Appendix A

One Dimensional Recirculation Model

Details of the one dimensional recirculation model of Kumar et al (1994) are given in this appendix. The method of evaluation of the input model parameters, using experimental data from CARPT (present investigation) and CT (Kumar 1994), is illustrated. The analysis of Kumar et al. (1994) is based on the approach of Rice and Geary (1990). The main difference between the two approaches lies in the functional form and method of evaluation of the mixing length profile for closure of the Reynolds shear stress.

For a steady, one dimensional, axisymmetric two-phase flow in a bubble column the Reynolds equation of motion, neglecting end effects, is written as:

$$-\frac{1}{r}\frac{d}{dr}(r\tau_{rz}) = \frac{dP}{dz} + \rho_l(1-\epsilon_g(r))g \qquad \text{(A.1)}$$

where

$$-\frac{dP}{dz} = \frac{2\tau_{rz}}{R} + \rho_l(1-\overline{\epsilon_g})g \qquad \text{(A.2)}$$

ϵ_g is the gas holdup, τ_{rz} is the Reynolds shear stress and τ_w is the wall shear stress. The following power law expression for the gas holdup profile is assumed:

$$\epsilon_g(\xi) = \tilde{\epsilon}_g\frac{m+2}{m}(1-c\xi^m) \qquad \text{(A.3)}$$

in which 'm' is the power law exponent (a constant) and represents the steepness of the holdup profile. Parameter c allows for non zero gas holdup at the wall, which is observed from CT measurements (Kumar 1994; Adkins et al. 1996). $\tilde{\epsilon}_g$ is a parameter related to the cross-sectional mean holdup $\bar{\epsilon}_g$ by the relation:

$$\bar{\epsilon}_g = \tilde{\epsilon}_g \frac{m+2-2c}{m} \tag{A.4}$$

Following the procedure of Rice and Geary (1990) and using the dimensionless radial position of maximum downward flow, λ, to eliminate the axial pressure gradient, Equation A.1 can be integrated along with Equation A.3 to obtain:

$$\tau_{rz}(\xi) = \frac{\rho_l g R}{2}\left(\frac{2\tilde{\epsilon}_g}{m\lambda^2}\right)\xi c\left[1-\left(\frac{\xi}{\lambda}\right)^m\right]; \qquad \xi \leq \lambda \tag{A.5}$$

$$\tau^*_{rz}(\xi) = \frac{\rho_l g R}{2}\left(\frac{\bar{\epsilon}_g}{\lambda^2}\right)\left[\frac{\lambda^2-\xi^2}{\xi}\right]; \qquad \xi > \lambda \tag{A.6}$$

The following expression was derived by Rice and Geary (1990) for the maximum downward liquid velocity

$$u_z(\xi=\lambda) = u_\lambda = \frac{gr^2\bar{\epsilon}_g}{4\nu_l\lambda^2}(\lambda^2 - 1 - 2\lambda^2\ln\lambda) \tag{A.7}$$

Prandtl's mixing length model is used for describing the Reynolds shear stress, τ_{rz}, giving

$$\tau_{rz}(\xi) = \frac{\rho_l\nu_l}{R}\left(-\frac{du_z}{d\xi}\right) + \rho_l\frac{l^2(\xi)}{R^2}\left(-\frac{du_z}{d\xi}\right)^2; \qquad \xi \leq \lambda \tag{A.8}$$

$$\tau^*_{rz}(\xi) = \frac{\rho_l\nu_l}{R}\left(-\frac{du^*_z}{d\xi}\right); \qquad \xi > \lambda \tag{A.9}$$

Combining these equations with Equations A.5 and A.6 and using the boundary conditions

$$\text{at} \quad \xi = \lambda, \quad u_z = u^*_z$$

and

$$\text{at} \quad \xi = 1, \quad u^*_z = 0$$

the equation for the liquid velocity profile is given by:

$$u_z(\xi) = u_\lambda - \frac{\nu_l R}{2}\int_\xi^\lambda \frac{1-\sqrt{1+\frac{2gR}{\nu_l^2}l^2(\xi')\beta(\xi')}}{l^2(\xi')}d\xi'; \qquad \xi \leq \lambda \tag{A.10}$$

$$u_z^*(\xi) = \frac{gR^2\bar{\epsilon}_g}{4\nu_l\lambda^2}(\xi^2 - 1 - 2\lambda^2 \ln \lambda); \qquad \xi > \lambda \tag{A.11}$$

β in Equation A.10 is defined as:

$$\beta(\xi) = \frac{2\tilde{\epsilon}_g}{m\lambda^2}\xi c \left[1 - \left(\frac{\xi}{\lambda}\right)^m\right] \tag{A.12}$$

The mixing length profile is fitted to an expression of the form:

$$l(\xi) = \frac{a(1-\xi)}{(\xi+b)^c} + d(1-\xi)^e \tag{A.13}$$

The functional form for $l(\xi)$ in Equation A.13 was developed by Kumar et al. (1994) based on experimental data for the liquid velocity profile from CARPT and the Reynolds shear stress. a, b, c, d and e are constants obtained by nonlinear regression. The input parameters, ϵ_g and $l(\xi)$ can therefore be obtained from experimental data, using which the above equations can be solved by numerical integration. There is still an unknown, λ, which is calculated by iteration while checking for liquid continuity in the system.

The one dimensional model is illustrated with an example which considers a 14 cm diameter column (distributor: **6A**) at a superficial gas velocity of 9.6 cm/s. Experimental data from CARPT for the axial liquid velocity profile (Figure A.1) and the Reynolds shear stress (Figure A.2) are used to obtain a profile for the mixing length, shown in Figure A.3. The fitted parameters for $l(\xi)$ in Equation A.13 are a = 4.572, b = 0.6002, c= 0.2299, d = -4.713 and e = 1.169. The gas holdup profile (defined by the parameters $\tilde{\epsilon}_g = 0.148$, $m = 3.05$ and $c = 0.85$) for the present operating conditions is obtained from Kumar (1994). Using these input parameters, the axial liquid velocity profile calculated from the one dimensional model is shown in Figure A.1. It is noted that there is reasonable agreement between the CARPT measured Reynolds shear stress and that obtained from Equation A.5 using the parameters obtained from holdup measurements, for the present set of data.

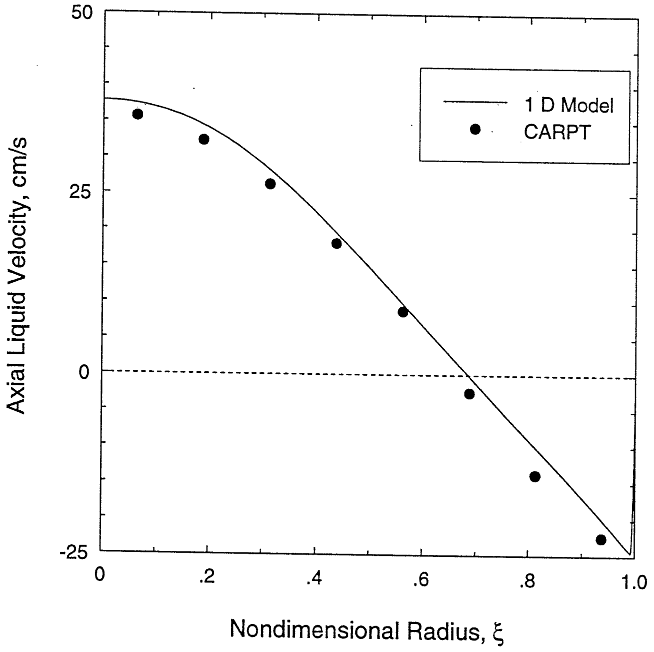


Figure A.1: One Dimensional Axial Liquid Velocity Profile, $D_c = 14$ cm, $U_g = 9.6$ cm/s

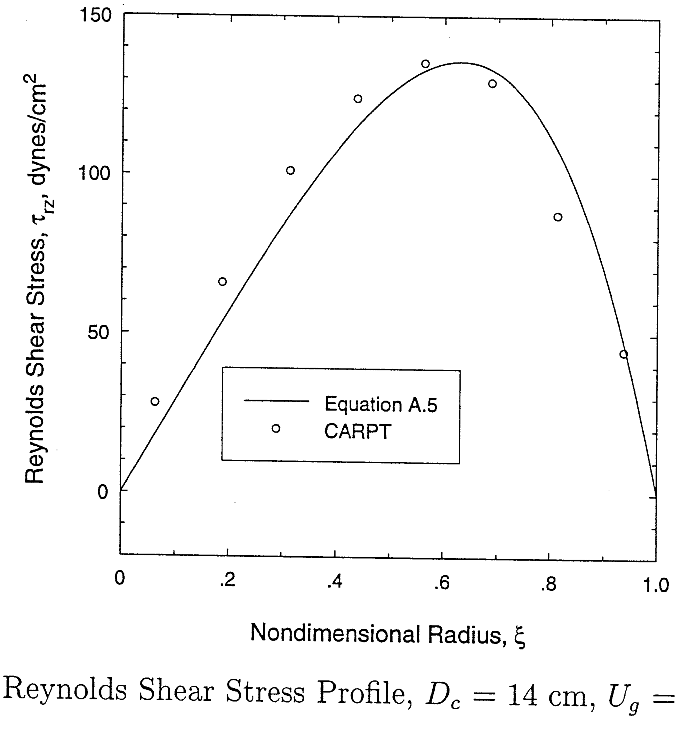


Figure A.2: Reynolds Shear Stress Profile, $D_c = 14$ cm, $U_g = 9.6$ cm/s

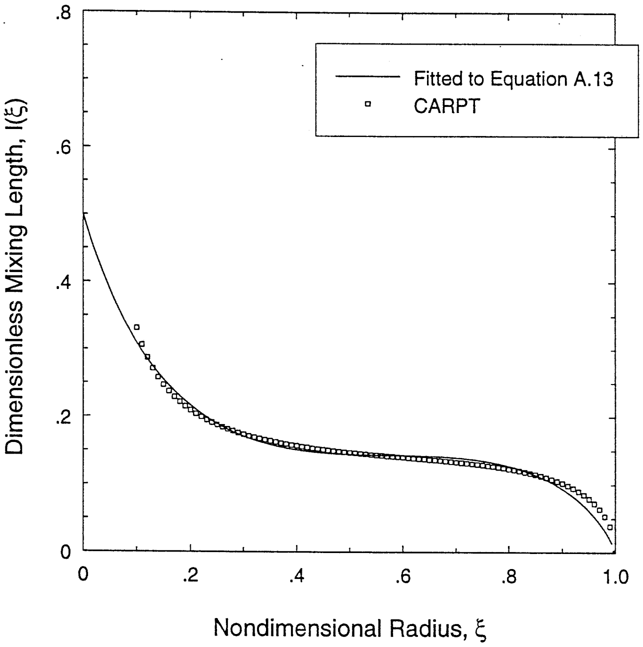
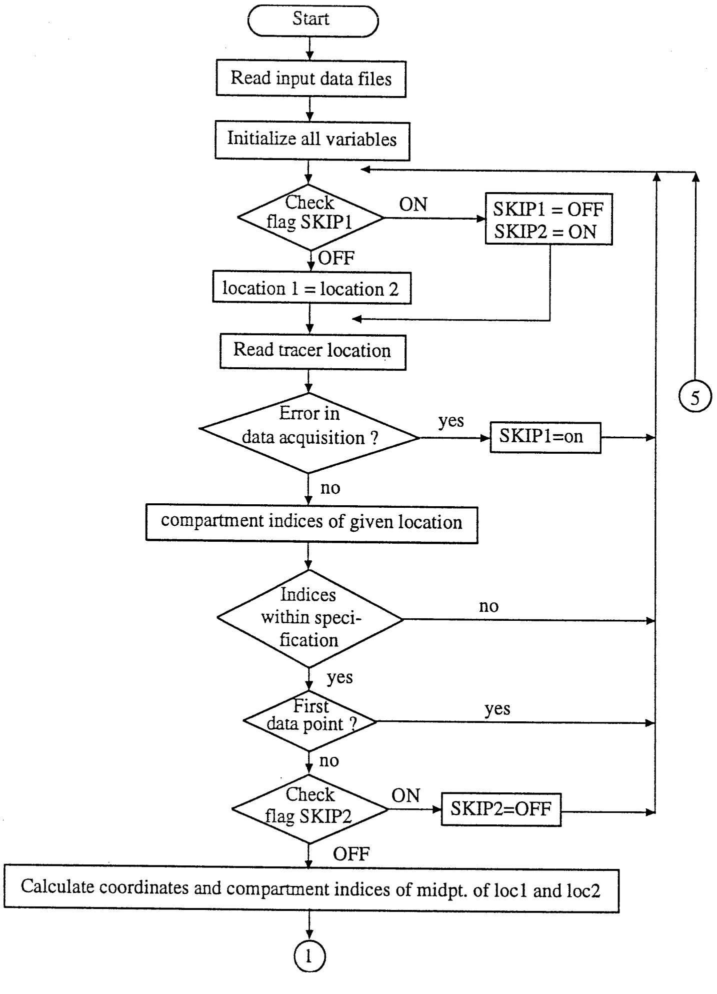
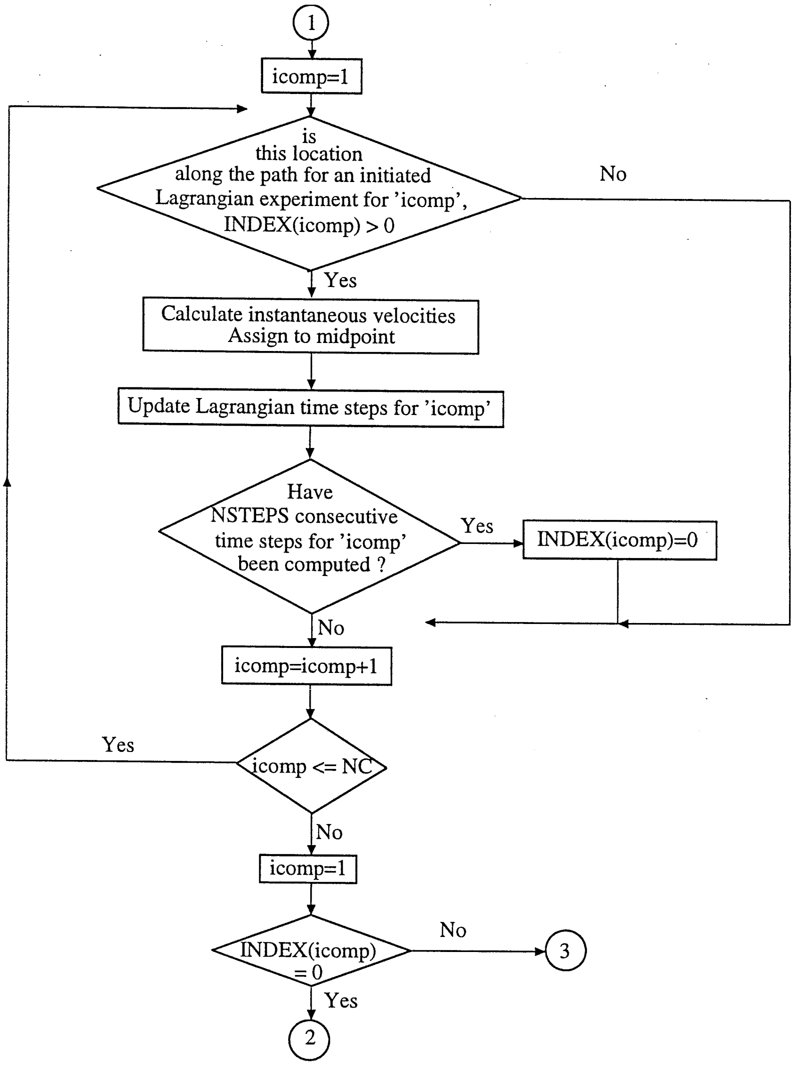


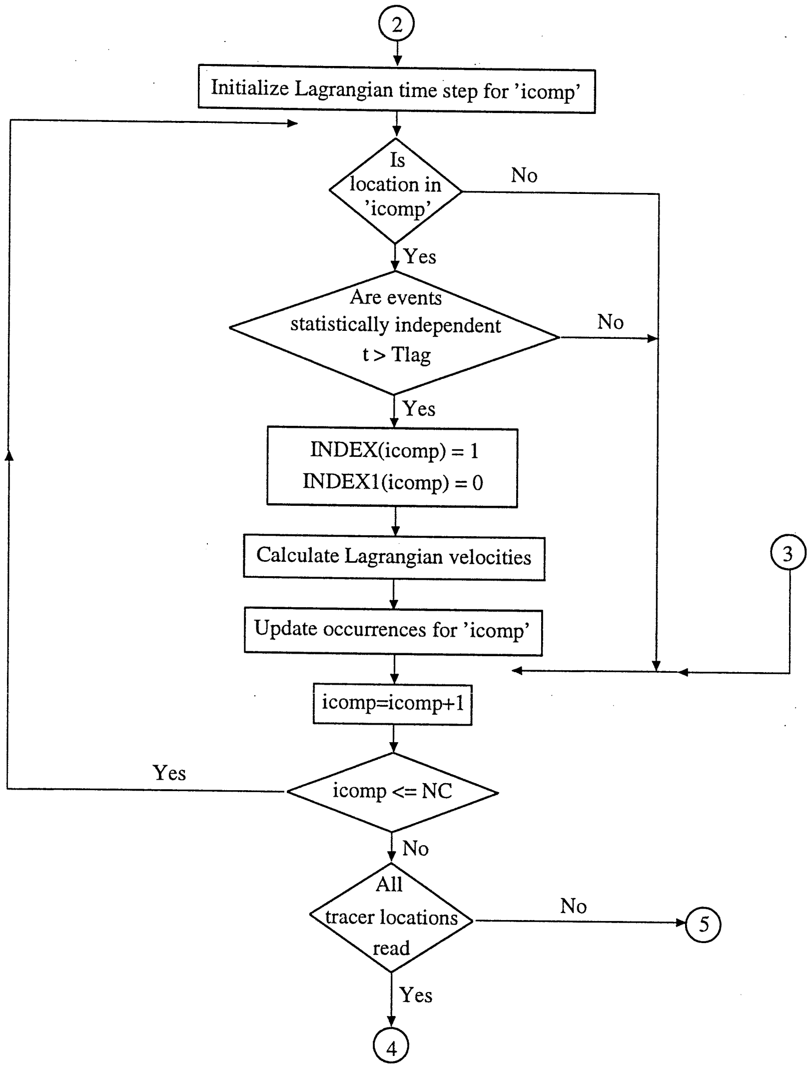
Figure A.3: Mixing Length Profile, $D_c = 14$ cm, $U_g = 9.6$ cm/s

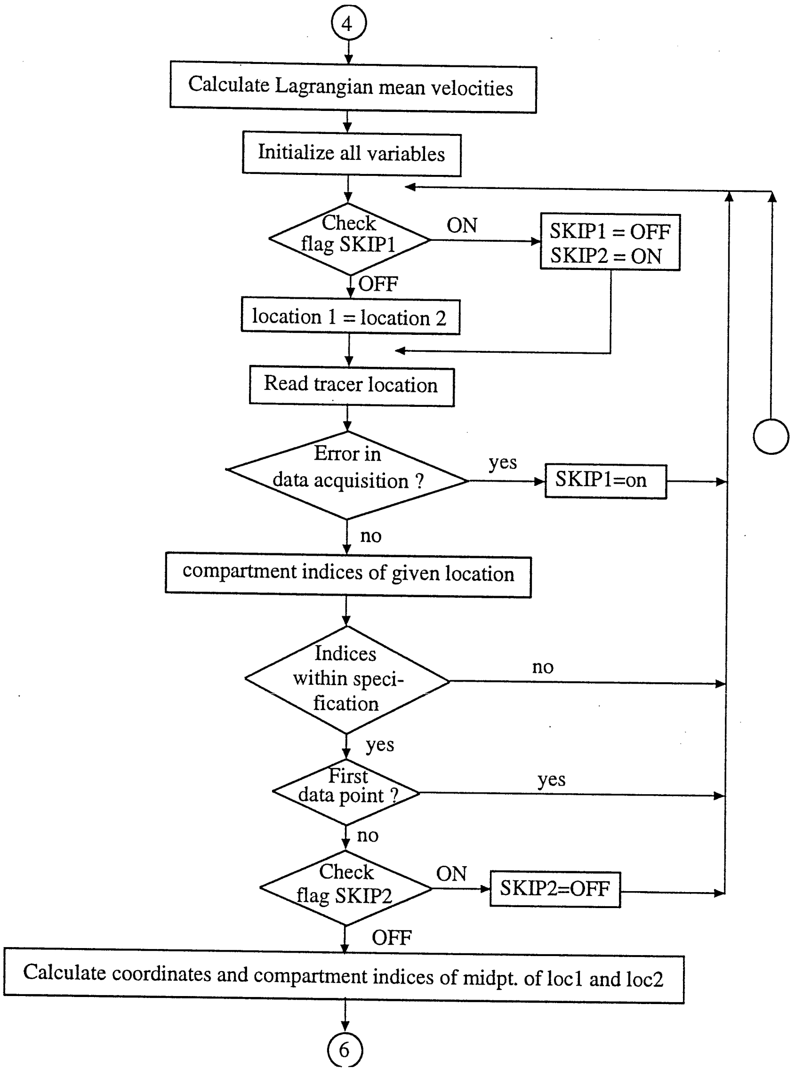
Appendix B

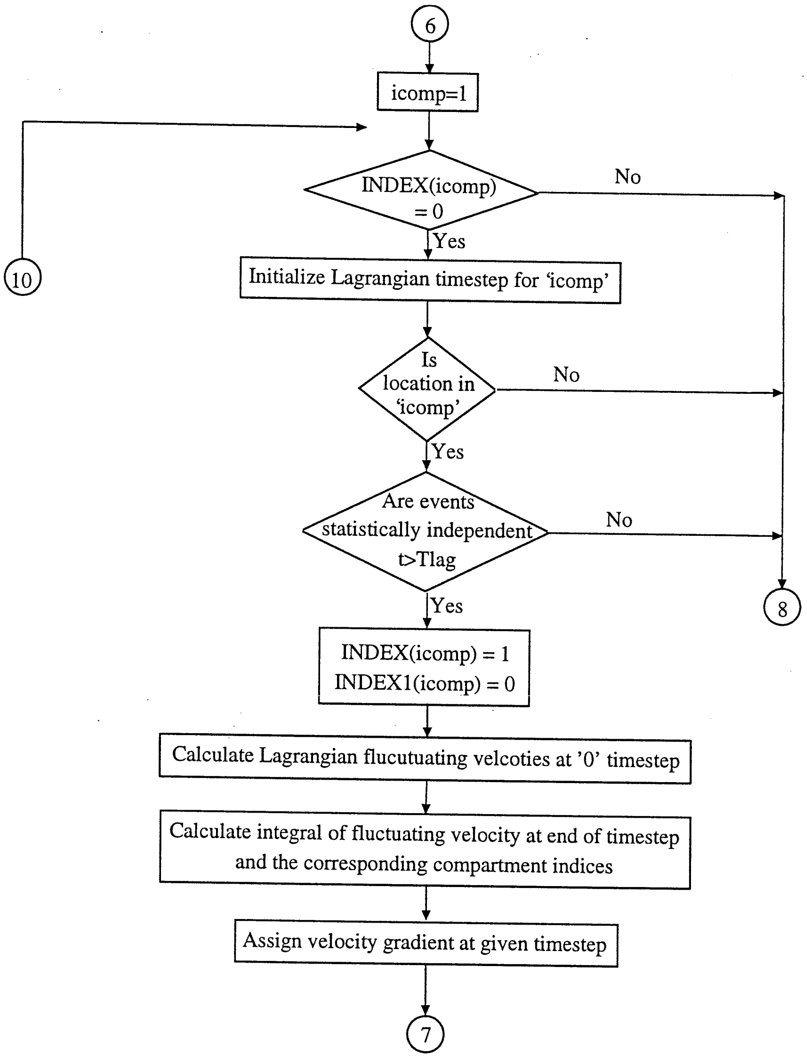
Flowchart for Computation of Lagrangian Correlation Coefficients from CARPT data

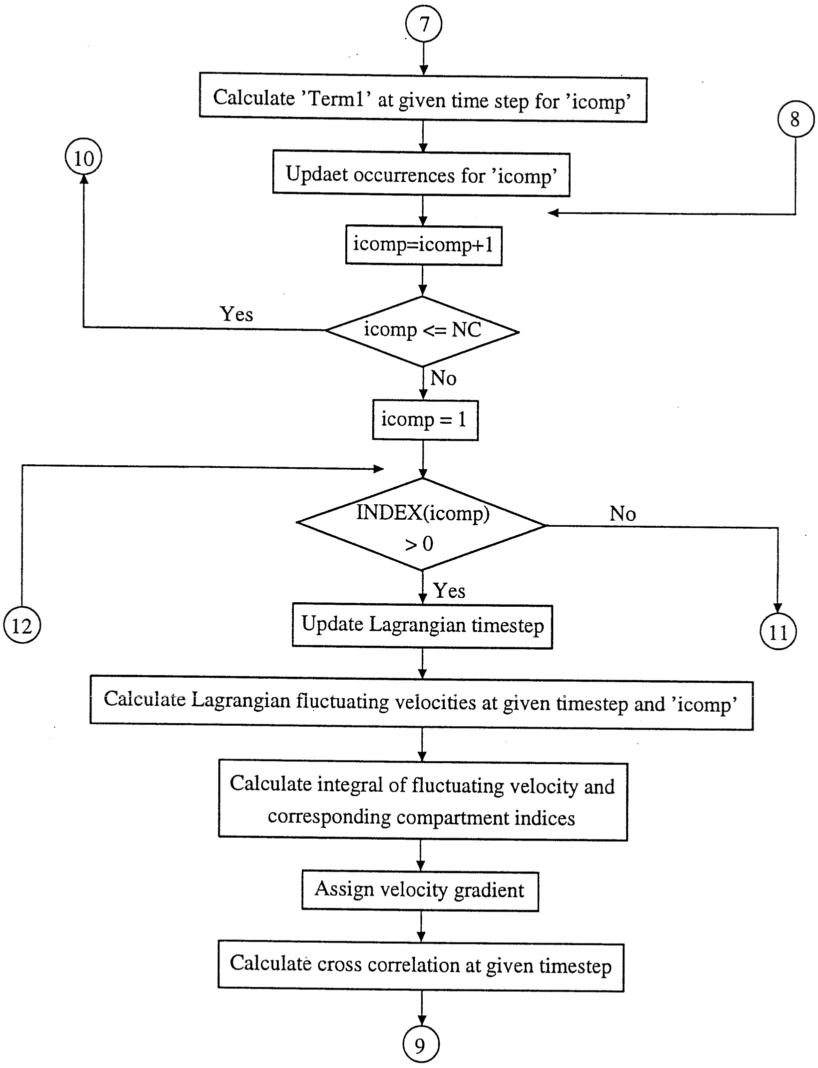


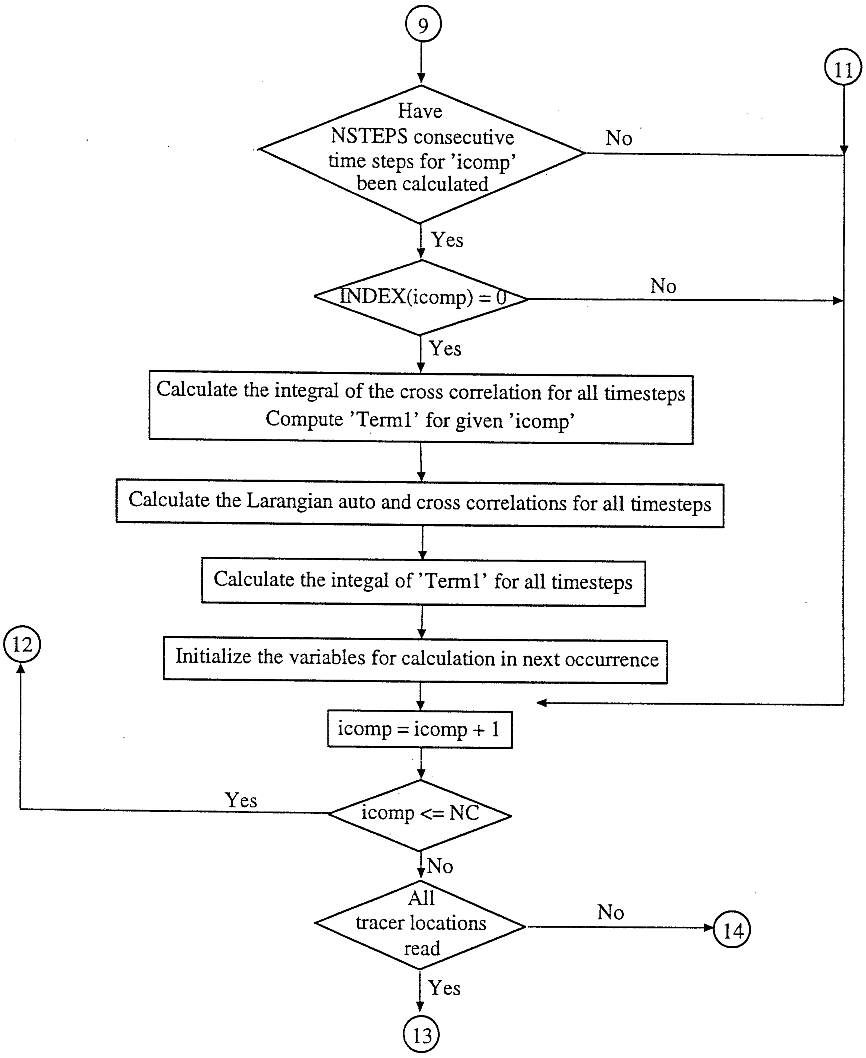

1
icomp=1
is
this location
along the path for an initiated
Lagrangian experiment for 'icomp',
INDEX(icomp) > 0
No
Yes
Calculate instantaneous velocities
Assign to midpoint
Update Lagrangian time steps for 'icomp'
Have
NSTEPS consecutive
time steps for 'icomp'
been computed ?
Yes
INDEX(icomp)=0
No
icomp=icomp+1
Yes
icomp <= NC
No
icomp=1
INDEX(icomp)
= 0
No
3
Yes
2

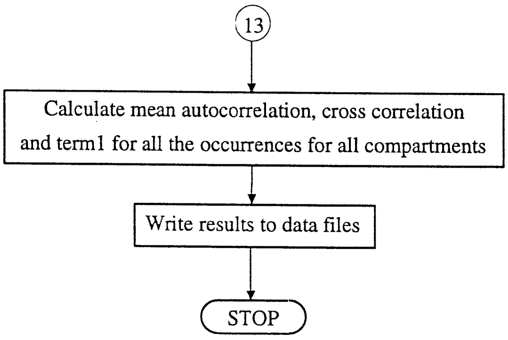

2
Initialize Lagrangian time step for 'icomp'
Is location in 'icomp'
No
Yes
Are events statistically independent t > Tlag
No
Yes
INDEX(icomp) = 1
INDEX1(icomp) = 0
Calculate Lagrangian velocities
3
Update occurrences for 'icomp'
icomp=icomp+1
Yes
icomp <= NC
No
All tracer locations read
No
5
Yes
4


4
Calculate Lagrangian mean velocities
Initialize all variables
Check flag SKIP1
ON
SKIP1 = OFF
SKIP2 = ON
OFF
location 1 = location 2
Read tracer location
Error in data acquisition ?
yes
SKIP1=on
no
compartment indices of given location
Indices within speci-fication
no
yes
First data point ?
yes
no
Check flag SKIP2
ON
SKIP2=OFF
OFF
Calculate coordinates and compartment indices of midpt. of loc1 and loc2
6


6
icomp=1
INDEX(icomp)
= 0
No
Yes
10
Initialize Lagrangian timestep for 'icomp'
Is
location in
'icomp'
No
Yes
Are events
statistically independent
t>Tlag
No
Yes
8
INDEX(icomp) = 1
INDEX1(icomp) = 0
Calculate Lagrangian flucutuating velcoties at '0' timestep
Calculate integral of fluctuating velocity at end of timestep
and the corresponding compartment indices
Assign velocity gradient at given timestep
7


7
Calculate 'Term1' at given time step for 'icomp'
8
10
Updaet occurrences for 'icomp'
icomp=icomp+1
Yes
icomp <= NC
No
icomp = 1
INDEX(icomp) > 0
No
Yes
12
11
Update Lagrangian timestep
Calculate Lagrangian fluctuating velocities at given timestep and 'icomp'
Calculate integral of fluctuating velocity and corresponding compartment indices
Assign velocity gradient
Calculate cross correlation at given timestep
9


9
11
Have NSTEPS consecutive time steps for 'icomp' been calculated
No
Yes
INDEX(icomp) = 0
No
Yes
Calculate the integral of the cross correlation for all timesteps Compute 'Term1' for given 'icomp'
Calculate the Larangian auto and cross correlations for all timesteps
Calculate the integal of 'Term1' for all timesteps
12
Initialize the variables for calculation in next occurrence
icomp = icomp + 1
Yes
icomp <= NC
No
All tracer locations read
No
14
Yes
13


13
Calculate mean autocorrelation, cross correlation and term1 for all the occurrences for all compartments
Write results to data files
STOP

Appendix C

Heat Pulse Anemometry (HPA): Experimental Details

The details of HPA are given in this appendix. The HPA technique uses time-of-flow measurements to measure the mean liquid velocity between two points in the flow field. 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 C.1). This response is interpreted by the following model (Lubbert and Larson 1990) which describes the mean flow of fluid particles between the emitter and the sensor by a Gaussian distribution function:

$$p(t) = \frac{c}{\sigma_0 t^\beta} \exp(-\frac{(t-\tau)^2}{2(\sigma_0 t^\beta)^2}) \tag{C.1}$$

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 during which several data points (pseudo random pulse) are sampled. The time of measurement, t_m, is the total time for a given experimental measurement over which t_m/t_s number of of sweeps are taken. For highly turbulent and unsteady flows such as in bubble columns, t_m must be significantly larger than t_s (Table C.1), in order to obtain good measurements,

Experiments using HPA have been conducted in the 19 cm column at three gas velocities, 2 cm/s, 5 cm/s and 12 cm/s. For a given radial position, r_h, the probes were placed at different axial distances by fixing the position of the emitter and varying the position of the sensor downstream. The minimum distance of 3.0 cm, between the emitter and sensor, and a maximum of 19.0 cm were used. Care was taken to position the probes in the middle section of the column, where the flow is well developed. Several experiments were conducted for a given set of positions of the emitter and sensor probe. However due to the sensitivity of the equipment to external disturbances (noise), a significant portion of the experiments had to be rejected, based on the nature of the measured experimental response. For a given radial location, the resulting mean residence times were used to calculate the mean velocity of the liquid between the emitter and sensor, the average of which has been considered for comparison with CARPT data. The experiments were conducted for four such radial locations of the probes for a given gas velocity.

Typical results for selected positions of the probes, at different gas velocities are tabulated in Table C.1. Figure C.2 shows a comparison of the one dimensional axial liquid velocities from CARPT with that obtained from the HPA time-of-flow measurements. The trends for the time average axial liquid velocity are the same for all the gas velocities considered. Velocities from HPA are consistently lower than those measured by CARPT in the center of the column, i.e., $r \leq 4$ cm. In the outer annular region of the column, $r \geq 4$ cm, the comparison between the two techniques is better. In general, the results from HPA show flatter profiles for the axial liquid velocity than that of CARPT. Considering the nature of the HPA measurements, in terms of deducing the velocity from the time-of-flow data, rather than obtaining direct velocity measurements, the present agreement between the two techniques is considered as satisfactory.

The other two parameters in Equation C.1, σ_0 and β denote the intensity and type of mixing, respectively (Lubbert and Larson 1990). There appears to be no specific dependence of β on gas velocity. On an average $\beta = 0.55$, indicating that mixing is diffusive in nature (Lubbert and Larson 1990). Turbulent mixing is typically characterized by $\beta = 1.5$ (Lubbert and Larson 199). σ_0 is referred to as the intensity of mixing (Lubbert and Larson 1990). Results show that on an average σ_0 decreases with increase in gas velocity, which implies that the intensity of turbulence decreases with increase in gas velocity. This is unexpected and contradicts with experimental results from CARPT and other measurements (Menzel 1990; Mudde et al 1997). As explained earlier, the experimental setup is extremely sensitive to electrical noise, due to which the rate of rejection of a set of experimental data is quite high (more than 50 %). The recommended addition of salt to improve the electrical conductivity and thereby reduce the noise, helps to a certain extent. However, the scatter in the data, especially for σ_0 and β, is still very high. This may be a possible reason for the lack of meaningful results for these parameters (σ_0 and β). Another reason is that a better model may be necessary for using the time-of-flow results from HPA for the analysis of turbulence in bubble column flows (Seinfeld 1986).

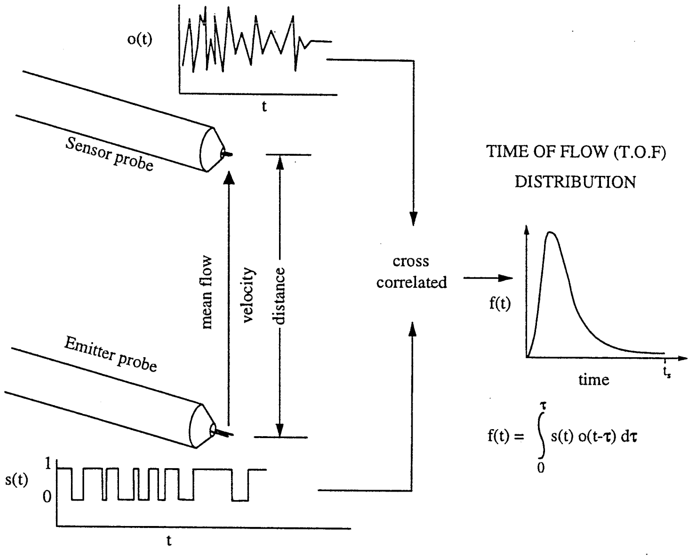


Figure C.1: Schematic of HPA

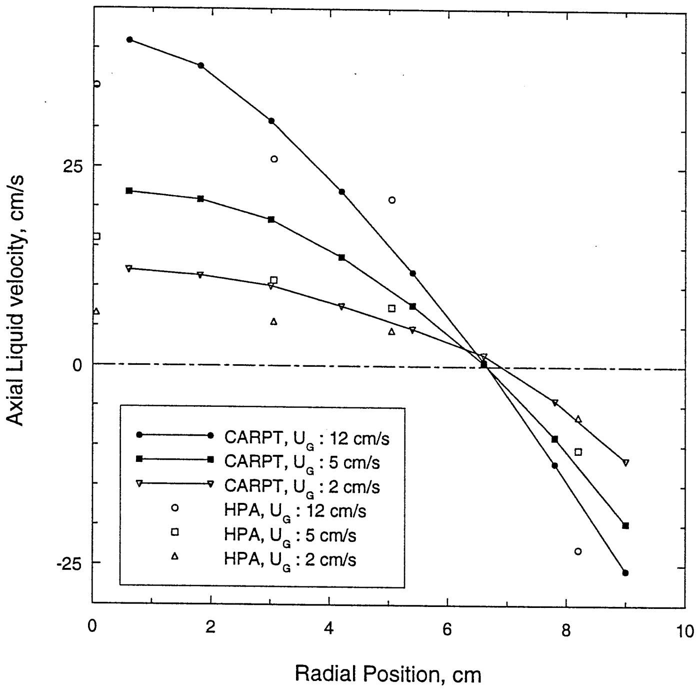


Figure C.2: Comparison of CARPT and HPA results for the Time Averaged Axial Liquid Velocity, Col. Dia. : 19 cm, Distributor: **8A**

Table C.1: Model Parameters from Time-of-Flow Measurements Using HPA

U_g	r_h	Δz	t_s	t_m	τ	σ_0	β
cm/s	cm	cm	s	s	s		
2	0.05	3.0	4.0	1500	0.482	0.445	0.538
	3.05	3.0	4.0	1600	0.591	0.63	0.509
	0.05	8.5	7	3000	1.272	0.688	0.463
	3.05	8.5	8.0	3000	1.611	0.908	0.673
5	0.05	8.5	5.0	3000	0.617	0.503	0.543
	3.05	8.5	6.0	3000	0.898	0.815	0.771
	0.05	14.0	9	4000	0.902	0.572	0.545
	3.05	14.0	9	4400	1.121	0.756	0.454
12.0	0.05	14.0	5.0	3600	0.417	0.342	0.622
	3.05	14.0	7.0	4000	0.516	0.406	0.578
	0.05	19.0	4.0	5500	0.555	0.353	0.587
	3.05	19.0	6.0	7200	0.719	0.512	0.584

Appendix D

Simulation of the Radiation Intensity from Radioactive Tracer Measured by a Shielded Detector

The intensity of radiation from a point source, recorded at a detector, is given by the following expression:

$$n_p = AF.BF.\Omega.\eta.S \tag{D.1}$$

n_p is the count rate (counts/time) at the detector due to a point source. Each factor is defined below.

The attenuation factor AF is defined as

$$AF = \exp[-(\mu_g l_g + \mu_{sl} l_{sl} + \mu_w l_w)] \tag{D.2}$$

in which μ_g, μ_{sl} and μ_w are the linear attenuation coefficients in the gas, the slurry and the wall of the reactor, and l_g, l_{sl} and l_w are the effective distances or depths of penetration in the respective media. The attenuation coefficient in the gas phase is negligible when compared with the other phases and so the term for the gas phase is neglected. l_{sl} takes into account the liquid (slurry) holdup. The calculation of l_{sl} depends on the nature of the holdup distribution. This assumes that the slurry is pseudohomogeneous. If that is not the case and if the attenuation coefficients for the solid and liquid are considerably different, then the term $\mu_{sl} l_{sl}$ must be replaced by $\mu_l l_l + \mu_s l_s$, where subscripts s and l refer to solid and liquid, respectively.

The buildup factor BF represents the ratio of the intensity due to all photons to the intensity due to unscattered photons alone. It is defined empirically using the Berger equation (Tsoulfanidis 1983):

$$BF = 1 + (a_{sl}\mu_{sl}l_{sl} + a_w\mu_w l_w)[\exp(b_{sl}\mu_{sl}l_{sl} + b_w\mu_w l_w)] \qquad (D.3)$$

where a and b are the empirical constants depending on the medium and energy of radiation.

The solid angle Ω is the fraction of photons emitted by the source that is seen by the detector. For a shielded detector, only the front circular surface of the detector is exposed to the γ rays. For such a case, the solid angle is given by:

$$\Omega = \frac{1}{2}(1 - \cos(\tan^{-1}(R_c/d)) \qquad (D.4)$$

where R_c is the radius of the circular face of the detector, and d is the distance between the source and the detector.

η, the efficiency of the detector is taken to be a constant. S is the source strength. This is proportional to the concentration of tracer at a given location.

The detectors used are 2″ x 2″ NaI crystals, shielded on their sides. The various material constants at the energy levels of the source used, are tabulated in Table D.1 (Tsoulfanidis 1983). The objective here is to estimate the spatial range at a given axial position in the column over which the detector receives its signal. The simulation is done for an assumed uniform distribution of tracer, and uniform distribution of phases.

The medium is considered to be homogeneous, with uniform phase and tracer distribution. Therefore the effective distance in the liquid (slurry) medium used in Equation D.2 and D.3 is given as

$$l_{sl} = l_{sd}(1 - \epsilon_g) \qquad (D.5)$$

where l_{sd} is the distance between the source and center of the detector. The source strength or local activity is the same at all locations, since the concentration of tracer (which is proportional to the local source strength) is uniform. Substituting for all the factors into Equation D.1, the count rate recorded at the detector due to the individual uniformly distributed point sources is calculated. The resulting spatial distribution of intensity (counts/time) at a given axial position is shown in Figure D.1. The position of the detector relative to the intensity distribution is shown in Figure D.2. The shaded region in Figure D.2 represents the volume (area) considered for the contribution of the radiation to the overall radiation received at the detector. The total radiation from this shaded region, which forms less than 1 % of the entire reactor volume, is 90 % of the total radiation from the entire domain. Since the detector is shielded on its sides, the contribution of radiation from different axial positions other than the cross sectional slice (10 cm in thickness) at the axial position of the detector is negligible. Therefore it can be assumed that the radiation measured at the detector at a given axial position is a proportional to the concentration of tracer at that axial location.

Table D.1: Constants for Radiation Simulation

μ_{sl}	0.065 cm^{-1}	μ_w	0.40 cm^{-1}
a_{sl}	1.4	a_w	1.27
b_{sl}	0.027	b_w	0.032

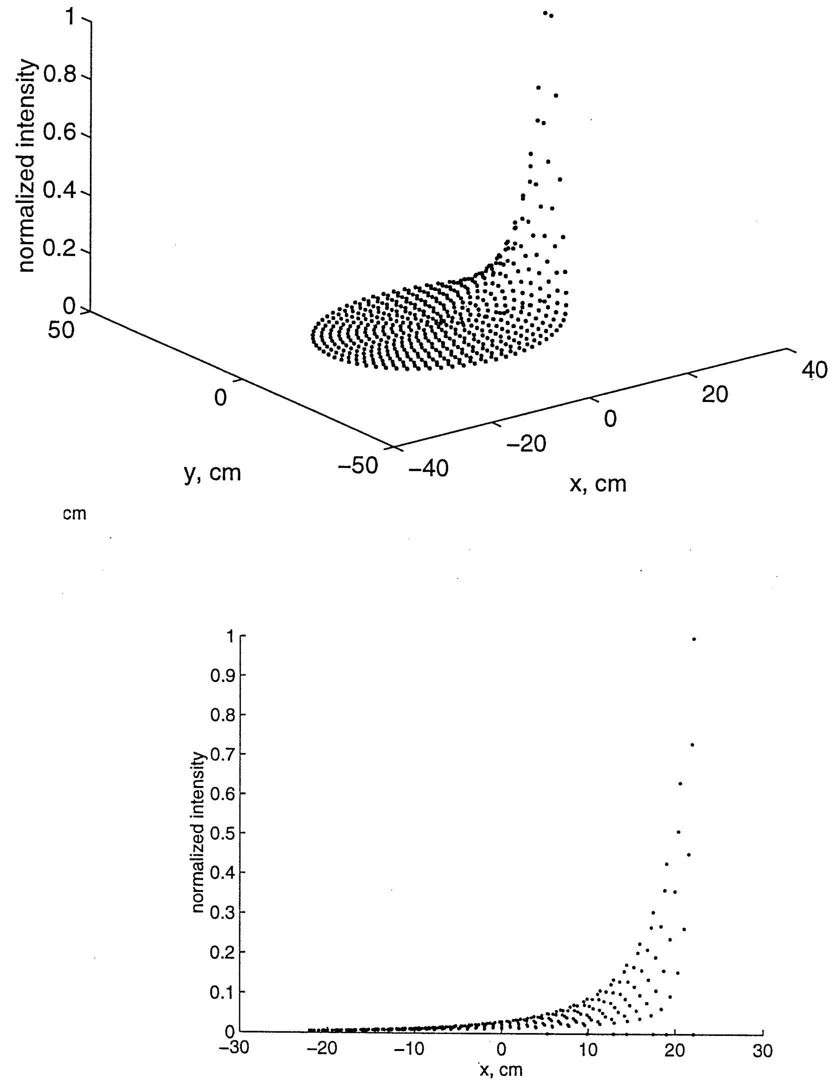


Figure D.1: (a) Three dimensional view of the (x,y) spatial distribution of intensity in a cross sectional slice of the reactor. Each '.' denotes a discrete source point at an (x,y) location. Position of detector is shown in Figure D.2 . Contribution of the shaded region in Figure D.2 is 90 %. (b) Front view (along x-axis)

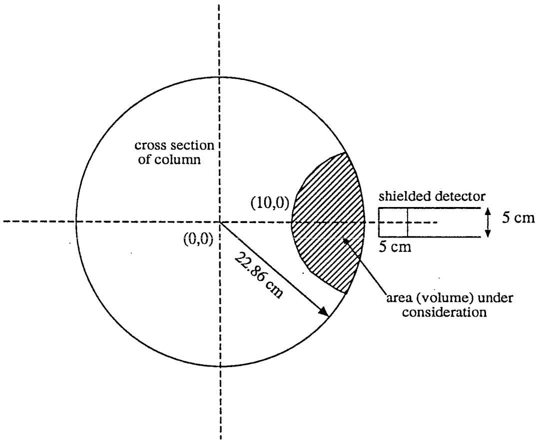


Figure D.2: Cross sectional view of the column with detector positioned along the 'x' axis. Shaded region represents the region considered for the contribution of radiation to the overall radiation received by detector

Appendix E

Calibration of Detectors for Radioactive Tracer Experiments in AFDU

This appendix discusses some of the issues regarding calibration of the scintillation detectors for radioactive tracer measurements in the AFDU reactor, and provides suggestions for improvement in the quality of tracer data.

E.1 Background Radiation

The background radiation is usually subtracted from the tracer response data of each detector. This is done by subtracting each detector reading recorded before the tracer experiment, with the syringe containing the tracer positioned along the reactor at the injection point. This is not the true background, since before the tracer experiment, some of the detectors close to the injection syringe see radiation from the syringe. Once the tracer is injected into the column, the syringe is empty. Therefore subtracting the reading from a detector close to the syringe results in a biased output. This is seen from Figure E.1 (a) - (c). Fig E.1 (a) shows an arbitrary tracer response as measured by a detector close to the injection point. The radiation seen by the detector from the tracer in the syringe prior to injection is 50 counts/time. If 50 was considered to be the background noise and sustracted from the detector response, this would result in a response as shown in Fig E.1 (b). However, supposing the true background is 10 counts/time, subtracting this would result in a tracer response as shown in Figure E.1 (c).

Normalizing each of these responses, in Figure E.1 (b) and (c), by its individual maximum, as is done for comparison with model predictions, results in responses as shown in Figure E.1 (d). The dotted line indicates the correct response, while the solid line indicates the biased response due to improper background subtraction.

Therefore the background readings for the detectors should be taken before loading the syringe with the tracer onto the column, i.e. the background reading should truly be what the detector measures in the absence of any significant radiation source. This then will be the lowest reading that the detector records.

E.2 Normalization of Detectors

The procedure used for normalization apparently consists of stacking all your detectors (6" tall, 2' wide pile) and placing in front of them a point source of 1 mCi Co-60 approximately 1 m away, to create a field strength of 1mrem. Noting the readings in each of the detectors, the detector with the maximum counts is considered to have an efficiency of 100 %. The efficiency of the other detectors is calculated by dividing the individual reading by that of the detector with 100 % efficiency. These efficiencies are then used to normalize each detector for a given experiment, after subtracting the background radiation.

In the above procedure

1. The detectors when they are stacked up are not shielded.
2. In addition, the source is aligned along the axis of one detector in the center, while for others it is totally off the axis.

The combination of 1. and 2. results in effects of solid angle, which is larger for the detectors at the edge of the stack than for those in the center. Figure E.2 shows the view of the detectors seeing a point source. For the sake of clarity only two detectors are shown. Detector A, for which the source is aligned along the axis of the detector, "sees" the radiation with only its front circular face. In contrast detector B is exposed to radiation on both its front and side. Thereby the intensity measured by B (at the edge of the stack) is larger than A (in the center).

Calculation of the solid angle subtended by detectors A and B using dimensions given above, show that for detector B the solid angle is 1.17 times larger than that of A. 25 % of the solid angle for detector B comes from the contribution of the cylindrical (side) surface.

In practice, there is a whole stack of detectors. Therefore the path for the γ radiation between the source and the side (cylindrical) surface of detector B is affected by the presence of other detectors. Nevertheless, detector B will still be exposed to more radiation than A. This becomes important since, during the actual tracer experiment all the detectors are shielded. Therefore the above procedure of recording the radiation will lead to a bias, which may become significant during normalization.

To rectify this, it is necessary to place all the detectors in a perfectly uniform field. Ideally one must place all the detectors in a circle as shown in Figure E.3, in the same horizontal plane. By placing an isotropic point source in the center of the circle (Figure E.3), a uniform solid angle is subtended by each detector at the source location. This rules out any sort of bias due to non-uniform "viewing" by each detector and may result in better normalization of the detector responses. However, this is not practical since the source is usually shielded, with a small angled window for passage of the γ radiation. Therefore, an alternative to the above ideal situation is to place all the detectors on a ring similar to what is shown in Figure E.3, but vertically, with the active surface of the detectors pointing downwards. This ring should be held at a certain distance above the ground. Below the ring of detectors, in the center of the ring, the source can be placed with its window directed upwards, such that the cone beam of radiation from the source points upwards. Provided the source emits isotrpically, all the detectors which are now symmetric with respect to the source will be in a uniform radiation field and will have the same solid angle. If however, the beam of radiation from the shielded source is only a fan beam, then the detectors should be arranged in groups (of certain number) in a fan beam array (similar to CT mode of scanning), for measurement of radiation.

As a precaution, it is necessary in the above procedure to rotate the source, or the ring of detectors about its center of radius, to ensure that the source is isotropic.

To summarize, the normalization must be done by recording the detector responses in a completely unifrom field strength with uniform "viewing factor" for each detector. This should be done after background subtract.

E.3 Remnant Tracer in Injection Line

Any remnant tracer in the injection lines must be removed, in order to get a true estimate of the tracer distribution in the reactor and the exit line at large times.

All the above described effects contribute to unequal intensity measurements by the detectors at large times. With the suggested changes, better measurements should be obtained, with uniform readings at large times indicating uniform tracer distribution. In fact, if indeed there is settling of solids (and therefore the tracer), this should also be seen from the tracer data.

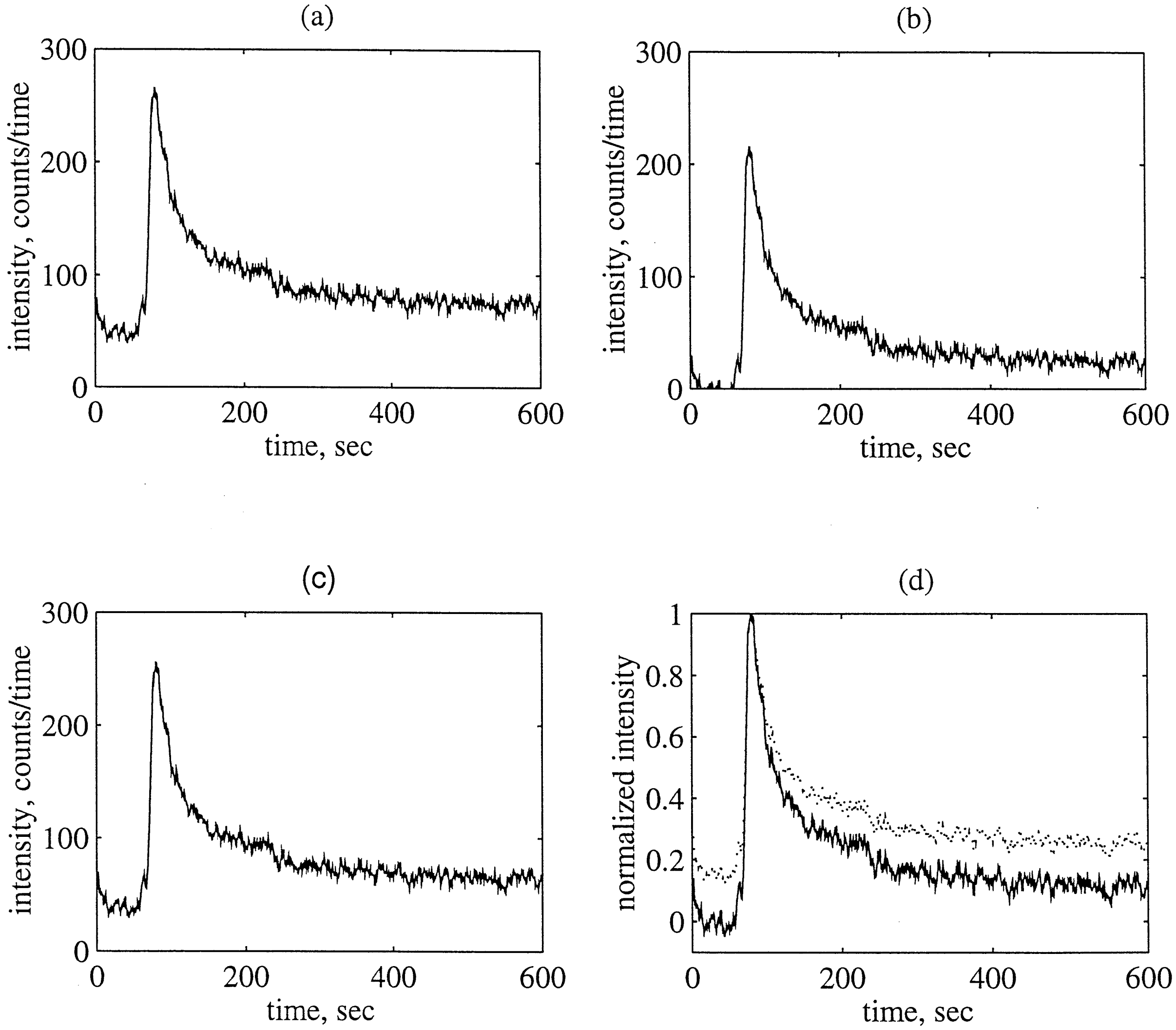


Figure E.1: Effects of the type of Background Subtract on Radiation Measurements

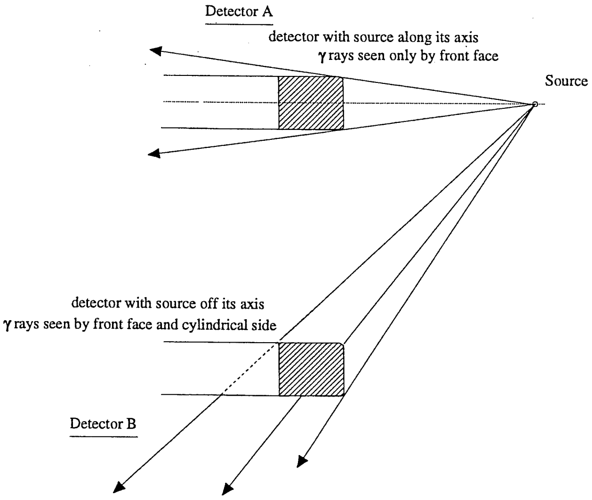


Figure E.2: Top View of Detectors Positioned for Measurement to Calculate Detector Efficiencies

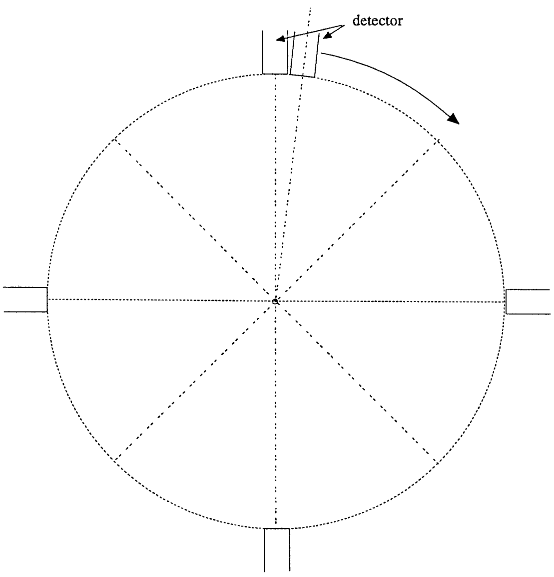


Figure E.3: Top View of Proposed Arrangement of Detectors for Measurement to Calculate Detector Efficiencies

Appendix F

Radioactive Liquid Tracer Response Measurements in the AFDU During Methanol Synthesis

F.1 Individual Detector Responses at Two Axial Measurement Levels for Run 14.6, Wall Injection at Level N1

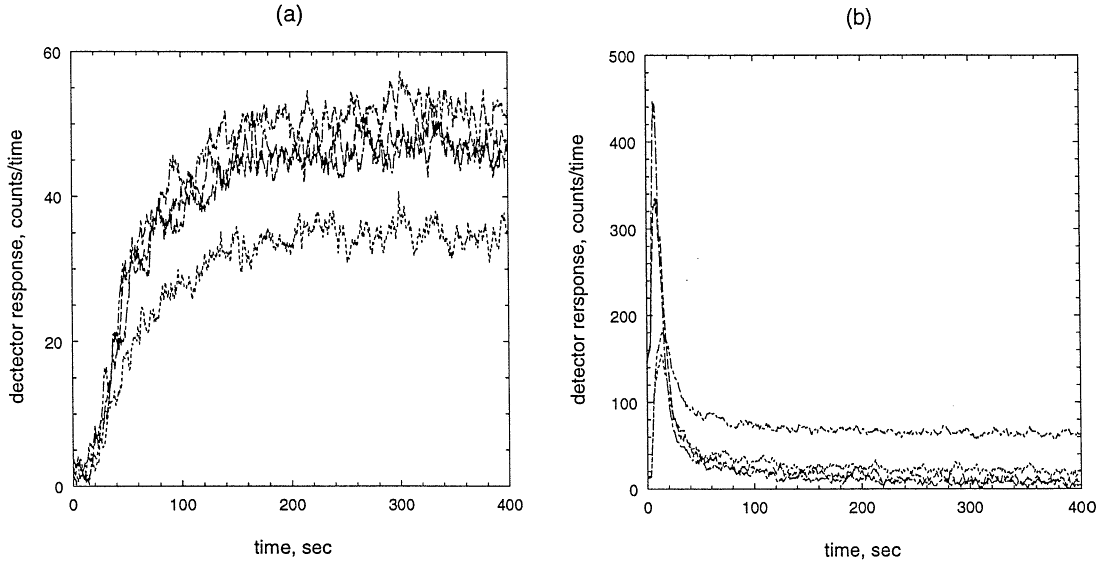


Figure F.1: Individual Detector Responses at (a) Level 1 (b) Level 5

F.2 Comparison of 2 D Model Predictions with Experimental Data

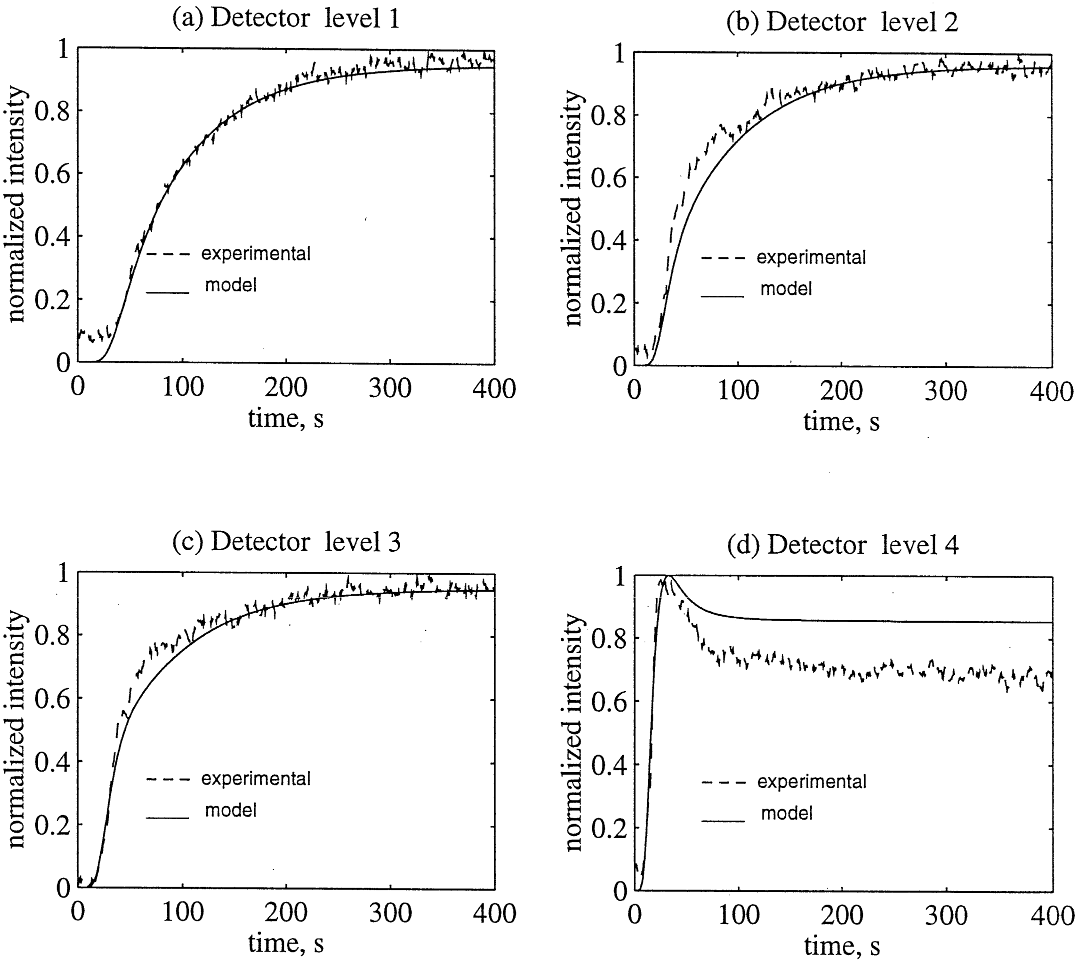
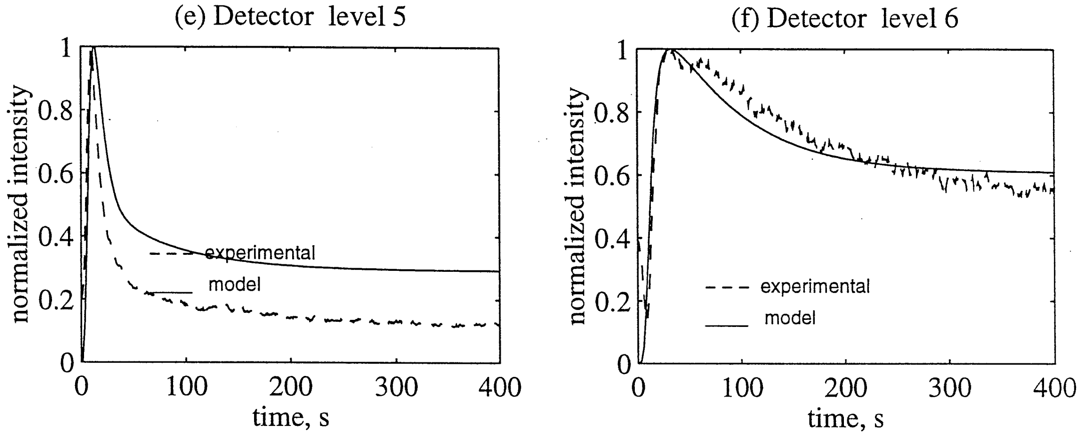


Figure F.2: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N1, Run 14.7



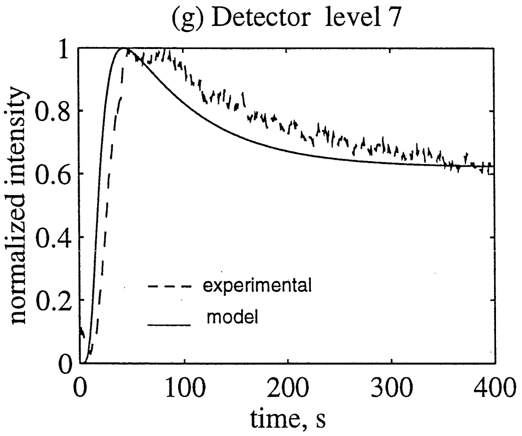
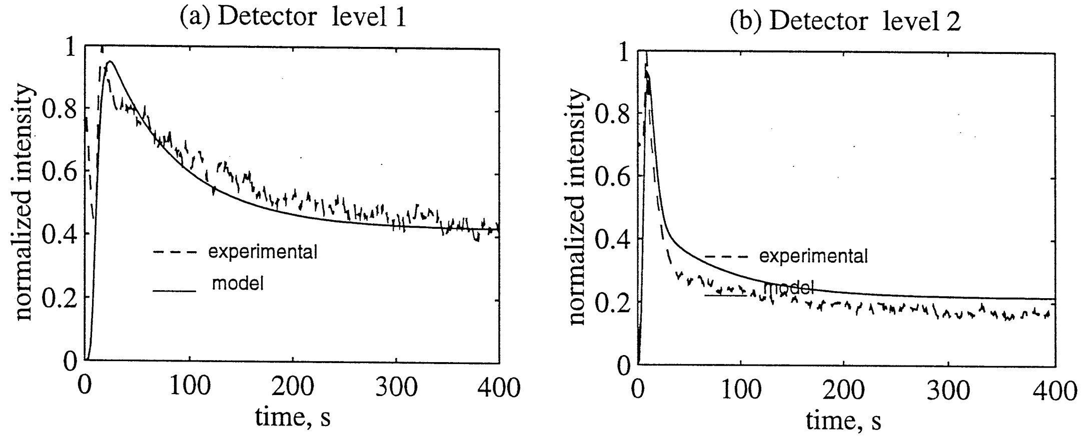


Figure F.3: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N1, Run 14.7



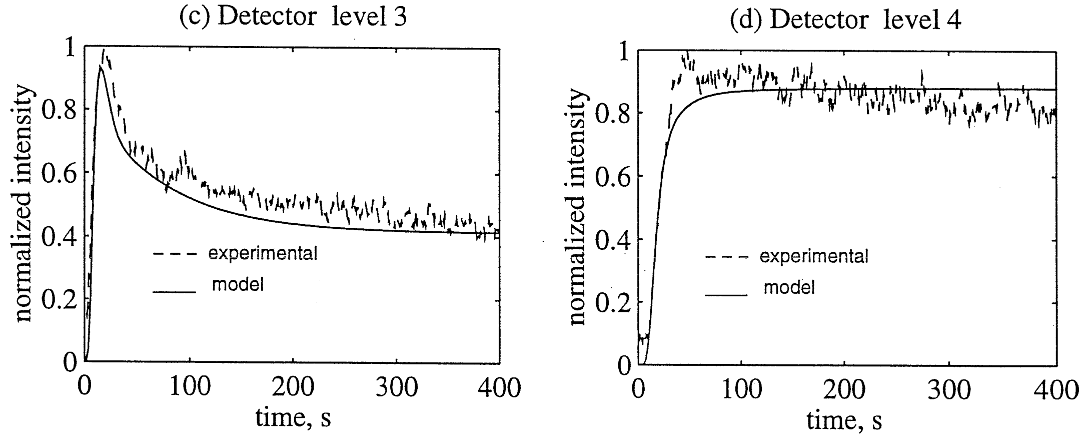
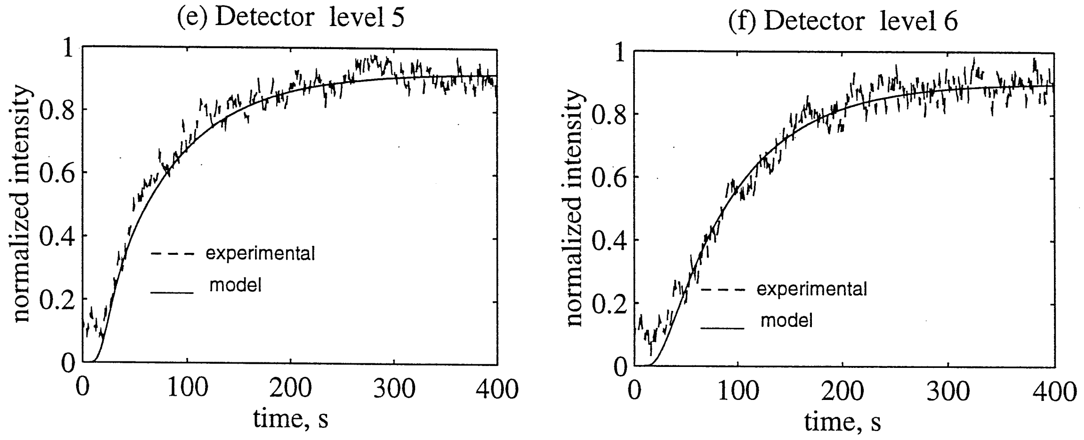


Figure F.4: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N2, Run 14.7



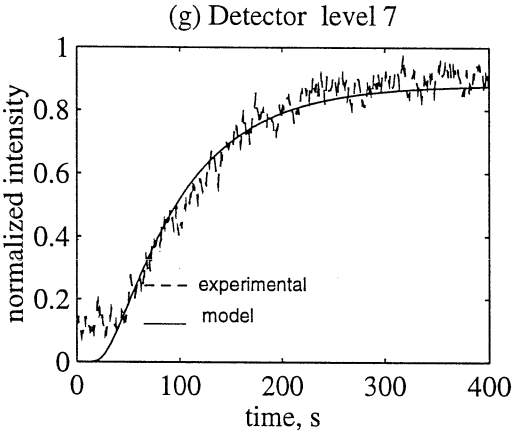
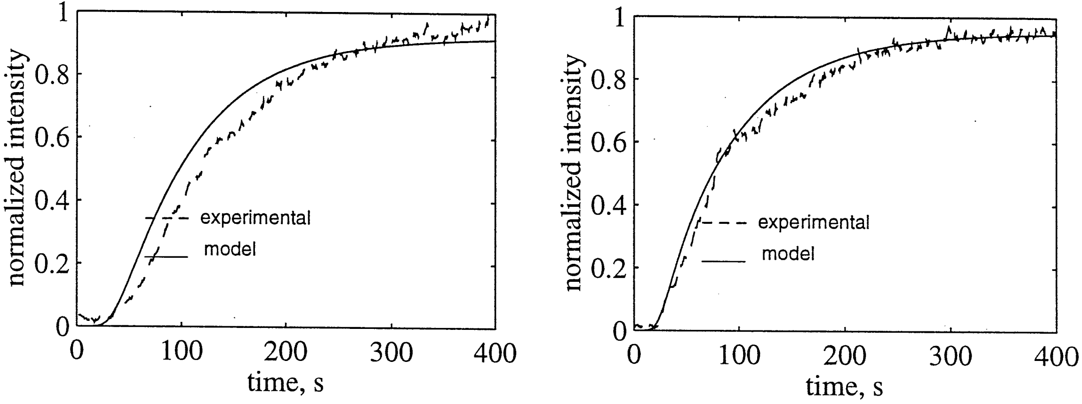
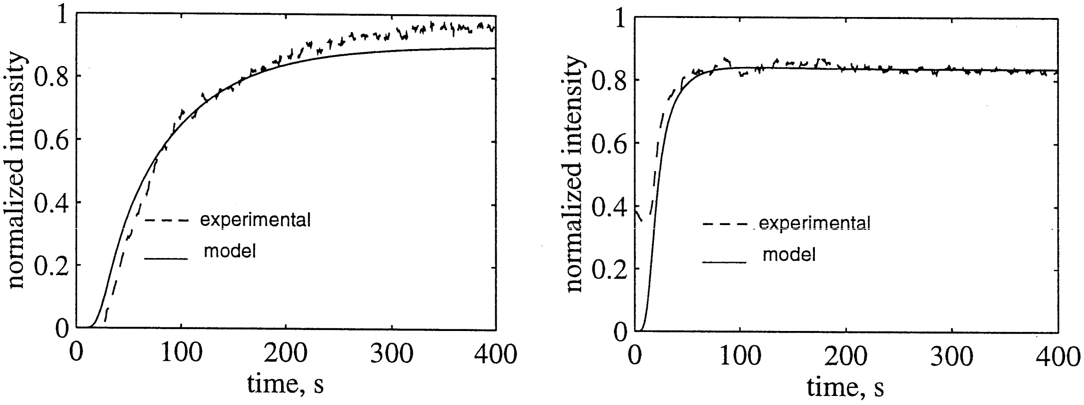


Figure F.5: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N2, Run 14.7



(a) Detector level 1

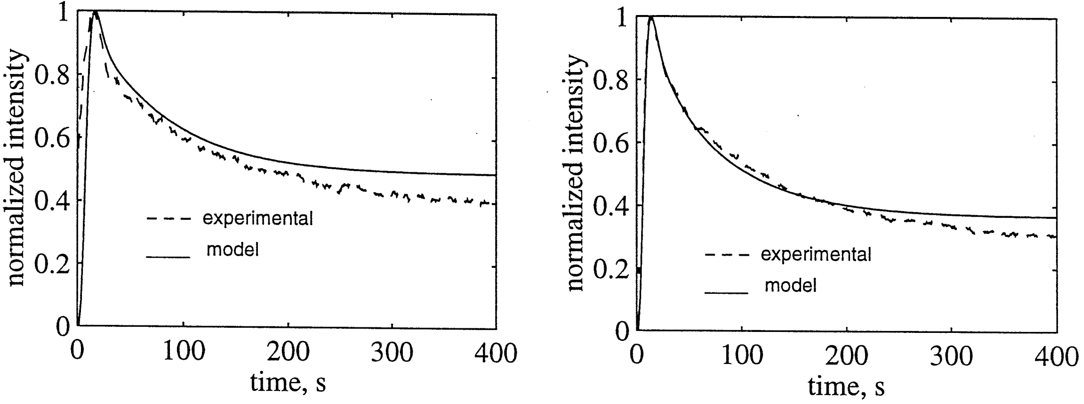
(b) Detector level 2



(c) Detector level 3

(d) Detector level 4

Figure F.6: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N1, Run 14.7



(e) Detector level 5

(f) Detector level 6

(g) Detector level 7

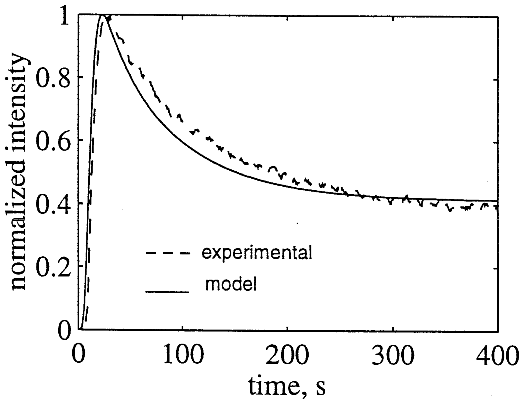
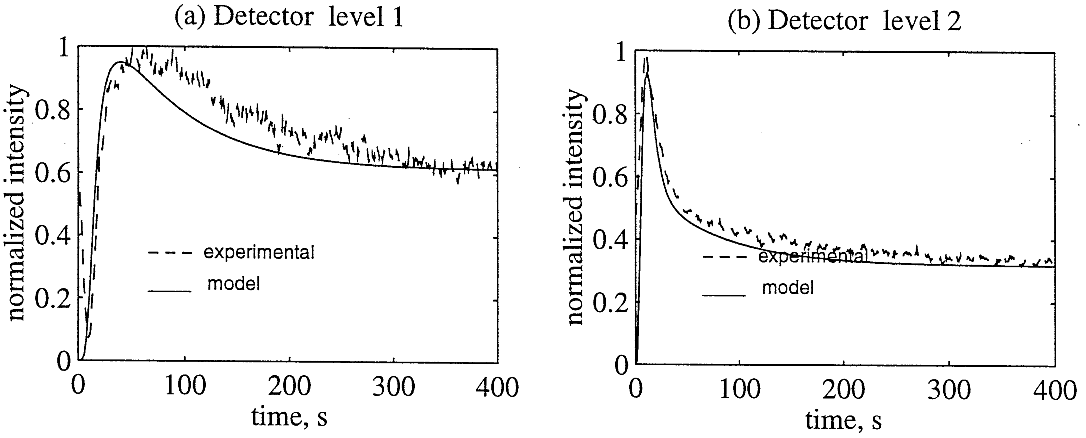


Figure F.7: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N1, Run 14.7



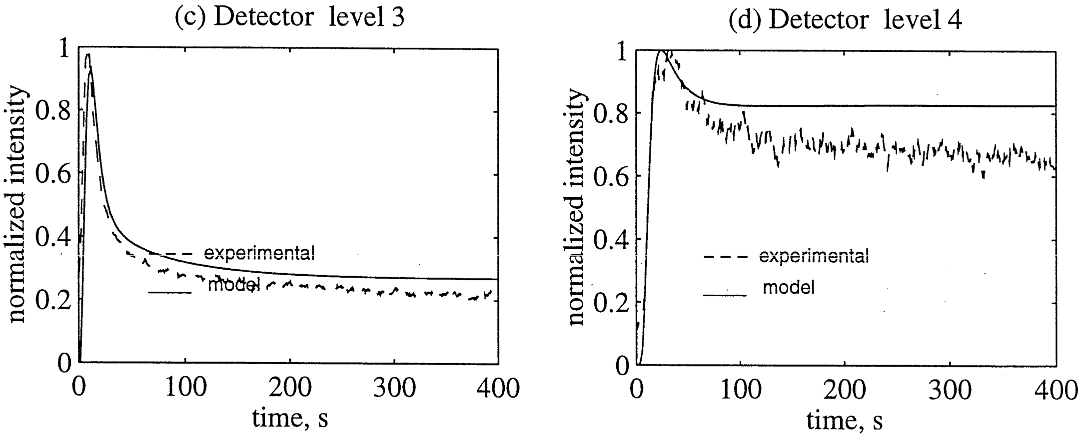


Figure F.8: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N2, Run 14.7

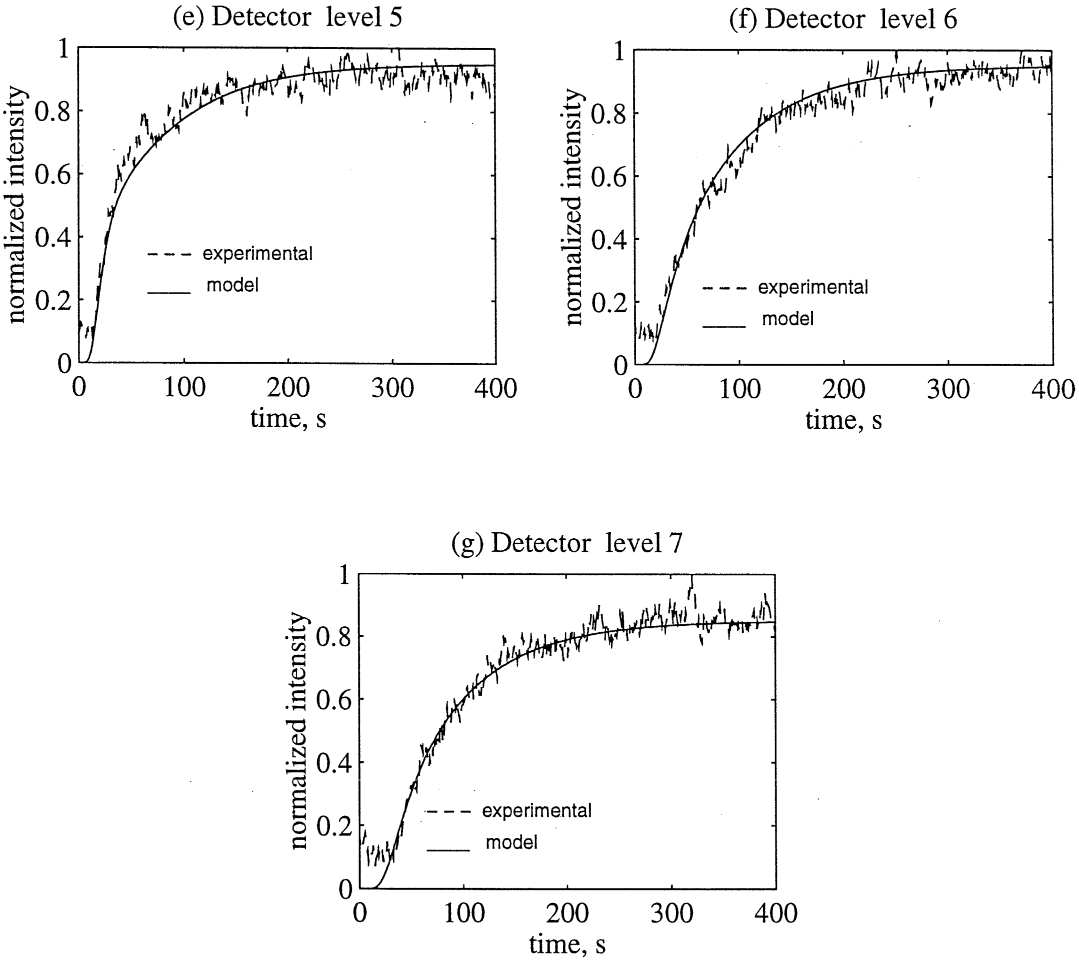
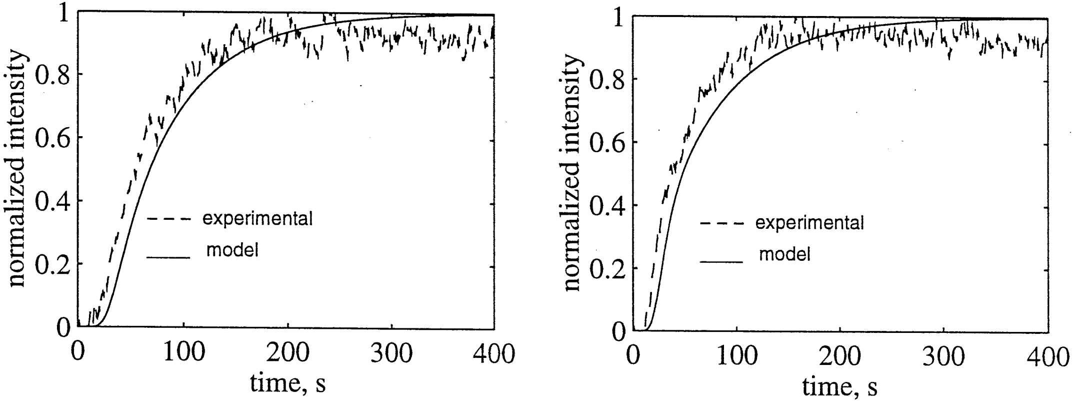
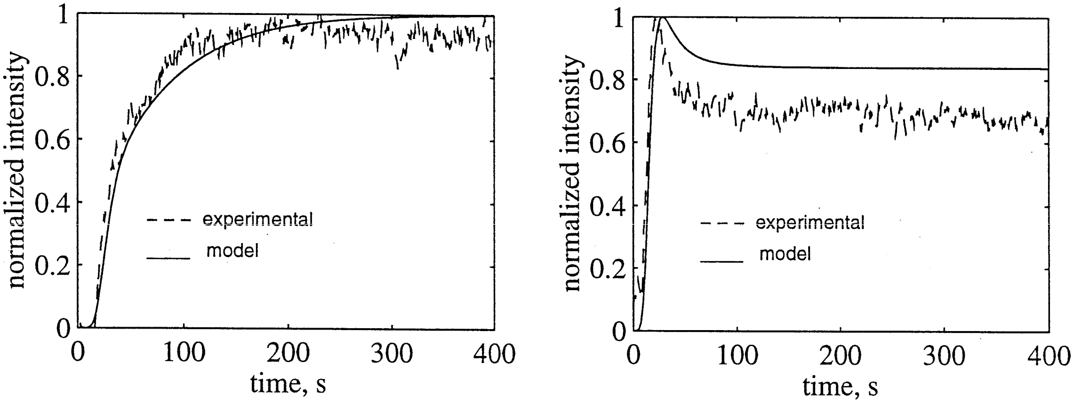


Figure F.9: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N2, Run 14.7


(a) Detector level 1

(b) Detector level 2


(c) Detector level 3

(d) Detector level 4

Figure F.10: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N1, Run 14.8

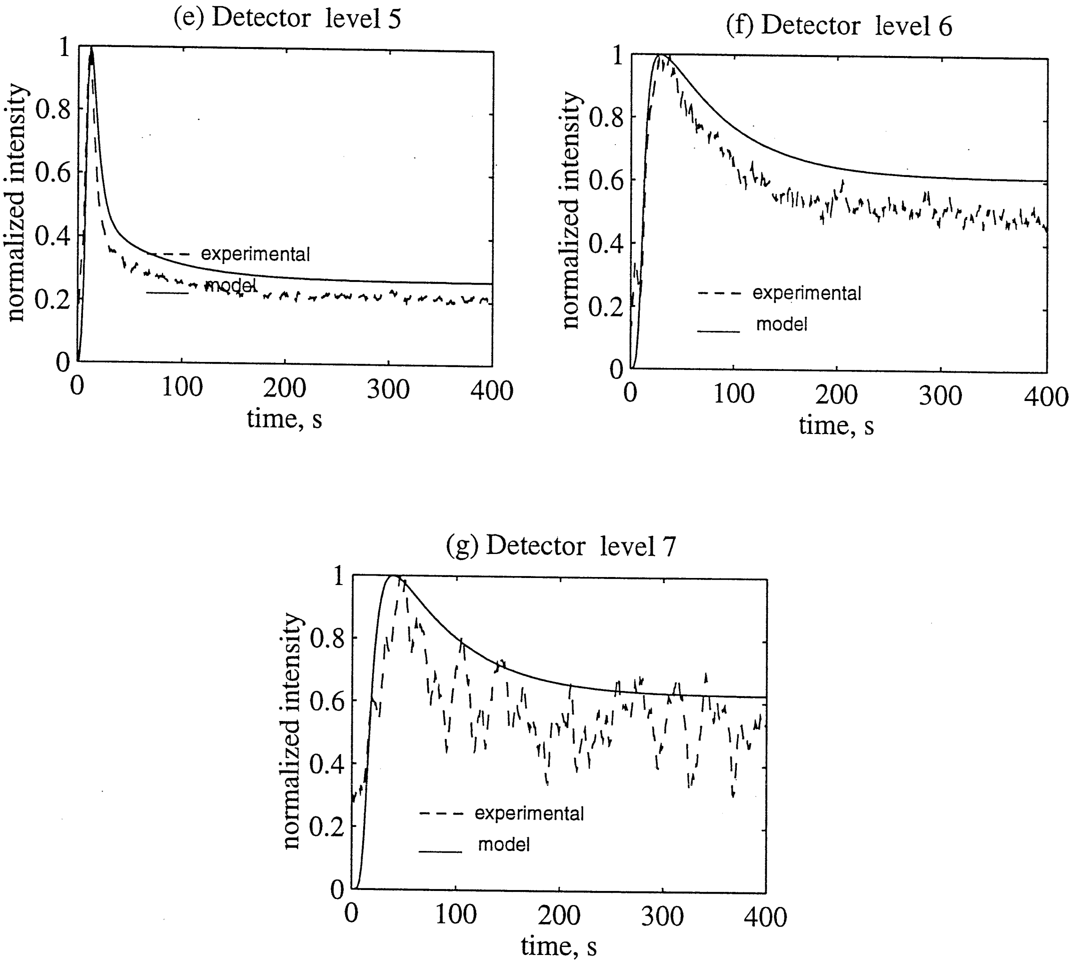


Figure F.11: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N1, Run 14.8

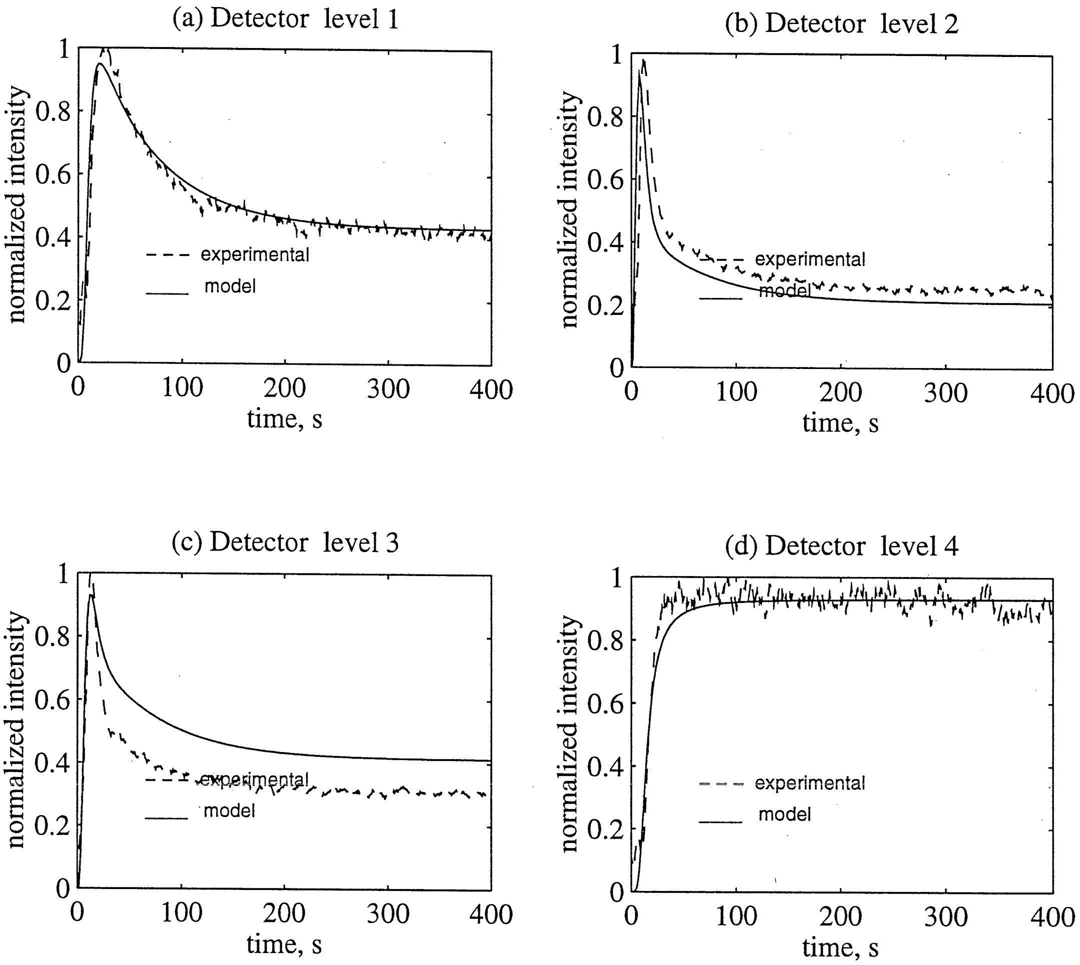
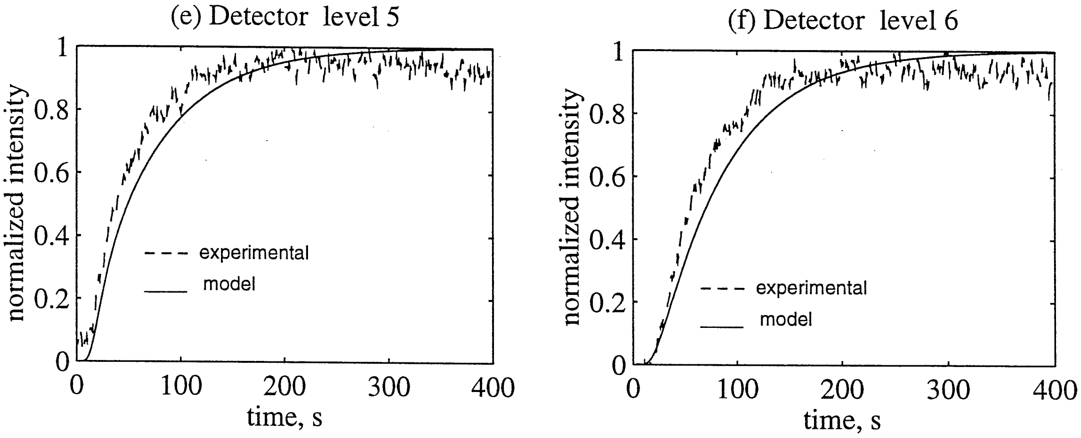


Figure F.12: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N2, Run 14.8


(e) Detector level 5

(f) Detector level 6

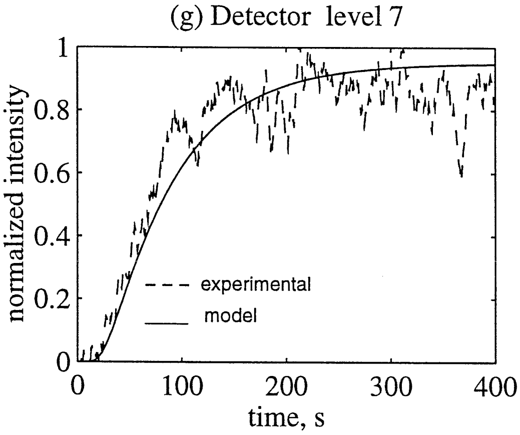

(g) Detector level 7

Figure F.13: Comparison of Model Prediction with Experimental Detector Responses for Wall Injection at Level N2, Run 14.8

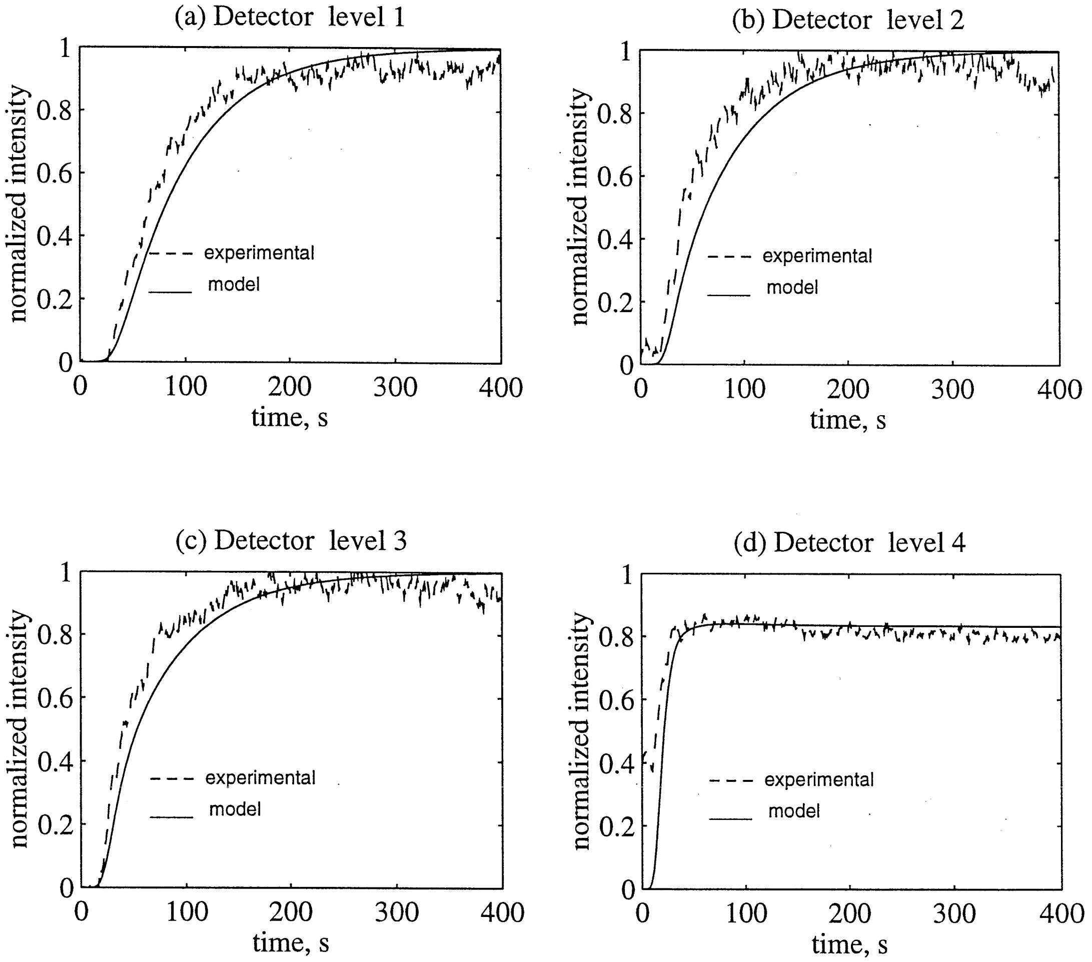
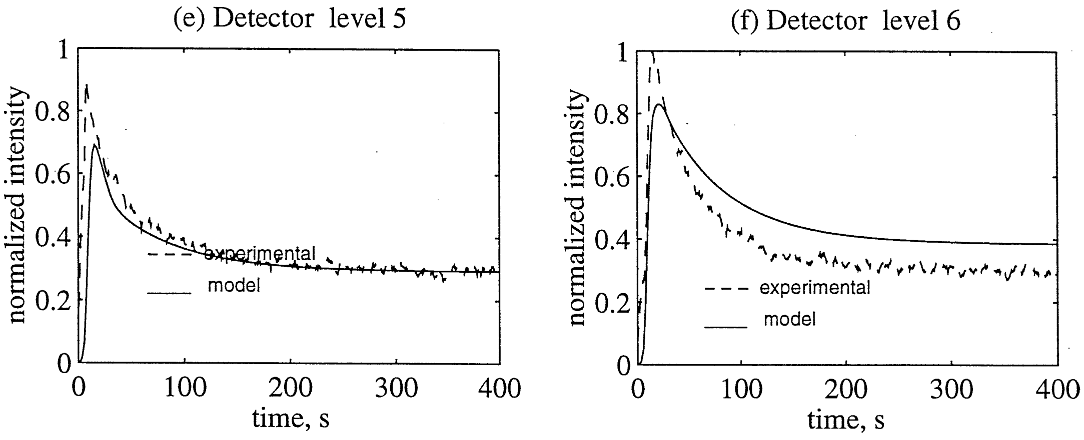


Figure F.14: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N1, Run 14.8



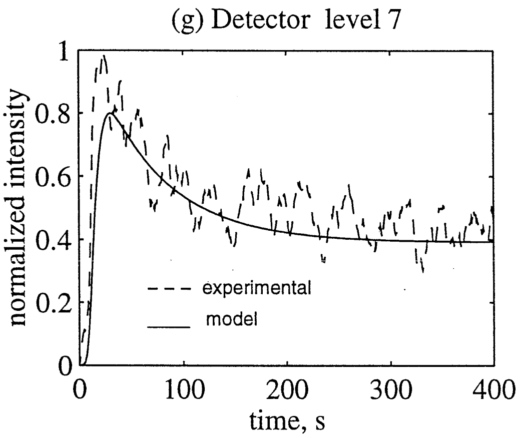
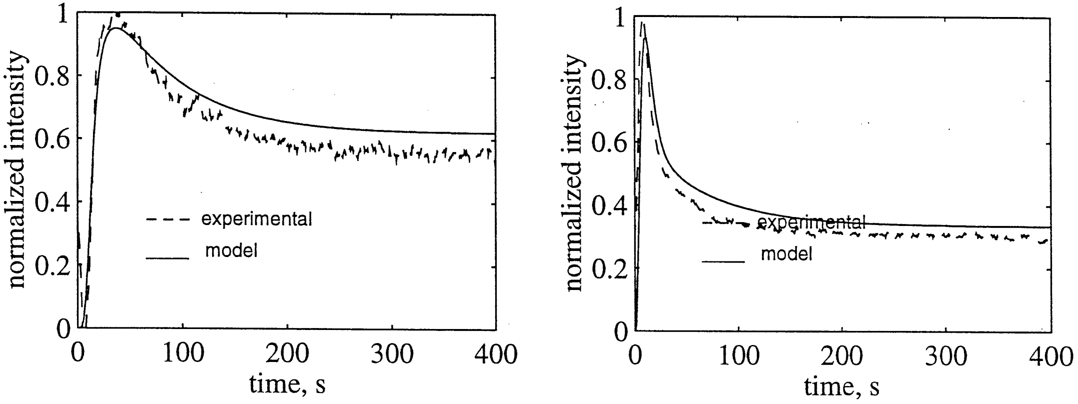
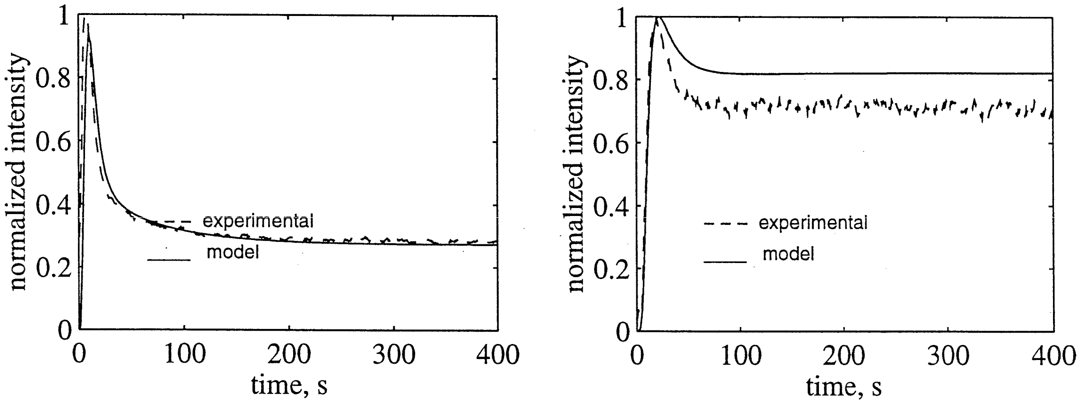


Figure F.15: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N1, Run 14.8


(a) Detector level 1

(b) Detector level 2

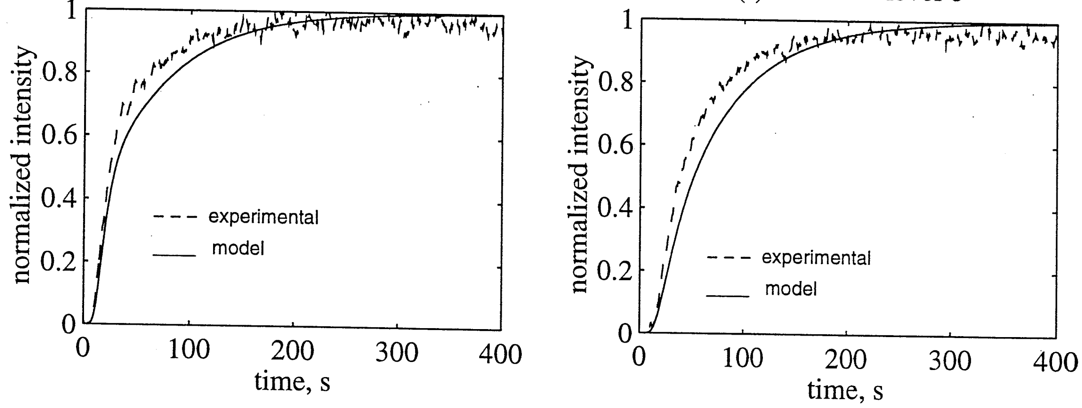

(c) Detector level 3

(d) Detector level 4

Figure F.16: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N2, Run 14.8

(e) Detector level 5

(f) Detector level 6



(g) Detector level 7

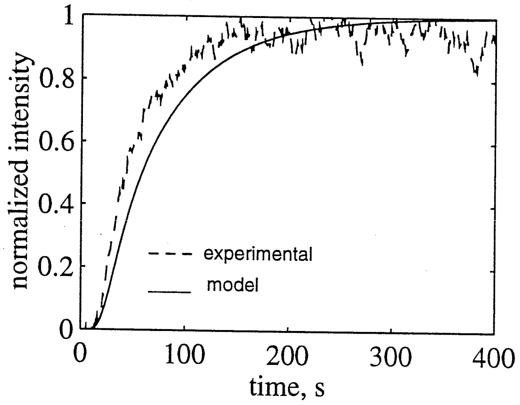


Figure F.17: Comparison of Model Prediction with Experimental Detector Responses for Center Injection at Level N2, Run 14.8

Appendix G

Application of RCFDM in the Presence of Homogeneous Liquid Phase Reaction

In this appendix the behavior of the recycle with cross flow and dispersion (RCFD) model in the presence of homogeneous liquid phase reaction (nonlinear kinetics) is studied. The objective is to compare the RCFDM with the one dimensional Axial Dispersion Model (ADM), using model parameters obtained for the same RTD. For this purpose, a set of two parallel irreversible reactions is considered:

$$2A \xrightarrow{k_1} P \qquad r_P = k_1 C_A^2 \tag{G.1}$$

$$A \xrightarrow{k_2} S \qquad r_S = k_2 C_A \tag{G.2}$$

The operating conditions of Myers et al. (1986), whose experiments were conducted in a column of diameter 19 cm, at a superficial gas velocity of 10 cm/s and a liquid velocity of 1 cm/s, are considered here. The reported mean residence time, for a gas-liquid dispersion height of 244 cm, is 203 s. The model parameters for RCFDM : D_1=285 cm^2/s, D_2=440 cm^2/s and $D_{ri} = 34$ cm^2/s, are obtained from CARPT/CT experiments as described in Chapter 6.2. The axial dispersion coefficient, obtained by fitting the ADM (without reaction) to the tracer response data of Myers et al. (1986), is D_{ax}=352 cm^2/s.

The behavior of the RCFDM is studied for various values and ratios of k_1 and k_2. Results are tabulated in Table G.1. The conversion of reactant A is given by $X_A = (C_{A_o} - C_A)/C_{A_o})$. Both RCFD and ADM yield near about the same results for both conversion and selectivity with only minor discrepancies. This suggests that with model parameters for the same RTD, both the models yield similar predictions for the conversion and selectivity for the set of parallel reactions considered here. It is noted, however, that for all cases the assumption of complete backmixing reduces the conversion. For situations involving close to complete conversion, the assumption of complete backmixing will result in considerable over-sizing of the reactor.

Table G.1: Predicted Conversion and Selectivity for Various Values of k_1 and k_2

k_1 cc/mol. s	k_2 1/s	CSTR	RCFDM		ADM	
		X_A	X_A	C_P/C_{A_o}	X_A	C_P/C_{A_o}
0.0006	0.0018	0.307	0.321	0.2585	0.3186	0.2571
0.05	0.15	0.968	0.998	0.9696	0.9973	0.9630
0.015	0.005	0.6661	0.7244	0.3482	0.7184	0.3466
0.0018	0.0006	0.2256	0.2895	0.0894	0.2877	0.0890
0.01	0.001	0.5317	0.5756	0.0972	0.5708	0.0967
0.05	0.05	0.9155	0.9730	0.8598	0.9690	0.8527

References

[1] Adkins, D. R., K. A. Shollenberger, T. J. O'Hern and J. R. Torczynski, 'Pressure Effects on Bubble Column Flow Characteristics', *ANS Proceedings of the National Heat Transfer Conference*, THD-Vol. 9, 318-325 (1996).

[2] Adrian, R. J., 'Imaging Techniques for Experimental Fluid Mechanics', *Ann. Rev. Fluid. Mech.*, Vol. 23, 261-304 (1991).

[3] Akita, K and F. Yoshida, 'Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns', *Ind. Eng. Chem. Proc. Des. Dev.*, Vol. 12, 76-80 (1973).

[4] Anderson, K. G., *Analytical Prediction of Circulation and Dispersion in Bubble Columns*, M.S. Thesis, Luisiana State University, Baton Rouge LO (1989).

[5] Anderson, K. G. and R. G. Rice, 'Local Turbulence Model for Predicting Circulation Rates in Bubble Columns', *AIChE Journal*, Vol. 35, 514-518 (1989).

[6] Aoyama, Y., K. Ogushi, K. Koide and H. Kubota, 'Liquid Mixing in Concurrent Bubbles Columns', *J. Chem. Eng. Japan*, Vol. 1, 158-163 (1968).

[7] Argo, W. B. and D. R. Cova, 'Longitudinal Mixing in Gas-Sparged Tubular Vessels', *Ind. Eng. Chem. Proc. Des. Dev.*, Vol. 4, 352-359 (1965).

[8] Azbel, D., "Two Phase Flows in Chemical Engineering", Cambridge University Press, Cambridge (1981).

[9] Baird, M. H. and R. G. Rice, 'Axial Dispersion in Large Unbaffled Columns', *Chem. Eng. J.*, Vol. 9, 171-174 (1975).

[10] Berg, S., S. Schluter, P. -M. Weinspach, 'Ruckvermischung in Blasensaulen mit Einbauten', *Chem. -Ing. -Tech.*, Vol. 67, 289-299 (1995).

[11] Chabot, J and H. I. De Lasa, 'Gas Holdup and Bubble Characteristics in a Bubble Column Operated at High Temperature', *Ind. Eng. Chem. Res.*, Vol. 32, 2595-2601 (1993).

[12] Chen, R. C., J. Reese and L. -S. Fan, 'Flow Structure in a Three-Dimensional Bubble Column and a Three-Phase Fluidized Bed', *AIChE Journal*, Vol. 40, 1093-1104 (1994).

[13] Chui, C. K., "Wavelet Analysis and its Applications: Volumne I, An Introduction to Wavelets", Academic Press (1992).

[14] Clark, N. N., C. M. Atkinson and R. L. C. Flemmer, 'Turbulent Circulation in Bubble Columns', *AIChE Journal*, Vol. 33, 575-578 (1987).

[15] Coifman, R. and M. V. Wickerhauser, 'Entropy-Based Algorithms for Best Basis Selection', *IEEE Trans. on Inf. Theory*, Vol. 38, 713-718 (1992).

[16] Coifman, R. R., F. Majid and M. V. Wickerhauser, 'Denoise', Preprint, Yale University (1993).

[17] Corrsin, S., 'An Account of Some Features of the Phenomenon in Fully Turbulent Regions', *Proc. of Iowa Thermodynamics Symposium*, 5-29, (1953).

[18] Csanady, G. T., 'Turbulent Diffusion of Heavy Particles in the Atmosphere', *J. Atmosh. Sci.*, Vol. 20, 201-208 (1963).

[19] Darton, R. C., R. D. LaNauze, J. F. Davidson and D. Harrison, 'Bubble Growth Due to Coalesence in Fluidized Beds', *Trans. Inst. Chem. Engr.*, Vol. 55, 274-280 (1977).

[20] Dasgupta, S. R. Jackson and S. Sundaresan, 'Turbulent Gas-Particle Flow in Vertical Risers', *AIChE Journal*, Vol. 40, 215-228 (1994).

[21] Daubechies, I., 'Orthonormal Bases of Compactly Supported Wavelets', *Comm. Pure Appl. Math.*, 41, 909-996 (1988).

[22] Daubechies, I., 'Ten Lectures on Wavelets', *CBMS-NSF Regional Conference Series in Applied Mathematics*, SIAM, Philadelphia (1992).

[23] Deckwer, W. D., U. Graeser, Y. Serpemen and H. Lanemann, 'Zones of Different Liquid Mixing in the Liquid Phase of Bubble Columns', *Chem. Engng. Sci.*, Vol. 28, 1223-1225 (1973).

[24] Deckwer, W. -D., R. Burckhart and G. Zoll, 'Mixing and Mass Transfer in Tall Bubble Columns', *Chem. Engng. Sci.*, Vol. 29, 2177-2188 (1974).

[25] Deckwer, W. -D., 'On the Mechanisms of Heat Transfer in Bubble Column Reactors', *Chem. Engng. Sci.*, Vol. 35, 1341-1346 (1980).

[26] Deckwer, W. D. and A. Schumpe, 'Bubble Columns- the State of the Art and Current Trends', *Int. Chem. Eng.*, Vol. 27, 405-422 (1987).

[27] Deckwer, W. D. and A. Schumpe, 'Improved Tools for Bubble Column Reactor Design and Scale-up', *Chem. Engng. Sci.*, Vol. 48, 889-911 (1993).

[28] Degaleesan, S, S. Roy, S. B. Kumar and M. P. Duduković, 'Liquid Mixing Based on Convection and Turbulent Dispersion in Bubble Columns', *Chem. Engng. Sci.*, Vol. 51, 1967-1976 (1996).

[29] Degaleesan, S., M. P. Duduković, B. A. Toseland and B. L. Bhatt, 'Tracer Studies of the LaPorte AFDU Reactor During Methanol Synthesis', Fourth Quarterly Report, DOE Contract DE-FC 2295 PC 95051 (1996b).

[30] De Lasa, H. I., S. L. P. Lee and M. A. Bergougnou, 'Bubble Measurement in Three-Phase Fluidized Beds Using a U-Shaped Optical Fiber', *Can. J. Chem. Eng.*, Vol. 62, 165-169 (1984).

[31] Delhaye, J. M., 'Hot-Film Anemometry in Two Phase Flow', Two Phase Flow Instrumentation, *Eleventh National ASME/AIChE Heat Transfer Conference*, Minneapolis, 58-69 (1969).

[32] Delnoij, E., F. A. Lammers, J. A. M. Kuipers and W. P. M. van Swaaij, 'Dynamic Simulation of Dispersed Gas-Liquid Two-Phase Flow Using a Discrete Bubble Model', *Chem. Engng. Sci.*, Vol. 52, 1429-1458 (1997).

[33] Deshpande, N. S., M. Dinkar and J. B. Joshi, 'Disengagement of the Gas Phase in Bubble Columns', *Int. J. Multiphase Flow*, Vol. 21, 1191-1201 (1995).

[34] De Swart, J. W. A., *Scale-up of a Fischer-Tropsch Slurry Reactor*, Ph.D. Thesis, University of Amsterdam, The Netherlands (1996).

[35] Devanathan, N., D. Moslemian and M. P. Duduković, 'Flow Mapping in Bubble Columns Usin CARPT', *Chem. Engng. Sci.*, Vol. 45, 2285-2291 (1990).

[36] Devanathan, N., *Investigation of Liquid Hydrodynamics in Bubble Columns via Computer Automated Radioactive Particle Tracking (CARPT)*, D.Sc. Thesis, Washington University, St. Louis, MO (1991).

[37] Dickin, F. J., R. A. Williams and M. S. Beck, 'Determination of Composition and Motion of Multicomponent Mixtures in Process vessels Using Electrical Impedance tomography - I. Principles and Process Engineering Applications', *Chem. Engng. Sci.*, Vol. 48, 1883-1897 (1993).

[38] Draper, N. R. and H. Smith, "Applied Regression Analysis", John Wiley and Sons, New York (1981).

[39] Drew, D. A., 'Mathematical Modeling of Two-Phase Flow', *Ann. Rev. Fluid Mech.*, Vol. 15, 261-291 (1983).

[40] Duduković, M. P., S. Degaleesan, P. Gupta and S. B. Kumar, 'Fluid Dynamics in Churn-Turbulent Bubble Columns: Measurements and Modeling', Proceedings

of the *ASME Fluids Engineering Division Summer Meeting*, Vancouver, June 22-26 (1997).

[41] Durst, F., A. Melling and J. H. Whitelaw, "Principles and Practice of Laser-Doppler Anemometry", Academic Press, London (1981).

[42] Elgobashi, S. E. and T. W. Abou-Arab, 'A Two-Equation Turbulence Model for Two-Phase Flows', *Phy. Fluids*, Vol. 26, 931-938 (1983).

[43] Euzen, J. P., P. Trambouze and J. P. Wauquier, "Scale-Up Methodology for Chemical Processes", Editions Technip, Paris (1993).

[44] Fan, L. -S., "Gas-Liquid-Solid Fluidization Engineering", Butterworths Series in Chemical Engineering, Boston (1989).

[45] Fan, L. -S. and K. Tsuchiya, "Bubble Wake Dynamics in Liquids and Liquid-Solid Suspensions", Butterworth-Heinemann, Boston (1990).

[46] Favre, A, 'Equations des Gaz Turbulents Compressibles', *J. Mechanique*, Vol. 4, 361-390 (1965).

[47] Franz, K., T. Borner, H.J. Kantorek and R. Buchholz, 'Flow Structures in Bubble Columns', *Ger. Chem. Eng.*, Vol. 7, 365-374 (1984).

[48] Gardner, R. P. and K. Verghese, 'On the Solid Angle Subtended by a Circular Disc', *Nucl. Instr. Meth.* , Vol. 93, 163-167 (1971).

[49] Gouesbet, G., A. Berlemont and A. Picart, 'Dispersion of Discrete Particles by Continuous Turbulent Motions', *Phys. Fluids*, Vol. 27, 827-837 (1984).

[50] Goto, Y, T. Okamoto and T. Terahata, 'Liquid Dispersion Coefficients in Bubble Columns', *Paper Presented at the 34th Annual Meeting of the Soc. Chem. Engrs. Japan* (1969).

[51] Govier, G. W. and K. Aziz, "The Flow of Complex Mixtures in Pipes", Van Nostrand Reinhold, New York (1972).

[52] Grienberger, J. and H. Hofmann, 'Investigations and Modelling of Bubble Columns', *Chem. Engng. Sci.*, Vol. 47, 2215-2220 (1992).

[53] Groen, J. S., R. F. Mudde and H. E. A. van den Akker, 'Time Dependent Behavior of the Flow in a Bubble Column', *Trans. Inst. Chem. Engr.*, A9-A16 (1995).

[54] Groen, J. S., R. G. C. Oldeman, R. F. Mudde and H. E. A. van den Akker, 'Coherent Structures and Axial Dispersion in Bubble Column Reactors', *Chem. Engng. Sci.*, Vol. 51, 2511-2520 (1996).

[55] Guy, C., P. J. Carreau and J. Paris, 'Mixing Characteristics and Gas Hold-Up of a Bubble Column', *Can. J. Chem. Eng.*, Vol. 64, 23-35 (1986).

[56] Hammer, H., H. Schrag, K. Hektor, K. Schonau, W. Kuster, A. Soemarno, U. Sahabi and W. Napp, ' New Sub-Functions on Hydrdynamics, Heat and Mass Transfer for Gas/Liquid and Gas/Liquid/Solid Chemical and Biochemical Reactors', *Frontiers in Chemical Reaction Engineering*, 464-474 (1984).

[57] Hatton, T.A. and E. N. Lightfoot, 'Dispersion, Mass Transfer and Chemical Reaction in multiphase Contactors- Part I. Theoretical Developments', *AIChE Journal*, Vol. 30, 235-243 (1984).

[58] He, J. and O. Simonin, 'Modilisation Numerique Des Ecoulements Turbulents Gaz-Solides En Conduite Verticale', Rapport HE-44/94/021A, Electricite de France (1994).

[59] Herringe, R. A. and M. R. Davis, 'Detection of Instantaneous Phase Changes in Gas-Liquid Mixtures', *J. Phys. E: Sci. Instr.*, Vol. 7, 807-812 (1974).

[60] Hida, T., "Brownian Motion", Springer Verlaag, New York (1980).

[61] Hikita, H and H. Kikukawa, 'Liquid-Phase Mixing in Bubble Columns: Effect of Liquid Phase Properties', *Chem. Eng. J.*, Vol. 8, 191-197 (1974).

[62] Hikita, H., S. Asai, K. Tanigawa, K. Segawa and M. Kitao, 'Gas Holdup in Bubble Columns', *Chem. Eng. J.*, Vol. 20, 59-67 (1980).

[63] Hills, J. H., 'Radial Non-Uniformity of Velocity and Voidage in a Bubble Column', *Trans. Inst. Chem. Engrs.*, Vol. 52, 1-9 (1974).

[64] Hills, J. H. and R. C. Darton, 'The Rising Velocity of a Large Bubble in a Bubble Swarm', *Trans. Inst. Chem. Engr.*, Vol. 54, 258-264 (1976).

[65] Hinze, J. O., "Turbulence", McGraw-Hill, New York (1975).

[66] Hjelmfelt, A. T. and L. F. Mockros, 'Motion of Discrete Particles in a Turbulent Fluid', *Appl. Sci. Res.*, Vol. 16, 149-161 (1966).

[67] Hochman, J. M. and J. R. McCord, 'Residence Time Distributions in Recycle Systems with Crossmixing', *Chem. Engng. Sci.*, Vol. 25, 97-107 (1970).

[68] Hughes, R. R., A. E. Handlos, H. D. Evans and R. L. Maycock, *Chem. Eng. Progr.*, Vol. 51, 57- (1955).

[69] Idogawa, K., K. Ikeda, F. Fukuda and S. Morooka, 'Effect of Gas and Liquid Properties on the Behavior of Bubble in a Bubble Column Under High Pressure', *Int. Chem. Eng.*, Vol. 26, 468-474 (1987).

[70] Ishii, M., "Thermo-Fluid Dynamic Theory of Two-Phase Flow", Eyrolles, Paris (1975).

[71] Jakobsen, H. A., *On the Modelling and Simulation of Bubble Column Reactors Using Two-Fluid Model*, Dr. Ing. Thesis, Universitet I Trondheim, Norway (1993).

[72] Jakobsen, H. A., B. H. Sannaes, S. Grevskott and H. F. Svendsen, 'Modeling of Bubbly Flows', presented at *Engineering Foundation Conference in Computational Fluid Dynamics in Chemical Reaction Engineering*, San Diego, October 13-18 (1996).

[73] Joseph, B. and R. L. Motard, "Wavelet Applications in Chemical Engineering", Kluwer Academic Publishers (1994).

[74] Joshi, J. B. and M. M. Sharma, 'A Circulation Cell Model for Bubble Columns', *Trans. Inst. Chem. Engrs.*, Vol. 57, 244-251 (1979).

[75] Joshi, J. B., 'Axial Mixing in Multiphase Contactors - A Unified Correlation', *Trans. Inst. Chem. Engrs.*, Vol. 58, 155-165 (1980).

[76] Joshi, J. B., V. V. Ranade, S. D. Gharat and S. S. Lele, 'Sparged Loop Reactors', *Can. J. Chem. Eng.*, Vol. 68, 705-741 (1990).

[77] Kantak, M. V., S. A. Shetty and B. G. Kelkar, 'Liquid Phase Backmixing in Bubble Column Reactors - A New Correlation', *Chem. Eng. Commun.*, Vol. 127, 23-34 (1994).

[78] Kara, S., B. G. Kelkar, Y. T. Shah and N. L. Carr, 'Hydrodynamics and Axial Mixing in a Three-Phase Bubble Column', *Ind. Eng. Chem. Process Des. Dev.*, Vol. 21, 584-594 (1982).

[79] Kashiwa, B. A. and R. A. Gore, 'A Four Equation Model for Multiphase Turbulent Flow', Presented at the *First Joint ASME/JSME Fluids Engineering Conference*, 1991.

[80] Kastanek, F., J. Zahradnik, J. Kratochvil and J. Cermak, "Chemical Reactors for Gas-Liquid Systems", Ellis Horwood, England (1993).

[81] Kato, Y., A. Nishiwaki, T. Fukuda and S. Tanaka, 'The Behavior of Suspended Solid Particles and Liquid in Bubble Columns', *J. Chem.. Eng. Japan*, Vol. 5, 112-118 (1972).

[82] Kato, Y. and A. Nishiwaki, 'Longitudinal Dispersion Coefficient of a Liquid in a Bubble Column', *Int. Chem. Eng.*, Vol. 12, 182-186 (1972).

[83] Kelkar, B. G. and Y. T. Shah, 'Hydrdynamics and Axial Mixing in a Three-Phase Bubble Column. Effect of Slurry Properties', *Ind. Eng. Chem. Process Des. Dev.*, Vol. 23, 308-313 (1984).

[84] Kelkar, B. G., S. R. Phulgaonkar and Y. T. Shah, 'The Effect of Electrolyte Solutions on Hydrodynamics and Backmixing Characteristics in Bubble Columns', *Chem. Eng. J.*, Vol. 27, 125-133 (1983).

[85] Kondukov, N. B., A. N. Kornilaev, I. M. Skachko, A. A. Akhromenkov and A. S. Kurglov, 'An Investigation of the Parameters of Moving Particles in a Fluidized Bed by a Radioisotopic Method', *Int. Chem. Eng.*, Vol. 4, 43-47 (1964).

[86] Krishna, R., P. M. Wilkinson, and L. L. van Dierendonck, 'A Model for Gas Holdup in Bubble Columns Incorporating the Influence of Gas Density on Flow Regime Transitions', *Chem. Engng. Sci.*, Vol. 46, 2491-2496 (1991).

[87] Krishna, R., D. E. Hennephof, J. Ellenberger, H. C. J. Hoefsloot, 'Analogous Description of the Hydrodynamics of Gas-Solid Fluidized Beds and Bubble Columns', *Chem. Eng. J. Bio. Eng. J.*, Vol 53, 80-101 (1993).

[88] Krishna, R., J. W. A. de Swart, D. E. Hennephof, J. Ellenberger, H. C. J. Hoefsloot, 'Influence of Increased Gas Density on Hydrodynamics of Bubble Column Reactors', *AIChE Journal*, Vol. 40, 112-119 (1994).

[89] Krishna, R. and J. Ellenberger, 'Gas Holdup in Bubble Column Reactors Operating in the Churn-Turbulent Flow Regime', *AIChE Journal*, Vol. 42, 2627-2634 (1996).

[90] Krishna, R., J. W. A. de Swart, J. Ellenberger, G. B. Martina and C. Maretto, 'Gas Holdup in Slurry Bubble Columns: Effect of Column Diameter and Slurry Concentrations', *AIChE Journal*, Vol. 33, 311-316 (1997a).

[91] Krishna, R., J. Ellenberger and C. Maretto, 'A Unified Approach to Dense Phase Backmixing in Fluidized Multiphase Reactors', Proceedings of The First

European Congress on Chemical Engineering, Florence, Italy, May 4-7, pp 1757-1760 (1997b).

[92] Koide, J., S. Morooka, K. Ueyama, A. Matsura, F. Yamashita, S. Jwamoto, Y. Kato, H. Inoue, M. Shigeti, S. Suzuki and T. Akehata, 'Behavior of Bubbles in Large Scale Bubble Columns', *J. Chem. Eng. of Japan*, Vol. 12, 98-104 (1979).

[93] Kolbel, H. and M. Ralek, 'The Fischer-Tropsch Synthesis in the Liquid Phase', *Catal. Rev. -Sci. Eng.*, Vol 21 (2), 225-274 (1980).

[94] Kuboi, R., I. Komasawa and T. Otake, 'Fluid and Particle Motion in Turbulent Dispersion- II', *Chem. Engng. Sci.*, Vol. 29, 651-657 (1974).

[95] Kumar, A., T. E. Degaleesan, G. S. Laddha and H. E. Hoelscher, 'Bubble Swarm Characteristics in Bubble Columns', *Can. J. Chem. Eng.*, Vol. 54, 503-508 (1976).

[96] Kumar, R. and N. R. Kuloor, 'The Formation of Bubbles and Drops', "Advances in Chemical Engineering", Edited by T. B. Drew, G. R. Cokelet, J. W. Hoopes and T. Vermeulen, Academic Press, Vol. 8, 256-368 (1970).

[97] Kumar, S. B., *Computed Tomography Measurements of Void Fraction and Modeling of the Flow in Bubble Columns*, Ph.D. Thesis, Florida Atlantic University, Boca Raton, FL (1994).

[98] Kumar, S. B., N. Devanathan, D. Moslemian and M. P. Duduković, 'Effect of Scale on Liquid Recirculation in Bubble Columns', *Chem. Engng. Sci.*, Vol. 49, 5637-5652 (1994).

[99] Kumar, S. B., W. B. Vanderheyden, N. Devanathan and N. T. Padial, 'Numerical Simulation and Experimental Verification of the Gas-Liquid Flow in Bubble Columns', *AIChE Symp. Ser. 0065-8812*, Vol. 305, 11-19 (1995).

[100] Kumar, S. B., M. P. Duduković and B. A. Toseland, 'Measurement Techniques for Local and Global Fluid Dynamic Quantities in Two and Three Phase Systems', "Non-Invasive Monitoring of Multiphase Flows", Edited by J. Chaouki, F. Larachi and M. P. Duduković, Elsevier, Chapter 1, 1-46 (1997).

[101] Lahey, R. T., 'The Analysis of Phase Separation and Phase Distribution Phenomena Using two-Fluid Models', *Nucl. Eng. Des.*, Vol. 122, 17-40 (1990).

[102] Lahey, R. T. Jr. and D. A. Drew, 'The Three Dimensional Time and Volume Averaged Conservation Equations of Two-Phase Flow', *Adv. Nucl. Sci. Tech.*, Vol. 20, 1-69 (1988).

[103] Lance, M. and J. Bataille, 'Turbulence in the Liquid Phase of a Uniform Bubbly Air-Water Flow', *J. Fluid Mech.*, Vol. 222, 95-118 (1991).

[104] Lapin, A. and A. Lubbert, 'Numerical Simulation of the Dynamics of Two-Phase Gas-Liquid Flows in Bubble Columns', *Chem. Engng. Sci.*, Vol. 49, 3661-3674 (1994).

[105] Larachi, F., G. Kennedy and J. Chaouki, 'A γ-Ray Detection System for 3-D Particle Tracking in Multiphase Reactors', *Nucl. Instr. Meth.*, Vol. A338, 568-576 (1994).

[106] Lee, N. and A. E. Dukler, 'Lagrangian Simulation of Dispersion in Turbulent Shear Flow with a Hybrid Computer', *AIChE Journal*, Vol. 22, 449-456 (1976).

[107] Lee, S. L. and F. Durst, 'On the Motion of Particles in Turbulent Duct Flows', *Int. J. Multiphase Flow*, Vol. 8, 125-146 (1982).

[108] Leibson, I., E. G., Holcomb, A. G. Cacoso and J.J. Jacmic, 'Rate of Flow and Mechanics of Bubble Formation from Single Submerged Orifices', *AIChE Journal*, Vol. 2, 296-306 (1956).

[109] Levenspiel, O. and T. J. Fitzgerald, 'A Warning on the Misuse of the Dispersion Model', *Chem. Engng. Sci.*, Vol. 38, 489-491 (1983).

[110] Lin, J. S., M. M. Chen and B. T. Chao, 'A Novel Radioactive Particle Tracking Facility for Measurement of Solids Motion in Gas Fluidized Beds', *AIChE Journal*, Vol. 31, 465-473 (1985).

[111] Lockett, M. J. and R. D. Kirkpatrick, 'Ideal Bubbly Flow and Actual Flow in Bubble Columns', *Trans. Inst. Chem. Engrs.*, Vol. 53, 267-273 (1975).

[112] Lubbert, A. T. Korte and B. Larson, 'Simple Measuring Techniques for the Determination of Bubble and Bulkphase Velocities in Bioreactors', *Appl. Biochem. Biotechnol.*, Vol. 14, 207-219 (1987).

[113] Lubbert, A. and B. Larson, ' Detailed investigation of the multiphase Flow in Airlift Tower Loop Reactors', *Chem. Engng. Sci.*, Vol. 45, 3047-3053 (1990).

[114] Lunin, G., J. Lamarre and K. Whitham, paper presented at the *UNITAR Third International Conference on Heavy Crude and Tar Sands*, Long Beach, CA, July 22-31 (1985).

[115] Luo, H. and H. F. Svendsen, 'Turbulent Circulation in Bubble Columns from Eddy Viscosity Distributions of Single-Phase Pipe Flow', *Can. J. Chem. Eng.*, Vol. 69, 1389-1394 (1991).

[116] Mallat, S. and Z. Zhong, 'Matching Pursuits with Time-Freqency Dictionaries', Preprint, NewYork University (1992).

[117] Mashelkar, R. A. and P. A. Ramachandran, 'Longitudinal Dispersion in Circulation Dominated Bubble Columns', *Trans. Inst. Chem. Engrs.*, Vol. 53, 274-277 (1975).

[118] Maxey, M. R. and J. J. Riley, 'Equation of Motion for Small Rigid Sphere in a Nonuniform Flow', *Phys. Fluids*, Vol. 26, 883-889 (1983).

[119] McHenry, K. W. and R. H. Wilhelm, 'Axial Mixing of Binary Gas Mixtures Flowing in a Random Bed of Spheres', *AIChE Journal*, Vol. 3, 83-91 (1957).

[120] Meek, C. C., *Statistical Characterization of Dilute Particulate Suspensions in Turbulent Fluid Fields*, Ph.D. Thesis, Univeristy of Illinois, Urbana, IL (1972).

[121] Mei, R., R. J. Adrian and T. J. Hanratty, 'Particle Dispersion in Isotropic Turbulence Under Stokes Drag and Basset Force with Gravitational Settling', *J. Fluid Mech.*, Vol. 225, 481-495 (1991).

[122] Menzel, T., T. in der Weide, O. Staudacher, O. Wein and U. Onken, 'Reynolds Shear Stress for Modelling of Bubble Column Reactors', *Ind. Eng. Chem. Res.*, Vol. 29, 988-994 (1990).

[123] Millies, M. and D. Mewes, 'Calculation of Circulating Flows in Bubble Columns', *Chem. Engng. Sci.*, Vol. 50, 2093-2106 (1995).

[124] Millies, M. and D. Mewes, 'Back-Mixing of the Continuous Phase in Bubble Columns', *Chem. Engng. Sci.*, Vol. 50, 2107-2116 (1995).

[125] Miyauchi, T., S. Furusaki, S. Morooka and Y. Akida, 'Transport Phenomena and Reaction in Fluidized Catalyst Beds', "Advances in Chemical Engineering", Edited by T.B. Drew, G.R. Cokelet, J.W. Hoopes, Jr. and T. Vermeulen, Vol. 11, 275-448, Academic Press, New York (1981).

[126] Monin, A. S. and A. M. Yaglom, "Statistical Fluid Mechanics: Mechanics of Turbulence (Volume 1)", The MIT Press, Cambridge (1971).

[127] Moslemian, D. *Study of Solids Motion, Mixing and Heat Transfer in Gas-Solid Fluidized Beds*, Ph.D. Thesis, University of Illinois, Urbana, IL (1987).

[128] Moslemian, D., N. Devanathan and M. P. Duduković, 'Radioactive Particle Tracking technique for Investigation of Phase Recirculation and Turbulence in Multiphase Systems', *Rev. Sci. Instrum.*, Vol. 63, 4361-4372 (1992).

[129] Mudde, R. F., J. S. Groen and H. E. A. van den Akker, 'Liquid Velocity Field in a Bubble Columns: LDA Experiments', Paper submitted to the *Third International Conference on Gas-Liquid-Solid Reactor Engineering* (1997).

[130] Myers, K. J., *Liquid-Phase Mixing in Churn-Turbulent Bubble Columns*, D.Sc. Thesis, Washington University, St. Louis, MO (1986).

[131] Myers, K. J., M. P. Duduković and P. A. Ramachandran, 'Modeling of Churn-Turbulent Bubble Columns- I: Liquid Phase Mixing', *Chem. Engng. Sci.*, Vol. 42, 2301-2311 (1986).

[132] Neti, S. and O. E. E. Mohamed, 'Numerical Simulation of Turbulent Two-Phase Flows', *Int. J. Heat and Fluid Flow*, Vol. 11, 204-213 (1990).

[133] Nottenkamper, R., A. Steiff and P. -M. Weinspach, 'Experimental Investigation of Hydrodynamics of Bubble Columns', *Ger. Chem. Engng.*, Vol. 6, 147-155 (1983).

[134] O'Hern, T. J., J. R. Torczynski, S. L. Ceccio, A. L. Tassin, G. L. Chahine, R. Duraiswami and K. Sarkar, 'Development of an Electrical Impedance Tomography System for an Air-Water Vertical Bubble Column', Forum on *Measurement Techniques in Multiphase Flows, ASME IMEC&E* (1995).

[135] Ohki, Y. and H. Inoue, 'Longitudinal Mixing of the Liquid Phase in Bubble Columns', *Chem. Engng. Sci.*, Vol. 25, 1-16 (1970).

[136] Palavajjahala, S., R. L. Motard and B. Joseph, 'Computational Aspects of Wavelets and Wavelet Transforms', "Wavelet Applications in Chemical Engineering", Edited by R. L. Motard and B. Joseph, Kluwer Academic, Chapter II, 33-85 (1994).

[137] Patankar, S. V., "Numerical Heat Transfer and Fluid Flow", Hemisphere Publishing Corportation, New York (1980).

[138] Patel, S. A., J. G. Daly and D. B. Bukur, 'Holdup and Interfacial Area Measurements Usin Dynamic Gas Disengagement', *AIChE Journal*, Vol. 35, 931-942 (1989).

[139] Pismen, L. M and A. Nir, 'On the Motion of Suspended Particles in Stationary Homogeneous Turbulence', *J. Fluid Mech.*, Vol. 84, 193-206 (1978).

[140] Ranade, V. V., 'Flow in Bubble Columns: Some Numerical Experiments', *Chem. Engng. Sci.*, 47, 1857-1869 (1992).

[141] Reith, T, S. Renken and B. A. Israel, 'Gas Hold-up and Axial Mixing in the Fluid Phase of Bubble Columns', *Chem. Engng. Sci.*, Vol. 23, 619-629 (1968).

[142] Reilly, I. G., D. S. Scott, T. J. W. de Bruin, A. Jain and J. Piskorz, 'Correlation for Gas Holdup in Turbulent Coalescing Bubble Columns', *Can. J. Chem. Eng.*, Vol. 64, 705-717 (1986).

[143] Reilly, I. G., D. S. Scott, T. J. W. de Bruin and D. MacIntyre, 'The Role of Gas Momentum in Determining Gas Holdup and Hydrodynamic Flow Regimes in Bubble Column Operations', *Can. J. Chem. Eng.*, Vol. 72, 3-12 (1994).

[144] Rice, R. G., J. M. I. Tupperainen and R. M. Hedge, 'Dispersion and Hold-up in Bubble Columns-Comparison of Rigid and Flexible Spargers', *Can. J. Chem. Eng.*, Vol. 59, 677-687 (1981).

[145] Rice, R. G. and N. W. Geary, 'Prediction of Liquid Circulation in Viscous Bubble Columns', *AIChE Journal*, Vol. 36, 1339-1348 (1990).

[146] Richardson, L. F. 'Atmoshperic Diffusion Shown on a Distance-Neighbour Graph', *Proc. Roy. Soc*, Vol. A110, 709-737 (1926).

[147] Richardson J. F. and W. N. Zaki, 'Sedimentation and Fluidization: Part I', *Trans. Inst. Chem. Engrs.*, Vol. 32, 35-53 (1954).

[148] Riquarts, H. -P., 'A Physical Model for Axial Mixing of the Liquid Phase for Heterogeneous Flow Regime in Bubble Columns', *Ger. Chem. Eng.*, Vol. 4, 18-23 (1981).

[149] Rustemeyer, U., J. Pauli, Th. Menzel, R. Buchholz and U. Onken, 'Liquid-Phase Mixing Model for Hydrodynamics of Bubble Columns', *Chem. Eng. Process.*, Vol. 26, 165-172 (1989).

[150] Sannaes, B. H., *Solids Movement and Concentration Profiles in Column Slurry Reactors*, Dr. Ing. Thesis, Norwegian University of Science and Technology, Norway (1997).

[151] Saxena, S. C., 'Bubble Column Reactors and Fischer-Tropsch Synthesis', *Catal. Rev. -Sci. Eng.*, Vol. 37, No. 2, 227-309 (1995).

[152] Schlichting, H., "Boundary Layer Theory", McGraw Hill, New York (1960).

[153] Schumpe, A. and G. Grund, 'The Gas Disengagement Technique for Studying Gas Holdup Structure in Bubble Columns', *Can. J. Chem. Eng.*, Vol. 64, 891-896 (1986).

[154] Seinfeld, J. H., "Atmospheric Chemistry and Physics of Air Pollution", Wiley Publications, New York (1986).

[155] Serizawa, A., I. Kataoka and I. Michiyoshi, 'Turbulence Structure of Air-Water Bubbly Flow-I. Measuring Techniques', *Int. J. Multiphase Flow*, Vol. 2, 221-233 (1975).

[156] Shah, Y. T., G. J. Stiegel and M. M. Sharma, 'Backmixing in Gas-Liquid Reactors', *AIChE Journal*, Vol. 24, 369-400 (1978).

[157] Shah, Y. T., B. G. Kelkar, S. P. Godbole and W. D. Deckwer, 'Design Parameter Estimations for Bubble Column Reactors', *AIChE Journal*, Vol. 28, 353-379 (1982).

[158] Shollenberger, K. A., J. R. Torczynski, D. R. Adkins, T. J. O'Hern and N. B. Jackson, 'Gamma Densitometry Tomography of Gas Holdup Spatial Distribution in Industrial Scale Bubble Columns', Symposium Volume of *Chem. Engng. Sci.* for Frontiers in Industrial Process Tomography (1995a).

[159] Shollenberger, K. A. and T. J. O'Hern, Report entitled "Hydrodynamic Characterization of Slurry-Phase Flow in the La Porte Alternative Fuels Development Unit (AFDU) using Differential Pressure Measurements", Sandia National Laboratories (1995b).

[160] Snyder, W. H. and J. L. Lumley, ' Some Measurements of Particle Velocity Autocorrelation Functions in a Turbulent Flow', *J. Fluid Mech.*, Vol. 48, 41-71 (1971).

[161] Sokolichin A. and G. Eigenberger, 'Gas-Liquid Flow in Bubble Columns and Loop Reactors: Part 1. Detailed Modelling Numerical Simulation', *Chem. Engng. Sci.*, Vol. 24, 5735-5746 (1994).

[162] Sriram, K. and R. Mann, 'Dynamic Gas Disengagement: A New Technique for Assessing the Behavior of Bubble Columns', *Chem. Engng. Sci.*, Vol. 32, 571-580 (1977).

[163] Sussman, M., P. Smereka and S. Osher, 'A Level Set Approach For Computing Solutions to Incompressible Two-Phase Flows', *J. Comp. Physics*, Vol. 114, 146-159 (1994).

[164] Svensen, H. F., H. A. Jakobsen and R. Torvik, 'Local Flow Structures in Internal Loop and Bubble Column Reactors', *Chem. Engng. Sci.*, Vol. 45, 2325-2332 (1992).

[165] Svendsen, H. F. and H. Luo, 'Theoretical Model for Drop and Bubble Breakup in Turbulent Dispersions', *AIChE Journal*, Vol. 42, 1225-1233 (1996).

[166] Tan, R. B. H. and I. J. Harris, 'A Model for Non-spherical Bubble Growth at a Single Orifice', *Chem. Engng. Sci.*, Vol. 41, 3175-3182 (1986).

[167] Tarmy, B. L., M. Chang, C. A. Coulaloglou and P. R. Ponzi, 'The Three-Phase Hydrodynamic Characteristics of the EDS Coal Liquefaction Reactors: Their

Development and Scale-up', *Proceedings of the Eighth International Symposium on Chemical Reaction Engineering*, Elsevier Scientific, NY (1984).

[168] Taylor, G. I., 'Diffusion by Continuous Movements', *Proc. Lond. Math. Soc.*, Vol. 20, 196-211 (1921).

[169] Taylor, G. I., 'The Dispersion of Matter in Turbulent Flow through a Pipe', *Proc. Roy. Soc. London*, Vol. A223, 446-468 (1954).

[170] Tchen, C. M., *Mean Values and Correlation Problems Connected with the Motion of small Particles in a Turbulent Fluid*, Ph.D. Thesis, Delft, Netherlands (1947).

[171] Tennekes, H. and J. L. Lumley, "A First Course on Turbulence", The MIT Press, Cambridge (1972).

[172] Torvik, R. and H. F. Svendsen, 'Modelling of Slurry Reactors: A Fundamental Approach', *Chem. Engng. Sci.*, Vol. 45, 2325-2332 (1990).

[173] Towell, G. D. and G. H. Ackerman, 'Axial Mixing of Gas and Liquid in Large Bubble Reactors', *Proceedings of the Symposium on Chemical Reaction Engineering*, Amsterdam, Holland, B3-1 - B3-13 (1972).

[174] Tsoulfanidis, N., "Measurement and Detection of Radiation", McGraw Hill, New York (1983).

[175] Tsuge, H. and S. -I. Hibino, 'Bubble Formation From an Orifice Submerged in Liquids', *Chem. Eng. Commun.*, Vol. 22, 63-79 (1983).

[176] Tsuge, H., 'Hydrdynamics of Bubble Formation from Submerged Orifices', *Encyclopedia of Fluid Mechanics*, Gulf Publishing Company, Houston, Vol. 3, Chapter 9 (1986).

[177] Turner, J. R. and P. L. Mills, 'Comparison of Axial Dispersion and Mixing Cell Models for Design and Simulation of Fischer-Tropsch Slurry Bubble Column Reactors', *Chem. Engng. Sci.*, Vol. 45, 2317-2324 (1990).

[178] Tzeng, J. W., R. C. Chen and L. -S. Fan, 'Visualization of Flow Characteristics in a 2-D Bubble Column and Three-Phase Fluidized Bed', *AIChE Journal*, Vol. 39, 733-744 (1993).

[179] Ueyema, K. and T. Miyauchi, 'Properties of Recirculating Turbulent Two Phase Flow in Gas Bubble Columns', *AIChE Journal*, Vol. 25, 258-265 (1979).

[180] Verghese, K., R. P. Gardner and R. M. Felder, 'Solid Angle Subtended by a Circular Cylinder', *Nucl. Instr. Meth.*, Vol. 101, 391-393. (1972).

[181] Vermeer, D. J. and R. Krishna, 'Hydrodynamics and Mass Transfer in Bubble Columns Operating in the Churn-Turbulent Flow Regime', *Ind. Eng. Chem. Process. Des. Dev.*, Vol. 20, 475-482 (1981).

[182] Verstaag, H. K. and W. Malalasekera, "An Introduction to Computational Fluid Dynamics- The Finite Volume Method", Longman Scientific and Technical, John Wiley and Sons, New York (1995).

[183] Wallis, G. B., "One-Dimensional Two-Phase Flow", McGraw Hill, New York (1969).

[184] Wen, C. Y. and L. T. Fan, "Models for Flow Systems and Chemical Reactors", Marcel Dekker, New York (1975).

[185] Wickerhauser, M. V., "Lectures on Wavelet Packet Algorithms", preprint, Washington University (1991).

[186] Wielopolski, L., 'The Monte Carlo Calculation of the Average Solid Angle Subtended by a Right Circular Cylinder from Distributed Sources', *Nucl. Instr. Meth.* , Vol. 143, 577-581 (1977).

[187] Wilcox, D. C., "Turbulence Modeling for CFD", DCW Industries, La Canada, California (1994).

[188] Wilkinson, P. M., *Physical Aspects and Scale-up of High Pressure Bubble Columns*, Ph.D. Thesis, University of Groningen, The Netherlands (1991).

[189] Wilkinson, P. M., A. P. Spek and L. L. van Dierendonck, 'Design Parameters Estimation for Scale-Up of High-Pressure Bubble Columns', *AIChE Journal*, Vol. 38, 544-554 (1992).

[190] Wilkinson, P. M., H. Haringa, F. P. A. Stokman and L. L. van Dierendonck, 'Liquid Mixing in Bubble Columns Under Pressure', *Chem. Engng. Sci.*, Vol. 48, 1785-1792 (1993).

[191] Yang, Y. Y., 'Imaging of Multiphase Reactors: Tracer and Hydrodynamic Studies Using CARPT-CAT', CREL Report for 1991-1992 (1992).

[192] Yang, Y. B., N. Devanathan and M. P. Duduković, 'Liquid Backmixing in Bubble Columns', *Chem. Engng. Sci.*, Vol. 47, 2859-2864 (1992).

[193] Yang, Y. Y. and P. Gupta, 'Monte Carlo Applications for Multiphase Flow Mapping and Visualization Using CARPT', CREL Report for 1996-1997 (1997).

[194] Yao, B. P., C. Zheng, H. E. Gasche and H. Hofmann, 'Bubble Behavior and Flow Structure of Bubble Columns', *Chem. Eng. Process.*, Vol. 29, 25-75 (1991).

[195] Zehner, P., 'Impuls-, Stoff- und Warmetransport in Basensaulen', *Chem. -Ing. -Tech.*, Vol. 54, 248-251 (1982).

[196] Zuber, N. and J. A. Findlay, 'Average Volumetric Concentration in Two-Phase Flow Systems', *J. Heat Transfer*, Vol. 87c, 453-468 (1965).

Vita

Sujatha Degaleesan

Date of Birth	January 22, 1969
Place of Birth	Madras, India
Degrees	B.Tech. Chemical Engineering, May 1990, Anna University, Madras, India. M.S. Chemical Engineering, December 1994, Washington University, St. Louis, MO. D.Sc. Chemical Engineering, (expected) August 1997, Washington University, St. Louis, MO.
Industrial Experience	Summer Intern at Exxon Research and Engineering, Florham Park, NJ (1994).
Professional Societies	American Institute of Chemical Engineers

Presentations and Publications

Degaleesan, S. and M. P. Duduković, 'Measurement of Turbulent Dispersion Coefficients in Bubble Columns Using CARPT, Poster presented at *MIXING V*, Banff, Canada, June 1995.

Degaleesan, S., S. Roy, S. B. Kumar and M. P. Duduković, 'Liquid Mixing Model Based on Convection and Turbulent Dispersion in Bubble Columns', *Chem. Engng. Sci*, **52**, 1967-1976 (1996).

Degaleesan, S., M. P. Duduković, B. A. Toseland and B. L. Bhatt, Tracer Studies of the AFDU Reactor During Methanol Synthesis, *Fourth Quarterly Report for Contract DE-FC 2295 PC 95051*, March 1996.

Degaleesan, S., M. P. Duduković, B. A. Toseland and B. L. Bhatt, 'A Two-Compartment Convective-Diffusion Model for Slurry Bubble Column Reactors', accepted for publication in *Ind. Eng. Chem. Res.* (1997).

August 1997

Short Title: Bubble Column Fluid Dynamics Degaleesan, D.Sc. 1997