity and subsequent estimation of the particle positions yields results similar to those generated by direct filtering or denoising of the particle positions along each coordinate. The latter approach of filtering the position data is more efficient in both time and computing resources. Therefore the filtering method will be applied directly to the x, y, z position data.

Wavelet packet decomposition using Daubechies' orthonormal, nearly symmetric wavelets is employed for this analysis. The algorithm for analysis and filtering of the data is explained below. The original signal is divided into data sets of length $N = 2^L$; $L = 10$ to 13. Given a data set of length N sampled at constant frequency, the wavelet packet decomposition

and subsequently the best basis representation is obtained. The wavelet packet coefficients (wpc) in the chosen basis are arranged in descending order of energy (energy $E_{wpc} = wpc^2$), simultaneously keeping tag of the position of each coefficient. The first few significant coefficients correspond to the coherent part of the signal while the remaining weak coefficients depict the noise. The coherent part is extracted by retaining the first few largest wavelet packet coefficients that possess an energy ($E_c = \epsilon E_S = \sum_{i=1}^L wpc^2$) equivalent to a fraction ϵ of the total signal energy ($E_S = \sum_{i=1}^N wpc^2$). These coefficients are then re-ordered and reconstructed to yield the filtered signal. The weak coefficients (incoherent part) that remain are re-ordered and reconstructed to give the noise filtered. The tuning parameter in this algorithm is the energy threshold ϵ . This parameter is evaluated by conducting trial runs for a few data sets in the signal. The value of ϵ essentially depends on the results of calibration for a given experiment. This affects the magnitude of the spurious fluctuations in the position data, which is determined from the data for a stationary particle. Characteristics of white noise, such as the autocorrelation coefficient and power spectral density, are used as a check to select a proper threshold to ensure that no coherent part of the signal is removed. Experiments show that the energy threshold is generally around 95 – 98% of the total signal energy. It is found that the results are insensitive to minor variations in the threshold value. Filtering using the above algorithm ensures maximum extent of reduction of the noise in the data, resulting in a smoother version of the signal and retains the sharp features arising from the nature of the flow in the system.

The algorithm is implemented using the mathematical package MATLAB. The wavelet toolbox¹ provides the necessary subroutines for construction of wavelets, WPD and reconstruction of the signal.

In order to verify the applicability and effectiveness of the algorithm for filtering noise from the data, we test the algorithm with data collected from experiments for a controlled motion of the tracer particle.

2.4 Experimental Setup

The experimental setup consists of two motors, a screw conveyor and a plate as shown in Figure 3. Motor I is secured at the bottom of the structure and is geared to a screw conveyor that is positioned vertically. The screw conveyor supports a vertical frame on top of which the plate is mounted. The shaft of motor II, which is fixed to the top of the plate, is connected to a smooth, circular disc. The radioactive particle to be tracked is fixed to the tip of a thin plexiglas rod attached to the disc. Operation of motor II causes the particle to

¹wavbox is the wavelet toolbox written by Taswell for a MATLAB environment

move in a circular motion. The maximum frequency of motion is 3 Hz. The distance of the particle from the center of the circle varies from 7 to 8 cm. Simultaneously motor I causes the plate held to the frame to move vertically in “up and down” motion (with frequencies of the order of 0.1 Hz). The maximum vertical distance traversed by the particle is 6.4 cm. By this arrangement the particle is made to move in a spiraling 3D motion, with high (3 Hz) and low (0.2 Hz) frequencies. The two motors are driven by microprocessors, which are interfaced with a personal computer. This arrangement ensures the precision with which the particle moves. A trolley system with guiding wheels provided for guiding the frame helps in minimizing the vibration of the setup. The entire structure is supported on the plenum centered between the detector supports (not shown in figure). Sixteen strategically positioned detectors are used for detecting the γ radiation. Calibration is first done using various particle positions that cover the entire range of experimental runs. Subsequently the experimental runs are performed. In each run, the speed of the two motors is varied, thereby varying the velocity of the particle. Eight such runs are performed.

Figure 3: Experimental Setup for Controlled Motion of Particle

2.5 Results and Discussion

The details of the experimental runs carried out are shown in Table 1. Motor I moves the particle in a linear vertical motion, i.e. along the z axis in cartesian coordinates. Motor II moves the particle in a horizontal two dimensional circular trajectory, i.e. in a $x - y$ plane. A parametric representation of the trajectory of the tracer particle is given as:

$$x_t = x_c + r_p \cos(\theta_0 \frac{\pi}{180}) + r_p \cos(2\pi\omega_2 t); \quad y_t = y_c + r_p \sin(\theta_0 \frac{\pi}{180}) + r_p \sin(2\pi\omega_2 t); \quad z_t = z_0 + \omega_1 t \quad (3)$$

where x_c and y_c are biases in position due to experimental constraints. r_p is the radius of curvature which the particle traverses. θ_0 is the initial angular position of the particle. ω_2 is the frequency of rotation of motor I. ω_1 gives the displacement of the particle per unit time and is related to the rpm of motor I. Motor I is programmed to move 800 steps in the clockwise direction (125 steps in the clockwise direction is equivalent to 1 cm) and 800 steps in the counterclockwise direction, repeating this periodic motion several times. This induces a frequency of about 0.1 Hz in the z direction of motion. Based on the trajectories, the existing Lagrangian velocities v_{x_i} , v_{y_i} and v_{z_i} are calculated.

Table 1. Details of Experimental Runs

Run No.	r_p cm	θ_0 , deg	ω_1 cm/sec	z_0 cm	z_f cm	ω_2 1/sec
Run 1	6.964	315	2.0	112.21	118.61	2.75
Run 2	6.964	315	2.0	112.21	118.61	1.75
Run 3	7.180	315	2.0	112.21	118.61	1.00
Run 4	7.180	315	2.0	112.21	118.61	2.00
Run 5	7.180	315	2.0	112.21	118.61	2.75
Run 6	7.989	315	2.0	112.21	118.61	2.75
Run 7	7.989	315	2.0	112.21	118.61	1.50
Run 8	7.989	270	2.0	112.81	119.41	0.00

The instantaneous position data x_p , y_p and z_p resulting from CARPT experiments for the controlled motion of the particle are subject to wavelet packet filtering as discussed in the previous section, yielding filtered results x_f , y_f and z_f . Thereby the particle velocities from CARPT measurements (sampling frequency is 50 Hz) before filtering, v_{x_p} , v_{y_p} and v_{z_p} , and after filtering, v_{x_f} , v_{y_f} v_{z_f} , are obtained.

The results are analysed by comparing the magnitude of the error in positions and velocities in each direction. For this purpose the root mean square (rms) error in position and velocity are used. Figure 4a shows the actual trajectory y_t for a period of 10 secs, for Run 5 reported in Table 1. Figure 4b is a comparison of the error in estimating the successive y positions of the particle. Figure 5 show the velocity of the particle along the y axis with the errors before and after filtering. A summary of the results for the entire set of runs is presented in Table 2 which reports the errors in position x , y and z , and spurious rms velocities, before and after filtering. It is evident by examining the results, that there is significant improvement in the accuracy of estimation of both the positions and velocities of

the moving particle. The residual error (spurious rms velocities) after filtering the data is 2-5 cm/sec. There is an average of 75% reduction in the level of noise in the data. With regard to the magnitude of the rms fluctuating velocities of the liquid in bubble columns, which are an order of magnitude higher, the reduction in error is considered substantial.

Table 2. Errors in Estimation of Particle Position (cm) and Velocity (cm/sec)

Run No.	Direction	error in position, cm				error in velocity, cm/sec	
		Before Filtering		After Filtering		Before filtering	After Filtering
		rms	min/max	rms	min/max	rms	rms
Run 1	x	0.32	-1.17,1.12	0.19	-0.7,0.6	20.5	4.16
	y	0.36	-.15, 1.2	0.26	-0.75, 0.8	20.01	4.66
	z	0.49	-1.7,1.4	0.25	-0.7,0.74	30.36	1.68
Run 2	x	0.30	-1.23, 1.25	0.2	-0.76, 0.64	21.0	5.6
	y	0.33	-1.43, 1.34	0.22	-0.79, 0.86	19.4	5.7
	z	0.49	-1.6,1.6	0.2	-0.67,0.8	29.6	1.6
Run 3	x	0.32	-1.16,1.13	0.21	-0.7,0.9	19.3	3.2
	y	0.31	-1.2,1.2	0.21	-0.85,0.8	18.0	3.6
	z	0.47	-1.5, 1.75	0.17	-0.9, 0.6	28.9	1.34
Run 4	x	0.32	-1.08,1.12	0.22	-0.75,0.86	19.5	4.8
	y	0.32	-1.5,1.25	0.23	-0.7,0.75	19.0	4.5
	z	0.46	-1.4,1.4	0.21	-0.65,0.61	29.0	1.38
Run 5	x	0.3	-1.11,1.32	0.19	-0.9,0.66	20.2	5.4
	y	0.29	-0.89,0.9	0.16	-0.61,0.65	18.7	3.8
	z	0.47	-1.6,1.4	0.22	-0.87,0.72	29.2	1.56
Run 6	x	0.32	-1.36,1.08	0.19	-0.55,0.52	20.9	5.3
	y	0.29	-1.4,1.0	0.17	-0.68,0.7	19.11	3.4
	z	0.39	-1.42, 1.45	0.14	-0.64,0.32	26.1	1.01
Run 7	x	0.31	-1.16,1.08	0.21	-0.8,1.0	19.78	4.18
	y	0.28	-1.14,1.11	0.14	-0.84, 0.82	18.69	3.51
	z	0.37	-1.09,1.21	0.20	-0.86, 0.72	25.73	1.48
Run 8	x	0.31	-0.97,1.03	0.03	-0.04,0.03	16.99	0.07
	y	0.28	-1.10,1.15	0.007	-0.01, 0.02	17.94	0.04
	z	0.40	-1.3,1.03	0.25	-0.79, 0.5	24.29	1.05

Figure 4: Results for RUN 5 : Trajectory y of Particle

Figure 5: Results for RUN 5 : Velocity v_x and Error in Estimation of Velocity of Particle

The experiment for the controlled motion of the tracer particle thus provides a firm basis with which the effectiveness of the wavelet analysis technique for filtering the intrinsic noise in the instantaneous position data is substantiated.

2.6 Results for a Bubble Column Experiment

We now show results for filtering of the data from a bubble column experiment. The experimental conditions for the run considered are : column diameter 19.05 cm, superficial gas velocity 4.0 cm/sec and superficial liquid velocity 0 cm/sec. The results presented in Figures 6 and 7 are one dimensional profiles generated by averaging over the middle section of the column, where the flow is fully developed. As expected, there is no appreciable difference between the filtered and original mean axial velocity profiles shown in Figure 6. This is because time averaging of the instantaneous velocities, averages all the fluctuations in the data,

Figure 6: One Dimensional Mean Axial Liquid Velocity for an 8" Column, U_G 4.0 cm/sec

including the inherent noise due to statistical fluctuations of the radiation. Figure 7 shows the turbulent kinetic energy. Here it can be seen that filtering has reduced the magnitude of these parameters. The results from filtering experimental data are validated by comparing the Reynolds shear stress profiles obtained in a column of diameter 14 cm with results from Menzel et al. (1990) who used a hot wire anemometer to measure the instantaneous liquid velocities in a bubble column. The results shown in Figure 8 suggest a good comparison for the Reynolds shear stress using the two techniques.

2.7 Conclusions

A wavelet packet based algorithm reduces the level of noise in the CARPT data. The algorithm is validated by designing and conducting a CARPT experiment with the controlled motion of the particle, whereby an *a priori* knowledge of the trajectory of the particle is

Figure 7: One Dimensional Turbulent Kinetic Energy for an 8" Column, U_G 4.0 cm/sec

possible. When applied to data for a bubble column experiment, substantial reduction in the noise is seen. This yields more accurate results for the turbulence parameters estimated, which is of importance in the modeling of bubble columns and other multiphase reactors.

Figure 8: Comparison of Experimental data for Turbulent Shear Stress from CARPT with Data of Menzel* (1990), Col. Dia 14 cm

3 Monte Carlo Simulation of the Radiation Measurement Process

The specific objectives for this part of the research is as follows :

1. To develop an efficient Monte Carlo simulation program for calculating the efficiency of a cylindrical NaI detector receiving radiation emitted from a point source located at an arbitrary position inside the reactor with or without internals. This would basically eliminate the time-consuming in-situ calibration procedure in utilizing the Computer Automated Radioactive Particle Tracking (CARPT) facility to study the flow pattern/mixing mechanism in multiphase reactors.
2. To determine the dynamic location of a radioactive particle by using the 3-D position-counts maps for all detectors obtained by using the Monte Carlo simulation. This would improve the accuracy for locating the particle position from count data received by each detector, since 3-D mapping is used instead of 1-D mapping adopted by the in-situ calibration process.
3. Verify the Monte Carlo simulation by comparing the calculated counts with those measured at a number of known locations inside the reactor. Optimize the dead-time constant of detectors and the linear attenuation coefficient of reactor media to best fit the experimental and theoretical data.
4. Write a program to determine the particle location from the count data on all detectors and the position-counts maps obtained from the Monte Carlo simulation.
5. Verify the accuracy of the program by comparing the predicted particle position and its actual position by placing the radioactive particle into several known location.

Progress has been made in developing a Monte Carlo simulation program for calculating the detector solid angle, total efficiency and photo-peak efficiency. The tracer particle and detector can be at any position (particle inside reactor, and detector outside reactor). The distances travelled by the photons from the tracer inside the reactor and through reactor wall are calculated exactly. The absorption of γ -ray by the reactor media and reactor wall are also considered. The simulated results by this program are compared with other simulated results reported in literature and the comparisons are good.

The approach adopted for the Monte Carlo simulation is described in the paper by Beam et al. (1978). Some modifications and additions were made to account for the photons absorbed by the flowing phases in the reactor and by the reactor wall. Randomly chosen

γ -rays emitted within the detector solid angle (Ω) was employed by Beam et al. (1978) and Larachi (1994) to calculate the detector efficiencies. In order to obtain an accurate simulation, a large number of γ -rays (more than 4000) within the solid angle has to be calculated. To increase the accuracy and simulation speed, Gaussian quadrature, instead of randomly picked γ -ray within the solid angle, is applied to perform the multi-dimensional integration. It is shown that the results from the Monte Carlo simulation is accurate with 30 Gaussian points in one angular direction, i.e. total of 900 points for the surface integral.

3.1 Approach for Monte Carlo Simulation

In the following we briefly summarize the steps involved in computing the detector efficiencies. To calculate the detector efficiencies by the Monte carlo method, the following parameters need to be determined.

1. The solid angle Ω subtended by the detector surface as seen from the tracer particle position;
2. The probability of non-interaction f_a of γ -rays emitted within Ω with the reactor media (gas-solid mixture) and reactor wall, which is calculated by:

$$f_a(\alpha, \theta) = \exp \left[- \sum_{i=1}^n \mu_i d_i(\alpha, \theta) \right] \quad (4)$$

where μ_i is the total linear attenuation coefficient of the material i in the γ -ray path, and d_i is the distance it travels in the direction of (α, θ) , α is the angle with the line normal to the detector axis, θ is the angle with the detector axis. The geometry is illustrated in Fig. 9. The detector axis is normal to the detector front face, with the origin at the center of detector face.

3. The probability of interaction f_d of γ -ray with the detector crystal. For total efficiency

$$f_d(\alpha, \theta) = 1 - \exp [-\mu_d d(\alpha, \theta)] \quad (5)$$

where μ_d is the total attenuation coefficient of detector crystal and d is the distance of γ -ray travelled in the detector by an undisturbed γ -ray along the direction of (α, θ) .

4. For photo-peak efficiency, the calculation is more complicated since the Compton interaction has to be considered, the probability of photo-peak interaction f_p can be

Figure 9: Angles and Distances Used in Monte Carlo Simulation

written as:

$$f_p = w_1 \frac{\tau_1}{\mu_1} + w_\nu \frac{\tau_\nu}{\mu_\nu} \prod_{j=2}^{\nu} w_{j-1} \frac{\sigma_{j-1}}{\mu_{j-1}} \quad (6)$$

$$w_j = 1 - \exp[-\mu_j d_{eff}]$$

where w_1 is equal to f_d in eq.(2), d_{eff} is the effective distance of γ -ray travelled, τ_j , σ_j and μ_j is the photoelectric, Compton and total attenuation coefficients ($\mu_j = \tau_j + \sigma_j + j$), respectively. It should be mentioned that τ_j , σ_j and μ_j are a function of γ -ray energy. After each Compton interaction, the γ -ray (photon) energy and direction changes. The distance travelled in the new direction is randomly distributed between zero and the maximum distance it may travel inside detector crystal in the new direction.

The total efficiency ϵ and photo-peak efficiency P_ϵ can be calculated by:

$$\epsilon = \iint_{\Omega} \frac{\vec{r} \cdot \vec{n}}{r^3} f_a(\alpha, \theta) f_d(\alpha, \theta) ds \quad (7)$$

$$P_\epsilon = \iint_{\Omega} \frac{\vec{r} \cdot \vec{n}}{r^3} f_a(\alpha, \theta) f_p(\alpha, \theta) ds \quad (8)$$

where $\vec{r}$ is the vector from point source to a variable point p on the exposed detector surface, $\vec{n}$ is an external unit vector locally normal to the surface at p , and ds is the area around p .

According to Beam et al. (1978) an appropriate statistical weight $w(\alpha, \theta)$ can be assigned to each sample direction (α, θ) . If N randomly chosen γ -rays are sampled in the tracer-detector solid angle Ω , the solid angle, total and photo-peak efficiencies can be evaluated by:

$$\Omega = \frac{4\pi}{N} \sum_{i=1}^N w(\alpha_i, \theta_i) \quad (9)$$

$$\epsilon = \frac{1}{N} \sum_{i=1}^N w(\alpha_i, \theta_i) f_a(\alpha_i, \theta_i) f_d(\alpha_i, \theta_i) \quad (10)$$

$$P_\epsilon = \frac{1}{N} \sum_{i=1}^N w(\alpha_i, \theta_i) f_a(\alpha_i, \theta_i) f_p(\alpha_i, \theta_i) \quad (11)$$

The angle α_i and θ_i is determined by the tracer position and the point where γ -ray i entered the detector. In order to obtain accuracy values of ϵ and P_ϵ , a large number of N (5000 to 10000) is required since they are randomly selected. However, we can apply the Gaussian quadrature to efficiently perform the surface integration. It will be shown later that with $n = 30$ Gaussian points in one angular direction (total number of γ -rays sampled equals to 900 in two angular directions), the simulation results are comparable with those from randomly selected 5000 points. Actually, if one only wants to calculate the solid angle and total efficiency, 15 ($n = 15$) Gaussian points in one angular direction are sufficient to obtain accurate values. The equations for calculating the solid angle, total and photo-peak efficiencies using Gaussian quadrature become:

$$\Omega = \pi \sum_{i=1}^n \sum_{j=1}^n w_g(i) w_g(j) w(\alpha_i, \theta_j) \quad (12)$$

$$\epsilon = \frac{1}{4} \sum_{i=1}^n \sum_{j=1}^n w_g(i) w_g(j) w(\alpha_i, \theta_j) f_a(\alpha_i, \theta_j) f_d(\alpha_i, \theta_j) \quad (13)$$

$$P_\epsilon = \frac{1}{4} \sum_{i=1}^n \sum_{j=1}^n w_g(i) w_g(j) w(\alpha_i, \theta_j) f_a(\alpha_i, \theta_j) f_p(\alpha_i, \theta_j) \quad (14)$$

where $w_g(i)$ and $w_g(j)$ is the Gaussian weight corresponding to the Gaussian point x_i and x_j (corresponding to α_i and θ_j). The constant $1/4$ in front of the equations is due to the fact that the integral limit $(0, 1)$ of the dimensionless angle for eqs (6)–(8) is changed to $(-1, 1)$ for the Gaussian quadrature.

3.2 Simulation Results

Figure 10 and Figure 11 illustrates the error analysis in computing the total and photo-peak efficiencies with different numbers of Gaussian points in one angular direction, respectively. The true total efficiency and photo-peak efficiency is assumed to be one calculated with 200 Gaussian points in one angular direction (total of 40000 points). The results are calculated for a 2"x2" cylindrical NaI detector with the γ -ray energy of 1 MeV. The tracer particle is 15 cm from the detector face and 15 cm from detector axis. For calculating the total efficiency (as well as solid angle), 10 Gaussian points (total 100 γ -rays) can yield a very good efficiency value with relative error less than 0.1%. However, for computing the photo-peak efficiency, large number of Gaussian points in one direction ($n \geq 30$) is required in order to obtain a good approximation to the true efficiency value. As mentioned earlier, this is due to the fact that after γ -rays interact with the detector crystal by Compton interaction, its new direction and travelled distance changes randomly. In order to get a good statistical value, a relatively large number of Gaussian points are needed.

Figures 12 and 13 show the comparison of the present Monte Carlo simulation with other Monte Carlo simulation and experimental measurements (Beam et al. 1978) of the total and photo-peak efficiencies. The experimental data were obtained by placing a Cs-137 point source at various locations from the detector face and axis, and measuring the total and photo-peak counts.

The total source intrinsic efficiency and photo-peak efficiency are normalized with the efficiency for the particle locating on the detector axis, respectively. When the angle with the detector axis increases, both the source intrinsic efficiency and photo-peak efficiency increases as seen in Figs. 12 and 13. The results from the present Monte Carlo simulation are very close to those from Beam et al.'s (1978) Monte Carlo simulation. However, some differences between the Monte Carlo simulation and experimental data exist. The reasons are provided by Beam et al. (1978). When the distance between the detector and tracer particle increases, the differences between the experimental data and the simulation decrease as illustrated in Fig. 14 (45 cm from the center of detector face).

Attempts to reproduce the results of Beam et al. (1978) have been made. The plots of the total intrinsic efficiency and peak to total ratio as a function of γ -ray energy as shown in Figs. 15 and 16. These are computed with the same parameters as used by Beam et al. (1978). The symbols in Figs. 15 and 16 are the calculated efficiencies corresponding to different energy levels, and the solid lines are curve fits to the simulated data. The simulation results shown in Figs. 15 and 16 are very close to the results obtained by Beam et al. (1978).

The results of the Monte Carlo simulation have also been compared with those of other Monte Carlo simulations (In addition to Beam et al.'s (1978) work). They all show good

Figure 10: Error Analysis for Calculating Detector Total Efficiency with Different Numbers of Gaussian Points

Figure 11: Error Analysis for Calculating Detector Photo-Peak Efficiency with Different Numbers of Gaussian Points

Figure 12: Comparison of Present Monte Carlo Simulation with Other Simulation and Experimental Data on Total Efficiency, 15 cm from the Center of Detector Face

Figure 13: Comparison of Present Monte Carlo Simulation with Other Simulation and Experimental Data on Photo-Peak Efficiency, 15 cm From the Center of Detector Face

Figure 14: Comparison of Present Monte Carlo Simulation with Other Simulation and Experimental Data on Photo-Peak Efficiency, 45 cm From the Center of Detector Face

Figure 15: Total Intrinsic Efficiency as a Function of γ -ray Energy, 3"x3" NaI, 10 cm from Detector Face

agreement, and the present Monte Carlo code is more efficient than the others (much less CPU time).

Figure 16: Photo-Peak Efficiency to Total Efficiency Ratio as a Function of γ -ray Energy, 2"x2" NaI, 15 cm from Detector Face

4 Verification of CARPT Velocity Data by Independent Methods

The second objective for the first year of the project is to conduct studies in a single diameter column with the air-water system and compare the results obtained at CREL using the CARPT-CT experimental combination with the results obtained at OSU using Particle Image Velocimetry (PIV). The velocity measurements using CARPT were also to be compared with the results from heat pulse anemometry.

PIV tests at identical conditions as those performed at CREL by CARPT are now in progress. Preliminary results for the comparison between the velocity measurements by CARPT and those obtained using heat pulse anemometry at CREL are summarized here.

The Heat Pulse Anemometer (HPA) uses a time-of-flow measurement technique to measure the mean liquid velocity between two points in the flow field. It essentially measures the distribution of passage time of the particles that start at one point in the flow and happen to meet at another second point downstream. Heat is used as tracer to tag the fluid particles. A

small heating element, the emitter, is used to label the passing fluid elements. Downstream of this emitter a fast and sensitive detector (hot film anemometer probe) registers the passage of the heated elements of liquid. An impulse of heat tracer introduced at the emitter is therefore detected by the sensor probe similar to the case of a residence time distribution measurement.

In order to obtain sufficiently large signal-to-noise ratios, tracer inputs in the form of pseudo-random sequences of single pulses are used. The measured responses at the sensor which by themselves are meaningless, when cross correlated with the pseudo-random input pulse, yield an impulse response at the point of detection, called a time-of-flow distribution (see Figure 17). This response is interpreted by the following model which describes the

Figure 17: Schematic of HPA

mean flow of fluid particles between the emitter and the sensor by a Gaussian distribution function:

$$p(t) = \frac{c}{\sigma_0 t^\beta} \exp\left(-\frac{(t - \tau)^2}{2(\sigma_0 t^\beta)^2}\right) \quad (15)$$

where τ is the mean time-of-flow, σ_0 is the intensity of mixing and β denotes the type of mixing. Calculating τ from experimental measurements and knowing the distance of separation of the emitter from the detector, the mean velocity of the liquid between the emitter and sensor can be calculated.

The variables during a measurement are the time of sweep, t_s , which is the time for one sweep during which several data points are sampled, and the time of measurement, t_m , which is the total time for a given experimental measurement over which t_m/t_s number of sweeps are taken.

Table 3: Preliminary Results for Model Parameters from T.O.F. Measurements

U_G cm/s	t_s s	t_m s	τ s	σ_0 s	β
5	3.0	300	0.211	0.485	0.827
	2.0	"	0.234	0.493	0.762
	2.5	"	0.218	0.460	0.744
	2.5	2500	0.207	0.369	0.680
	2.5	3600	0.207	0.444	0.763
	2.5	5000	0.206	0.387	0.720
12	2.0	3500	0.124	0.218	0.496
	2.0	5000	0.126	0.349	0.651

Table 4: Comparison of Local Time Averaged Axial Velocities Using CARPT and HPA

U_G cm/s	CARPT cm/s	HPA (d/ τ) cm/s
5	16.5	14.5
12	46.5	24.2, 23.8

Preliminary results have been obtained for experiments conducted in an 8" column with the probes placed along the axis of the column at a distance of 3 cm apart. The axial position of the emitter is 47 cm. The results for measurements at two gas velocities are presented. Table 3 shows the model parameters at different values of t_m and t_s for each condition. The comparison of the calculated mean axial liquid velocities with those from CARPT measurements are shown in Table 4. The comparison of the results at the lower gas velocity is reasonably good. However at superficial gas velocity of 12 cm/s, the velocity obtained from HPA is quite lower than the CARPT measurements. At this high velocity it is possible that under the existing churn-turbulent flow conditions, the variables of measurement mentioned above, along with the distance between the emitter and sensor, may affect the measured signal and derived velocities from the heat pulse probe. Additional data collection and interpretation from HPA, and comparison with CARPT results are currently underway.

PIV is a technique based on recording the images of particles used to seed the fluid for tracing the motion. The algorithm essentially consists of image enhancement, identification of particle images, computation of particle centroids, and computation of displacements between particle image pairs to obtain the velocity and phase distribution. The gas-liquid flow in air-water bubble column of 10.54 cm (4") in diameter is considered for the comparison of the results from PIV and CARPT. This column dimension is chosen due to the fact that PIV measurements for the liquid phase velocity are more difficult to obtain in a larger diameter column. The time averaged liquid phase velocities along a diametral plane of the column are to be obtained at superficial gas velocities of 2.0, 4.0 and 8.0 cm/s. The operating conditions chosen are identical to the data available at CREL. The plane of the flow illuminated by the laser sheet is 4 in. $\times$ 8 in. and approximately 3 mm thick. The comparison between the results between PIV and CARPT will be provided in the next report. However, Figs. 18 and 19 demonstrate the results obtainable using PIV. Figure 18 shows the instantaneous velocity field of the gas and liquid phase in a two dimensional bubble column 15 cm wide at a superficial gas velocity of 1 cm/s. The time averaged velocity and Reynolds stress profiles for the same conditions are shown in Fig. 19.

5 Preparations for CARPT Runs on a High Pressure Bubble Column at Exxon

One of the key goals for this project is to conduct CARPT experiments in a high pressure air-water bubble column at Exxon. In addition to CARPT, a number of related experiments such as pressure drop measurements, local holdup measurements as well as velocity measurements by heat pulse anemometry are also being planned. The experiments are to be conducted in a 14.0 cm (6") diameter column approximately 240 cm (8 ft high). The flow behavior is to be studied over a range of pressures from 1 to 7 atmospheres.

A research team from CREL has spent one week on Exxon campus in Florham Park, NJ, to plan on the CARPT experiments for the study of a high pressure bubble column. Preliminary design for the hardware components required for setting up the CARPT system around the existing reactor setup at Exxon, and planning for the execution of the experiments were made during the visit. The detector support structures have been designed to make use of the available column support structure. Since it is for the first time that CARPT experiments are being conducted in an opaque reactor, calibration of the system is anticipated to be a more tedious process than usual. A positioning device that is capable of moving the tracer particle to various positions in the reactor, and such that its hardware does not hinder the radiation measurement process, is being designed. Conceptually, the system is

planned on being completely automated so that the manual part of the calibration process is minimized. The isotopes to be used as tracers are Scandium-46 and Cobalt-60, each of approximately 350 to 450 microcuries activity for gas-liquid and slurry bubble columns, respectively. The experiments in the high pressure bubble column at Exxon are planned on being accomplished in the summer of 1997, somewhat earlier than originally suggested since this will provide more time to analyze the data during this grant.

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Figure 18: Sample PIV Result of the Liquid and Gas Velocity Fields in the 15 cm Column over 3 Consecutive Frames at a Superficial Gas Velocity of 1 cm/s

Figures 19: Radial Profiles of the Averaged Vertical and Horizontal Liquid Velocities and the Reynolds Stresses for the 15 cm Column (Gas Velocity = 1 cm/s Column over 3 Consecutive Frames at a Superficial Gas Velocity of 1 cm/s

NOVEL TECHNIQUES FOR SLURRY BUBBLE COLUMN HYDRODYNAMICS

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**SECTION IV: REPORT FROM OHIO STATE UNIVERSITY
 (HEAT TRANSFER MEASUREMENTS)**

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OBJECTIVE

A special heat transfer probe is developed which is used to measure instantaneous local heat transfer coefficients due to the passage of single gas bubbles injected in liquid and liquid-solid systems. Also the reliability and accuracy of the probe are validated.

INTRODUCTION

High heat transfer rate is one of the most important characteristics in the operation of a slurry bubble column which results in effective reaction temperature control in such reactors. Fundamental heat transfer studies have been concerned mainly with the measurement of time-averaged heat transfer from the column wall to the bed and/or from the surface of immersed heating object to the bed under steady state conditions. Due to inherent complexity of multiphase flow systems, however, little has been known in the past about the intrinsic mechanism underlying the enhanced heat transfer in bubbling systems over non-bubbling systems. Therefore, a better understanding of the heat transfer behavior and the underlying mechanism is essential for the design, control, and optimum operation of such reactors.

The heat transfer property in the bed is intimately associated with the bubble motion, bubble, size, and phase holdups which are affected by fluid flow including wake flow. The wake flow behavior, such as temporal variations in the shear flow at the bubble edge, chaotic primary wake, and vortex-vortex interaction, differs distinctively from the fluid flow behavior in the bulk region (Fan and Tsuchiya, 1990). Thus, a fundamental understanding of bubble-wake dynamics forms a necessary basis for a complete

description of various transport processes in these systems, and to predict fully the heat transfer performance of gas-liquid and gas-liquid-solid systems, effects of bubble wake need to be considered. The bubble wake effect on heat transfer can be quantified by the measurement of the instantaneous local changes in the heat transfer coefficient, which depends strongly on the local hydrodynamics of the bed.

The complex behavior of bubble columns is a direct result of the local flow structure which are time-variant due to the intrinsic dynamic behavior of the dispersed gas-phase motion and associated wake interaction. Therefore, to obtain a better understanding of the extremely complex flow structure in bubble columns and its effects on the pertinent hydrodynamic properties and heat transfer characteristics, it is necessary to understand a simplified system involving a single bubble moving in liquid and liquid-solid systems.

To measure local instantaneous changes in heat transfer coefficients due to the passage of single gas bubble, a special heat transfer probe is developed. This report highlights the design of the novel heat transfer probe and its uniqueness and capability for accurately measuring the local instantaneous heat transfer coefficients in multiphase flow systems. Moreover, discussions of the mechanism of heat transfer enhancement due to the presence of bubble in simplified systems involving single bubble injection in liquid and liquid-solid systems is presented.

EXPERIMENTAL

A schematic diagram of the experimental apparatus is shown in Fig. 1. The experiments are performed in a three-dimensional Plexiglas column, 150 cm high and 1.62 cm ID. Liquid enters the column through a packed layer of 6 mm glass beads and a perforated-plate distributor ensuring uniform distribution of liquid in the column. The support for the fluidized particles is provided by a 200-mesh wire cloth. A steady liquid velocity is maintained by circulating water through a reservoir and a rotary pump. Tap water is used as the liquid phase in the experiments. Fluidized particles used are 163 μm (GB163) and 326 μm (GB326) glass beads. The physical properties of solid particles are given in Table 1.

Experiments involve single bubble injection in liquids and liquid-solid suspensions as shown in Figs. 2(a) and 2(b). A three-dimensional cup bubble injection system in Fig. 1 is designed in this study to introduce single bubbles without pressure perturbation or any satellites generation. A hemispherical cup of 2.5 cm diameter is inserted through the wall at 10 cm above the distributor. A known volume of air is injected into the cup through the stainless tube using a syringe. The trapped bubble is then released by turning the cup. The bubble volume varied from 3 cm^3 to 10 cm^3 with the corresponding bubble Reynolds number (based on equivalent bubble diameter) Re_b ranging from 5,300 to 9,000. Under these values of Re_b , the bubble is of spherical cap shape and the wake configuration is symmetric along the vertical axis of bubble. Furthermore, the bubbles rose almost rectilinearly. Miyahara *et al.* (1988) reported that for Re_b beyond 5,000 the bubble tends to discharge vorticity symmetrically and rises rectilinearly.

INSTANTANEOUS HEAT TRANSFER MEASUREMENT / PROBE DESIGN

The instantaneous local heat transfer rate is measured by a heat flow sensor/heater assembly (heat transfer probe). Figure 3 shows the details of the probe design. The probe assembly consists of five components; microfoil heat flow sensor, copper plate, foil heater, thermosetting material (insulator), and support. The foil heater is 2.54 cm high and 1.91 cm wide, and is heated by a constant voltage DC power source.

The local heat flux is measured directly by a microfoil differential heat-flow sensor (RdF corporation, Model 20453-1; Table 2). The overall dimension of the sensor is 1.27 cm $\times$ 1.27 cm $\times$ 0.008 cm. This sensor utilizes thin foil type thermopile bonded to both sides of a known thermal barrier (Fig. 4). The difference in temperature across the thermal barrier known, the sensor is factory-calibrated to provide the relation between the sensor output (voltage) and the local heat flux (Fig. 5). The unique construction of the sensor provides it with low thermal capacitance ($204.41 \text{ J}\cdot\text{m}^2/\text{K}$), low thermal impedance ($5.28 \times 10^{-4} \text{ m}^2\cdot\text{K}/\text{W}$), high sensitivity ($8.56 \times 10^{-3} \text{ }\mu\text{V}/\text{W}\cdot\text{m}^2$), fast response time (0.02 s), and minimal thermal perturbation to the heat flow. The microfoil heat flow sensor is flush mounted on the copper plate which is attached to the micro-foil heater and insulator as shown in Fig. 3.

The sensor can accurately measure the heat flux and its surface temperature over a small surface area. The heater/sensor probe assembly is usually positioned in the center of the column with the help of a support as shown in Fig. 1. Due to the rectilinear motion of bubbles, there is a high probability of bubbles striking the probe surface or at least passing very close to it. The probe is located at about 50 cm from the point of bubble injection,

which allows sufficient distance for the bubble to reach its terminal velocity (Miyahara *et al.*, 1988). Since the width of the probe at a horizontal section of the column is small (0.32 cm), the disturbance to the flow in the vicinity of the probe is minimal and the fluidized state remains relatively undisturbed. A sheathed copper-constantan thermocouple located at the column wall is used for the measurement of the bulk temperature. The average bulk temperature is also monitored by a digital thermometer.

MEASUREMENT TECHNIQUE

Signals for the heat flux as well as the temperature difference between the probe surface and bulk are sampled simultaneously at the rate of 186.2 Hz for 11 seconds. The signals from the sensor (typically in microvolt range) are amplified to millivolts range by the amplifier/multiplexer system (Metrabyte EXP-16) and interfaced with the high speed microcomputer data acquisition system (Metrabyte DASH-16). Digital signals stored in the computer are converted to the corresponding heat transfer rate and the temperature difference using proper calibration.

To reduce the high frequency noise in the original signal, software signal processing is performed. The signals are smoothed by employing a low-pass filter and the computations are performed using Fast Fourier Transforms. A typical raw and filtered signal of the temperature difference $\Delta T_i (= T_{si} - T_{\infty})$ for a signal bubble injection in a liquid-solid fluidized bed containing GB163 is shown in Fig. 6. There is a significant change in temperature difference due to the passage of bubble, but the change in q_i is not so significant compared to the temperature difference. Also, there is a large fluctuation in q_i

as compared to ΔT_i . Since the change in the instantaneous heat transfer rate depends on many factors including the thermal balance on both sides of the heater, the instantaneous heat transfer coefficient, h_i , is obtained from the instantaneous change in the temperature difference, ΔT_i , and the time averaged heat transfer rate, Q .

$$h_i = \frac{Q}{\Delta T_i} \quad (1)$$

Typical differential temperature ΔT_i in the stagnant liquid medium is 10°C, while that in the bubble column is 4°C. Due to the small dimension of the probe and minimal alteration in the hydrodynamic condition near the heat transfer surface, the measured instantaneous heat transfer coefficient in Eq. (1) is a direct measure of the local instantaneous heat transfer coefficients in the bed at that particular location. The local time-averaged heat transfer coefficient can be obtained by averaging the instantaneous heat transfer coefficient data over a number of sampling points (2048) as

$$h_{av} = \frac{1}{n} \sum_{i=1}^n \frac{Q}{\Delta T_i} \quad (2)$$

The small dimension of the probe (20 to 30 times smaller heat transfer area compared to conventional probes employed by Baker *et al.*, 1978 and Magliotou *et al.*, 1988), ease of installation, and high accuracy in measurements render its application limitless. For example, the probe could easily be positioned at any location in the bed to measure the instantaneous and time-averaged heat transfer coefficient. Also, since the heat transfer measurements are local in nature, the probe may be used for locating in-bed non homogeneity in a multiphase flow system. Thus, the probe is capable of instantaneous and local hydrodynamic characterization of a particulate multiphase reactor, thereby

providing significant information regarding the radial and axial variation of heat transfer in an industrial and pilot size reactor which would be of enormous practical significance in better design and control of such systems.

PROBE VALIDATION

The reliability and accuracy of the probe are validated by performing heat transfer measurements in liquid (water) systems and liquid-solid fluidized beds. Time-averaged local heat transfer coefficients in liquid-solid fluidized beds agree well with the immersed object-to-bed heat transfer coefficients data and correlations reported in the literature (*e.g.*, Baker *et al.*, 1978 and Kato *et al.*, 1984). Also, a good agreement is obtained between the measured heat transfer coefficient in stationary water with that predicted by the heat transfer correlation for laminar free convection on a vertical plate immersed in stationary water reported in the literature (*e.g.*, Incropera and De Witt, 1985).

INSTANTANEOUS HEAT TRANSFER COEFFICIENT

Figures 7, 8, and 9 show the instantaneous heat transfer coefficient due to the passage of a single gas bubble in liquid, in liquid-solid systems containing GB163, and in liquid-solid systems containing GB326, respectively. The instantaneous heat transfer coefficient increased rapidly, attained a maximum value, and then gradually recovered to the initial value in liquid and liquid-solid systems. It should also be noted from Figs. 7, 8, and 9 that due to the presence of secondary wake in liquid and liquid-solid systems, the heat transfer coefficient does not completely recover to the baseline value within the

sampling time of around 11 s. The effect of single bubble injection on heat transfer enhancement in the liquid system lasts much longer than in liquid-solid systems. Larger primary and secondary wakes and stronger vortex in such systems are primarily responsible for this phenomenon. All figures show that increased bubble volume V_b causes increased enhancement due to larger bubble wake and stronger vortices.

Particle sizes in liquid-solid systems affect the bubble-wake induced heat transfer enhancement. In Figs. 8 and 9, heterogeneous effects caused by the larger particle size reduce the bubble-wake induced enhancement in heat transfer although the baseline value is increased. The baseline values (time-averaged heat transfer coefficient with no bubble injection) for liquid is $285 \text{ W/m}^2\cdot\text{K}$, for GB163 system is $808 \text{ W/m}^2\cdot\text{K}$, and for GB326 system is $815 \text{ W/m}^2\cdot\text{K}$.

CONCLUDING REMARKS

A novel heat transfer probe is developed which accurately measured the instantaneous changes in heat transfer due to the passage of single gas bubble in liquid and liquid-solid systems. For a bubble passing through the probe, the maximum heat transfer is observed in the wake region at a short distance behind the bubble in the upward flow of fluid rising along the wake central axis.

In both liquid and liquid-solid systems, the observed local maximum in the heat transfer coefficient behind a rising bubble is due to the effect of bubble wake. The local maximum in heat transfer, however, is more pronounced in liquid than in liquid-solid

systems. Also, the heat transfer enhancement due to the bubble passage increases with the bubble size due to larger bubble wake and stronger vortices.

NOMENCLATURE

- h_{av} time-averaged heat transfer coefficient over the sampling time, $W/m^2 \cdot K$
- h_i instantaneous heat transfer coefficient, $W/m^2 \cdot K$
- n number of sampling points, 2048
- Q time-averaged heat flux, W/m^2
- V_b bubble volume, cm^3
- ΔT_i instantaneous temperature difference between the probe surface (T_{st}) and bulk (T_∞), K

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FIGURES AND TABLES

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- Figure 2 A schematic of experimental conditions.
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Figure 1 A schematic of experimental setup.

Figure 2 A schematic of experimental conditions.

Figure 3 **Heat-transfer probe design.**

Figure 4 A schematic of heat flow sensor.

Heat Flow Sensor Output at 70°F = $8.24 \times 10^{-3} \mu\text{V/W.m}^2$

Figure 5 Heat flow sensor calibration.

Figure 6 A typical raw and processed signal.

Figure 7 Effects of bubble size on instantaneous heat-transfer coefficient due to the passage of bubble in liquid for probe located at the center of column.

Figure 8 Effects of bubble size on instantaneous heat-transfer coefficient due to the passage of bubble in liquid-solid fluidized bed with GB163 for probe located at the center of column.

Figure 9 Effects of bubble size on instantaneous heat-transfer coefficient due to the passage of bubble in liquid-solid fluidized bed with GB326 for probe located at the center of column.

Table 1 Physical properties of spherical particles.

Particle	Notation	Average diameter (mm)	Density (g/cm ³)	ϵ_m^a	U_t^b (m/s)
Glass bead	GB163	0.163	2.50	0.63	1.7×10^{-2}
Glass bead	GB326	0.326	2.50	0.62	4.4×10^{-2}

^aPacked bed solids fraction

^bFan and Tsuchiya (1990)

Table 2 Types of microfoil heat flow sensor.

CONFIGURATION*	Part Number	Nominal Sensitivity ($\mu\text{V}/\text{Btu}/\text{ft}^2\text{-hr.}$)	Maximum Recommended Heat Flux ($\text{Btu}/\text{ft}^2\text{-Sec.}$)	Response Time (Seconds)	Sensor Resistance (Ω , Max.)	Maximum Operating Temp. ($^{\circ}\text{F}$)	Nominal Thickness in (Inches)	Thermal Capacitance $\text{Btu}/\text{ft}^2\text{-}^{\circ}\text{F}$	Thermal Impedance $^{\circ}\text{F per ft}^2\text{-hr.}$
	20450-1	0.02	50	.020	5	500	.003	.01	.003
	20450-2	0.05	25	.060	5	500	.005	.02	.005
	20450-3	0.2	10	.400	5	500	.012	.05	.012
	20452-1	0.2	50	.020	20	500	.003	.01	.003
	20452-2	0.6	25	.060	20	500	.005	.02	.005
	20452-3	2.0	10	.400	20	500	.012	.05	.012
	20453-1	0.02	50	.020	5	500	.003	.01	.003
	20453-2	0.06	25	.060	5	500	.005	.02	.005
	20453-3	0.2	10	.400	5	500	.012	.05	.012
	27036-1	0.1	50	.020	10	500	.003	.01	.003
	27036-2	0.3	25	.060	10	500	.005	.02	.005
	27036-3	1.0	10	.400	10	500	.012	.05	.012
	20455-1	0.2	50	.020	20	500	.003	.01	.003
	20455-2	0.6	25	.060	20	500	.005	.02	.005
	20455-3	2.0	10	.400	20	500	.012	.05	.012
	20456-1	1.1	50	.020	100	500	.004	.01	.003
	20456-2	3.3	25	.060	100	500	.006	.02	.005
	20456-3	11.0	10	.400	100	500	.013	.05	.012
	20457-1	1.1	50	.020	100	500	.004	.01	.003
	20457-2	3.3	25	.060	100	500	.006	.02	.005
	20457-3	11.0	10	.400	100	500	.013	.05	.012
	20466-1	0.2	50	.020	15	500	.003	.01	.003
	20466-2	0.6	25	.060	15	500	.005	.02	.005
	20466-3	2.2	10	.400	15	500	.012	.05	.012
	20472-1	0.2	50	.020	30	500	.003	.01	.003
	20472-2	0.6	25	.060	30	500	.005	.02	.005
	20472-3	2.0	10	.400	30	500	.012	.05	.012
	20480-1	0.2	50	.020	20	500	.003	.01	.003
	20480-2	0.6	25	.060	20	500	.005	.02	.005
	20480-3	2.0	10	.400	20	500	.012	.05	.012

NOVEL TECHNIQUES FOR SLURRY BUBBLE COLUMN HYDRODYNAMICS

FIRST ANNUAL REPORT FOR GRANT DE-FG 22-95-PC 95212

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**SECTION V: REPORT FROM EXXON RESEARCH AND ENGINEERING
ON JOINT WORK WITH WASHINGTON UNIVERSITY IN
PREPARATION FOR HIGH PRESURE MEASUREMENTS**

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Computation of Particle Source Strength for CARPT Experiment

Following are the details for the basis of computing the source strength of the radioactive particle required for the CARPT experiment, given the column size, material of construction and physical properties of the two or three phase system to be studied.

Figure 1 : Schematics of the detector setup for CARPT

For a given detector spacing, y , the lowest count rate for a given detector, say D1, would be obtained if the radioactive tracer particle was located half-way between points a & c (Fig. 1), and the maximum count rate would be obtained if the radioactive particle was in position b , or d for detector D2. For the CARPT data to be reasonable for reconstruction of a calibration map for future identification of particle position, a conservative estimate on the lowest count rate is 1500 photons/sec. Also, saturation of the detectors limits the maximum count rate to no more than 12000 photons/sec (again a slightly conservative estimate). These two constraints provide the bounds for the source strength of the radioactive particle that has to be used. The variable x is the distance of the detectors from the outer wall of the reactor, and is equal to zero if the detectors are flush mounted. At the worst location of the particle in the reactor, we would like to have a count rate of 1500 or more, and at the best location of the particle, we would want a count rate of 12000 or less. Keeping these in mind, an optimization problem could be set up to minimize the source strength requirements, with the distance of the detector from the reactor wall being an additional manipulated variable. Figures 2a and 2b show the different geometrical quantities to be estimated for the calculation of the attenuation factor (A.F.) and the solid angle (Ω) for the best and worst locations of the tracer particle, respectively. The following is the governing equation for the calculation of the count rate at a given detector.

$$CR = [(A.F.) (B.F.) \nu S \epsilon \Omega] / f \quad (1)$$

where,

f = sampling frequency, Hz

A.F. = attenuation factor

B.F. = build-up factor

Ω = solid angle

ϵ = detector efficiency

CR = count rate

S = particle source strength, Bq

ν = # of photons per disintegration, approximately equal to 2 for Co^{60} and Sc^{46}

Figure 2a : Particle at best location.

Figure 2b : Particle at worst location

In Figures 2a and 2b, r is the radius of the detector face, R is the radius of the reactor, t is the thickness of the reactor wall, d is the total path length of the radiation before being intercepted by the detector, l_{sa} is the path length through air, l_{st} is the path length through the material of the column wall, and l_{sl} is the path length through the multiphase medium.

The build-up factor (B.F.) and the efficiency of the detectors are to be chosen with some prior experience with the attenuation through the reactor wall material, whereas, the attenuation factor (A.F.) and the solid angle can be computed from the following relations.

$$\Omega = \frac{1}{2} \left(1 - \frac{d}{\sqrt{d^2 + r^2}} \right) \quad (2)$$

$$A.F. = \exp \left(-(\rho_{sa} \mu_{sa} l_{sa} + \rho_{st} \mu_{st} l_{st} + \rho_{sl} \mu_{sl} l_{sl}) \right) \quad (3)$$

where,

μ_{sa} $\equiv$ mass attenuation coefficient of air, cm^2/gm .

μ_{sl} $\equiv$ mass attenuation coefficient of the slurry, cm^2/gm .

μ_{st} $\equiv$ mass attenuation coefficient of the material of reactor wall (steel), cm^2/gm .

ρ_{sa} $\equiv$ density of air, gm/cm^3 .

ρ_{sl} $\equiv$ slurry density, gm/cm^3 .

ρ_{st} $\equiv$ density of the material of reactor wall (steel), gm/cm^3 .

$$d = l_{sa} + l_{st} + l_{sl} \quad (4)$$

Case I : Particle position as in Figure 2a.

$$l_{sa} = x \quad (5)$$

$$l_{st} = t \quad (6)$$

$$l_{sl} = 0 \quad (7)$$

Case II : Particle position as in Figure 2b.

$$d = \sqrt{(y/2)^2 + (R + t + x)^2} \quad (8)$$

$$l_{sa} = \frac{x d}{x + t + R} \quad (9)$$

$$l_{st} = \frac{t d}{x + t + R} \quad (10)$$

$$l_{sl} = \frac{R d}{x + t + R} \quad (11)$$

The above relationships define the various path lengths in terms of the geometrical parameters of the setup. The source strength S, as commonly referred to, is expressed in μCi (micro Curies), but for use in equation 1, it has to be converted to disintegrations/sec (Bq). The conversion between the two is

$$1 \mu\text{Ci} = 3.7 \times 10^4 \text{ Bq} \quad (12)$$

The optimization problem could now be setup as described below :

Minimize S

(13)

subject to the following constraints

$$S \geq 0$$

$$X \geq x \geq 0$$

$$(\text{CR})_{\text{Case I}} \leq 12,000$$

$$(\text{CR})_{\text{Case II}} \geq 1,500$$

where,

X = the maximum allowable distance of the detector face from the reactor wall (usually not more than an inch and a half).

(CR)_{Case I} = count rate when particle is in a position as given in Figure 2a.

(CR)_{Case II} = count rate when particle is in a position as given in Figure 2b.

This optimization could be carried out using the "MATLAB Optimization Toolbox". The routine was run for the following cases pertinent to the Exxon column.

Table 1 : Physical Properties.

Parameter	Value [units]
μ_{sa} [Sc ⁴⁶]	0.0674405 [cm ² /gm]
μ_{st} [Sc ⁴⁶]	0.0639 [cm ² /gm]
μ_{sl} [Sc ⁴⁶]	0.0726 [cm ² /gm]
μ_{water} [Sc ⁴⁶]	0.0749 [cm ² /gm]
μ_{sa} [Co ⁶⁰]	0.0594172 [cm ² /gm]
μ_{st} [Co ⁶⁰]	0.0561 [cm ² /gm]
μ_{sl} [Co ⁶⁰]	0.0640 [cm ² /gm]
μ_{water} [Co ⁶⁰]	0.0661 [cm ² /gm]
ρ_{water}	1.0 [gm/cm ³]
ρ_{sa}	1.2884 x 10 ⁻³ [gm/cm ³]
ρ_{st}	7.762 [gm/cm ³]
ρ_{sl}	1.45 [gm/cm ³]
r	2.75 [cm]
t	0.28 [inches]
R	3.025 [inches]

The results from the optimization procedure are as follows :

Detector level spacing, $y = 6.0$ inches, $X = 1.0$ inches

Radioactive Nuclide	Source Strength for slurry system [μCi]	Source Strength for Gas-Liquid system [μCi]	x [inches]
Co^{60}	328	248	0
Sc^{46}	395	288	0

Detector level spacing, $y = 12.0$ inches, $X = 1.0$ inches

Radioactive Nuclide	Source Strength for slurry system [μCi]	Source Strength for Gas-Liquid system [μCi]	x [inches]
Co^{60}	1267	891	1
Sc^{46}	1607	1077	1

Detector level spacing, $y = 12.0$ inches, $X = 0.5$ inches

Radioactive Nuclide	Source Strength for slurry system [μCi]	Source Strength for Gas-Liquid system [μCi]	x [inches]
Co^{60}	1371	935	0.5
Sc^{46}	1777	1149	0.5

For the above cases, the B.F. was taken as 2.5 and ϵ was taken as 0.35. These have been chosen after some experimental validation on a 7 mm thick steel pipe in our laboratory with a particle source strength of 400 μCi . These calculations thus provide the first basis for calculating the required source strengths, and since there are no strict guidelines to estimate the build-up factor and the detector efficiencies, some arbitrariness could not be avoided. More sophisticated techniques like Monte Carlo could be used to calculate the detector efficiencies and solid angles subtended by the detector, for particular particle locations inside the reactor, to greater accuracy. But the effort involved in their implementation may not yield significant improvements in predicting source strengths for particular applications.

Thus, we see that for the experiments to be conducted at Exxon, a Sc^{46} particle of source strength of 400 μCi would suffice.

The Design of Calibration Device for the High Pressure System

1. Introduction

The high pressure slurry bubble column reactor at EXXON is made of stainless steel. The present method of calibration, which uses fishing lines and hooks to position the radioactive particle, will not work because the column is not transparent. Thus a different calibration device should be designed and constructed. While the present fishing line-hook method is very time consuming and labor intensive, as known to all the members of CREL, a method based on Monte Carlo simulation is currently being developed to dramatically reduce the time required for calibration. In addition, an automatically controlled positioning device would be best to perform the calibration at EXXON. Such a device is a feasible alternative for the present calibration method in CREL, and may be called the third generation of calibration device. (The first generation of calibration device used a long rod connected by four short rods, the particle is fixed at the tip of the bottom rod, the other end of the rod is fixed on a rotating support to achieve different axial and azimuthal positions in the column. The problem of this device is that when the column is high, say higher than 6 feet, or the flow in the column is very turbulent, the positioning of the particle becomes difficult because of the vibration of the rod caused by the flow in the column. The second generation of the calibration device is the present one, fishing line-hook method, which is time consuming and labor intensive. Another problem of the present method is that if there is something wrong during the calibration, for example, the tangling and breaking of the lines, one will have to do the calibration from beginning because the detectors have to be removed and repositioned again in order to open the column. For stainless steel column, marking the lines will be more difficult and by no means one can check the positioning of the particle by matching the marks on the lines)

2. Description of the device

With the above ideas in mind, a preliminary configuration of a new calibration device is proposed and a draft drawing is presented (please see the attached drawings). The feasibility of the mechanics of the system and machining of the proposed design has been discussed among the EXXON project members as well as some mechanics in Washington University (Mr. Harkins, the Engineering School; Mr. Krietler, the Medical school and Mr. Jimes, the Art and Science School).

The design consists of the following parts:

1. Two supports made of four 3/8" tubes(1) (see Figure 1 and Figure 3) . One end of the tubes is screwed into a cross-shaped support to make the whole support more rigid as well as to be able to adjust the length of the tube to match the column diameter. One of the tubes is used to support the particle-holding rod and is made in such a way that the rod position can be varied to get different radial positions in the column. There is a ball fixed at the ends of the four tubes. The balls rotate in any direction to ensure that the supports can move up and down and also rotate in the azimuthal direction. Attached to the two adjacent balls of the four, which are not on the tube to support the particle-holding rod, is a spring, the other end of which is fixed on the tube. The springs are under tension so that they always push the attached ball against the inner wall of the column and so that the ball can rotate smoothly in any direction. On the end of the other two tubes, a ball of the same size is fixed with no spring. Such a structure is designed to make the whole support more stable and to reduce the time of vibration after the device move to a new position. The balls must be of the same size and the springs must have the same tension. Some small holes are drilled in the tubes to let the water in the tube flow out when the calibration is being performed . Two piece of supports are fixed on one end of the first measuring rod with a distance of about 1 foot to ensure that the whole device moves vertically without any slanting. In addition, a small bar (1/4" diameter) is fixed vertically between the two supports to make them more stable. Also the particle-holding rod is designed to be able to be

fixed either on both of the supports to prevent it from vibrating when there is a turbulent flow in the column or only on the bottom support.

2. Measuring rods(2) (see Figure 3). The measuring rods are five pieces of square bars (which are connected together with screws if head space is limited). Three of them are 2 feet long and the other two 1 foot long. Scales are made on one side of the rod for visual measurement. On the opposite side of the rod, a gear belt is fixed with which a step motor can be used to drive the rod up and down. It is essential that the gears of the belts exactly coincide in the joint when the two rods are connected together so that the step motor can drive the whole device smoothly.
3. Step motors(3 and 4) (see Figure 1 and Figure 2). Two step motors are used, one of which(4) drives the device up and down to different axial positions, while the other one(3) rotates the device to different azimuthal positions at a given radial position. It should be pointed out here that one has to change the radial position manually by fixing the particle support rod(5) at different radial positions on the two supports (or the bottom support). The two step motors (including the corresponding gears), are supported on a plate which is fixed on a separated flange connected with the top flange of the column. On the support plate some round windows are opened to let air out of the column when the system is running. For a given calibration, the axial position is set first. After finishing taking data at all azimuthal positions of the same plane, a new axial position is set (the axial positions are set from bottom to top). After finishing all the axial and azimuthal positions for a given radial position, a new radial position is set manually and axial and azimuthal calibration is repeated. Only 3 to 5 radial positions are needed.
4. Some kind of lock is need to prevent the measuring rod from dropping down when the system is running (in case), which may cause the cracking of the radioactive particle. A simple way to do this is that connecting a flexible steel rope to the top support, while the other end of the steel rope is fixed at somewhere of the top of the column. A maximum tolerable length is given to stop the device before it drop down to the bottom of the column.

3.0 Procedure and cost estimation

The cost for making the device has been estimated by the machine shop personnel on campus as follows:

Manual control for 6" column: \$ ~ 1500.00 ~ 2000.00

Step motor control for 6" column: \$ ~ 4500.00

Extend to 4", 8", 12", 18" columns : \$ ~ 5500.00

Since this is big project, it would be reasonable to start with manual control for a 6" column (such as the one at EXXON), to verify the feasibility of the proposed design and make some modifications if necessary. Next we will try to use the step motor control, automate the system and finally extend it to other columns.

Figure 1. Overall Configuration of the Calibration Device

Figure 2. Top View of the Calibration Device

Figure 3. Details of the Support, Particle-holding Rod and Measuring Rod

Computational Fluid Dynamics Case Studies (Simulation of a Two Dimensional Bubble Column)

For this simulation the experimental condition of interest is the two dimensional bubble column studied by Dr. Fan's group at the Ohio State University. The column has a width of 48.3 cm and a height of 160.0 cm. The gas distribution is by means of 0.0016 cm diameter injectors, although the number of injectors used is not clear. For this simulation the gas is assumed to be distributed uniformly across the column width. Measurements of the velocity and gas holdup profiles at different axial positions obtained using Particle Image Velocimetry have been reported (Lin et al., 1996). The figure for the experimental results at a superficial gas velocity of 3.34 cm/s (from their manuscript) is enclosed as Figure 1. The time averaged axial liquid velocity and gas holdup profiles at different axial positions are shown in Figure 1. The quantity L_m / L_s in the figure represents the ratio of the measuring point height to the static liquid height.

The simulation was performed in two dimensional planar coordinates, with the no slip boundary condition at the walls, inflow of gas at the bottom of the domain and pressure set to a reference value (atmospheric) at the free surface. Since the static liquid height has not been specified, the initial liquid height for the simulation was adjusted to ensure that the expanded height of the dispersion fills the available column height of 160.0 cm. In a two dimensional geometry as the present one, CFD simulations normally indicate the presence of a series of circulation cells along the axis of the column. This has also been observed experimentally by Chen et al., 1989, and is also consistent with the flow structure proposed by Dr. Fan's group. These circulation cells persist in the flow pattern even after time averaging.

For obtaining a flow field in a two dimensional column which shows the presence of circulation cells, such as those observed by Chen et al. (1989), the values for some parameters of the interfacial momentum exchange have been standardized for CFDLIB codes. These include a bubble size of 0.5 cm, a lift coefficient of 0.1 and a turbulence length scale about 0.5 to 1.5 cm (with column width ranging from 10 to 50 cm). For the present case a mixing length of 1.0 cm was used and the coefficient of virtual mass was set to 0.5 following standard practice. The first simulation attempt did show the presence of persistent circulation cells. However, with such a flow field the time averaged velocity profiles are different from the results reported by the Dr. Fan's group and are shown in Figure 2. The interval for time averaging was from 25 to 100 seconds. The downward axial liquid velocities are much larger than reported PIV values and the presence of the circulation cells gets reflected in the large magnitude of the radial velocities.

The PIV experimental results for the time averaged velocity and gas holdup profiles re-

ported (Figure 1) are more consistent with a flow structure that does not show the circulation cells after time averaging. To be able to obtain the velocity and holdup profiles reported experimentally the mixing length scale had to be increased to 1.8 cm and the pressure of the two phases had to be made significantly different. All other parameters in the models for interfacial momentum exchange were identical to the ones used for the simulation resulting in circulation cells. The circulation cells are now less pronounced and there appears to be a global character to the liquid recirculation, although two smaller cells are still observed close to the bottom as can be seen in the velocity vector plot in Figure 3. The simulated time-averaged velocity and holdup profiles are much closer to the reported experimental results. The simulation results for this case is also averaged over the period from 25 to 100 seconds. The gas holdup profiles in the simulations with and without the circulation cells are shown in Figures 4 (a) and (b). As is often the case with simulations of bubble columns with CFDLIB, the holdup profiles are relatively uniform across the column although the centerline magnitudes are close to the reported values. The message then is that it is possible to change the results of simulation to closely match any observed experimental result, but what is not clear is the direction and magnitudes of the change required in the model parameters, since a consistent pattern has not been observed from the cases that have been attempted so far.

References

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Figure 1. Radial gas holdup (a) and axial liquid velocity (b) distribution in 48.3 cm column at various axial locations $U_g = 3.34$ cm/s

Figure 2. Simulation for the presence of circulation cells.

Figure 3. Simulation inhibiting the circulation cells.

Figure 4. Gas holdup profiles with and without circulation cells.