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INVESTIGATION OF TRANSPORT PROCESS
INVOLVED IN FGD

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Final Technical Report
For the Third Year
Report Period: Sept, 1992 to August, 1993 FEB 22 1994

DEPARTMENT OF DEVELOPMENT
OHIO COAL DEV OFFICE

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September, 1993

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EXECUTIVE SUMMARY

This report describes the work done in the third year of the project "Investigation of Transport Processes Involved in FGD". The objectives of this five year plan of study is to experimentally obtain a basic understanding of (1) turbulent flow structure of the mixing zone and its influence on particle dispersion, (2) the effect of particle loading on turbulent properties and mixing, (3) the effect of jet entrainment, (4) water spray-sorbent interaction, sorbent wetting and mixing, (5) investigate the flow field where certain ratios of jet velocity to flue gas velocity result in regions of negative flow and define onset of negative flow (6) sorbent reactivity in immediate mixing zone and (7) effect of particle agglomeration.

In the first two years of the project a sorbent injection facility which can simulate the conditions encountered in COOLSIDE set up was designed and built. Non-intrusive laser based diagnostic tools PDA/LDA was used for flow characterization of particle laden jet in cocurrent flows. All tasks for third year were addressed. The accomplishments for the third year include the following.

For investigation Lime Laden Jet Flow (task 1), since no existing technique was capable of providing the simultaneous measurement of irregular shaped particle size and velocity, a new technique, TTLDV which utilizes the transit time in LDV measurement volume and the LDV velocity measurements to obtain simultaneous particle size and velocity measurements was developed. The

techniques applicability was ascertained using known size glass beads. The technique was then successfully tried on lime laden jet flow. Development of the TTLDV technique is a substantial achievement and provides a very useful tool for other solid-fluid multiphase flows. Some difficulties were faced with lime loadings higher than 2 (5 or more) since, the smaller size of lime particles (7.9 microns average size) resulted in optically very dense jets for such loadings. This issue of higher loading is being discussed with URC monitors and data analysis for lime jet flow is being performed.

Better Sorbent Injection Methods and Optimized Injection Schemes (Tasks 2 and 6) were investigated. Swirling atomizer (injector) seems to be an appropriate choice. URC mentors suggestions are being sought before conducting tests in the sorbent injection facility as per the recommendation of the URC Report of August 9.

Progress was made in the development of Technique to Study Particulate Droplet Interactions, (Task 3 and 4) the task was not completed because of difficulties encountered due to differences in the refractive index of glass beads and water droplets. In addition URC Report recommends that tests be conducted in heated air to simulate COOLSIDE operating conditions. This requires facility modifications and the associated difficulties will be discussed with URC. Completion of Task 4 will be undertaken in early part of the fourth year in consultation with URC mentors and OCDO.

The investigations of flow reversal resulting from spray jet

cocurrent flow interactions (Task 5) was completed. A 36 set data (about 144 axial measurement locations) was taken. Spray velocity to duct air velocity ratio greater than 6.0 results in flow reversals. The data is now being further analyzed to obtain correlations using nondimensional parameters to obtain the flow reversal locations as a function of parameters of interest. The characterization of SU 1/8 JJ nozzle is also useful for Task 3 and 4 tests. We are ready to continue on the fourth year tasks as outlined in the continuation proposal in consultation with URC mentor and OCDO.

Publications:

Papers on the TTLDV technique were presented at two different symposia. These were:

"Transit Time Technique for Simultaneous Measurement of Particle Size and Velocity in Two Phase Flows", authored by C. Yurteri, V. Kadaba, M. Assar and J. Kadambi, American Filtration Society's Annual Meeting, Multiphase Flow Symposium; Chicago, May, 1993.

'A Simultaneous Measurement of Irregular Particle Size and Velocity using Transit Time and LDV', Flow Instrumentation Forum, authored by J. Kadambi, C. Yurteri, M. Assar and V. Kadaba. Fluids Engineering Division Meeting, FED vol 163. ASME, Washington D.C. June, 1993.

A full length paper on the TTLDV technique is now being prepared to ASME's Fluid Engineering Division Symposium to be held at Lake Tahoe in June, 1994 and will be considered for publication in Journal of Fluids Engineering.

INTERACTION WITH PROFESSOR L.S. FAN(P.I. of Project OCRC 92-1.2),
OSU

We have had extensive interactions with Dr. L.S. Fan,PI for Project OCRC92-1.2, regarding the applicability of laser based techniques in the two projects, especially regarding the use of their PIV (Particle Image Velocimetry) system in our set up. The PIV System at OSU has been used to measure the dispersability of particles to velocities upto 2 m/s. The velocity ranges in our tests vary from 10 to 35 m/s. The PIV system cannot be used for obtaining instantaneous velocity, size and concentration at higher speed range of 10 to 35 m/s. The use of PIV system will entail obtaining very costly high speed CCD camera and allied instrumentation and development work. Therefore the TTLDV and PDA/LDV approach is more appropriate for our investigations.

Complimentary powder dispensing nozzles have been used in the two projects. We use cross current arrangement to mix the solid with air to obtain particle laden jet while at OSU cocurrent powder injection nozzle is used. At OSU limestone and dolomite are used as the powder in the experiments while glass particles, hydrated lime and water droplet (spray) are involved in our experiments.

TABLE OF CONTENTS

EXECUTIVE SUMMARY	i
TABLE OF CONTENTS	v
LIST OF FIGURES	vi
LIST OF TABLES	viii
1. INTRODUCTION	1
1.1 Five Year Plan Objectives	6
2. BRIEF REVIEW OF WORK DONE IN FIRST TWO YEARS (9/90-8/92)	7
3. THE THIRD YEAR TASKS	11
3.1 The third year tasks	11
3.2 Lime Laden Jet Flow (Task)	11
3.2.1 The Transit Time-LDV(TTLDV Technique)	
3.2.2 Rotating Wire Calibration Test	
3.2.3 TTLDV Test With Glass Particle Laden Jet	
3.2.4 Hydrated Lime Laden Jet Flow Tests	
3.3 Investigation of Better Sorbent Injection Methods and Development of Optimized Schemes and Tests(Tasks 2 and 6)	24
3.4 Develop Technique to Study Particulate Droplet Interactions and Conduct Tests (Tasks 3 and 4)	27
3.5 Investigation of Jet to Cocurrent Flow Velocity Ratio ranges which result in Regions of Negative Flow (Tasks 5)	28
4. SUMMARY AND STATUS	35
5. LITERATURE REFERENCES	37
6. FIGURES	39

LIST OF FIGURES

1.	Schematic of Sorbent Injection Facility	39
2.	LDV Parameters	40
3.	(a) Measurement Volume Details (b) The Wire Disk Assembly	41
4.	Histogram of the two rotating wire velocities	42
5.	Histogram of the two rotating wire transit time, the larger value is for the 1150 micron wire.	42
6.	Histogram of the product Vt for the two wires. The larger value is for the 1150 micron wire.	42
7.	Particle size histograms lens focal length 160mm, fringe count 40-200 (TTLDV mean 43.2 μm , PDA mean 41 μm)	43
8.	Particle size histogram, Lens focal length 310 mm, fringe count 35-50 (TTLDV mean 38.4 μm , PDA mean 38.7 μm)	43
9.	Particle size histogram, focal length 310 mm, fringe count 35-200 (TTLDV mean 49.2 μm , PDA mean 47.1 μm)	43
10.	Axial velocity profiles showing axisymmetry for lime laden jet tests.	44
11.	Coaxial crossflow injector	45
12.	Swirl atomizer (from reference 11)	46
13.	Radial profiles of size distribution in swirl atomizer (from reference 11)	46
14.	Vector representation of Droplet Velocities (a) 11-20 μm , (b) 61-75 μm (from reference 11)	47
15.	Droplet axial velocities along the horizontal and vertical axis showing axisymmetric spray.	48
16.	(a) Normalized Droplet axial velocity profiles at different axial locations, (no flow reversal test #12) (b) Normalized Droplet axial velocity profiles at different axial locations (no flow reversal test #27)	49 49

17.	Droplet axial velocity profile at different axial locations. Flow reversal took place in this test as indicated in the figure (Test #15)	50
18.	Droplet size (SMD) profiles at different axial locations (Test #12)	51
19.	Droplet size (SMD) profiles at different axial locations (Test #27)	51

LIST OF TABLES

1.	The TTLDV Results	17
2.	Test Matrix for Hydrated Lime	19
3.	Hydrated Lime Size and Glass Particle Size distribution and mean values	21
4.	Details of the Flow Reversal Test Data	30

1. INTRODUCTION

Complicated multiphase flows (solid-gas, gas-liquid-solid and liquid-gas) are involved in many FGD processes. Multiphase flows by themselves are not well understood and their impact on FGD processes are even less understood. Drummond et al.(1) in their discussion of duct injection technologies for SO_2 control have included the transport and chemical processes within the duct. fluid mechanics of the system, nozzle design and operation, and humidification system designs areas of concern which require research to develop a better understanding of the process. The improvements in the basic knowledge of fluid mechanics, heat and mass transfer rate effects are needed (Reference 2) to understand and achieve substantial improvements in many key areas of FGD processes and obtain scale-up criteria. Dry sorbent injection and dispersion, sorbent humidification by water injection, sorbent slurry injection, material handling aspects of sorbent slurry, sorbent powder and ash are some examples. In the utilization of high-sulfur Ohio coal emphasis has been placed on increasing the efficiency of dry, high sulfur flue gas scrubbing processes using calcium-based sorbents (LIMB, COOLSIDE). This entails the need to improve our understanding of the mixing processes which play a crucial role in enhancing sorbent utilization.

The reaction between SO_2 and sorbent particles involves mixing resulting from gross flow patterns and turbulence, mass transfer due to diffusion and dispersion and finally chemical reaction. Since the sorbent particles are injected into the flue gas, a prerequisite for fast reaction is the rapid mixing of the sorbent particle from the

injection nozzle with the flue gas stream. Free jet entrainment might probably be a very important mechanism of rapid mixing. Clearly mixing is determined by flow patterns and turbulent flow processes which are influenced by the characteristics of the injection jet and interactions with the surrounding stream. Additionally, the wetting of sorbent particles with water spray seems to improve the sorbent utilization. The literature review reported in the first year work Kadambi et al (3) indicated that the experimental data available in the area of induct flue gas desulfurization process (FGD) is sparse and does not cover the range of interest of dry FGD processes. So far, many of the fundamental questions involved in solid-gas and solid-liquid-gas flows have not resolved. In addition, the mixing of the sorbent particles in FGD processes can possess different features because of different particle size, jet Reynolds number, particle loading and agglomeration properties.

The particle-laden flows are inherently more complex than the single phase flows. This follows from the fact that the particles are distinct from the fluid, the continuous phase element. First, unlike the fluid element, the particles have finite size and shape and cannot deform under strain. Viscous forces result when particle surface velocity is different than the velocity of the surrounding fluid. Secondly, there is usually a substantial density difference between solids and the continuous gas phase. Thus, these particles have much more inertia than the fluid elements moving out at similar velocities and are, therefore, unable to follow every scale of fluctuation of the fluid flow. In case of mismatch between the fluid and particle

velocities, the particles exchange energy and momentum with the fluid through viscous drag. Faster moving particles might increase local fluid velocities by dragging along the fluid and vice versa. Particles may dampen or amplify the fluid fluctuation levels in different scales of eddies as a result of this interaction. A sufficiently large particle mass loading can result in the modification of the overall turbulence levels. For high particle loading, interaction among particles and the interaction of particles wakes can further complicate the flow.

The inertia of a particle in fluid flow can be assessed quantitatively by calculating a particle time constant. Assuming Stokesian flow, and that the particle density is substantially larger than fluid density, the time t_p , taken for the particle to accelerate from rest to 63% of the free stream velocity is given by

$$t_p = \rho_p d_p^2 / 18 \mu \quad (1.1)$$

where

ρ_p = particle density

d_p = particle diameter

μ = fluid viscosity.

A fluid time scale t_f , based upon a given eddy can be given by

$$t_f = L/U \quad (1.2)$$

where

L = eddy length scale

$\bar{U}$ = eddy velocity scale.

Based upon relating t_p and t_f , the particle and fluid time scales, we can divide the possibilities of particle responses to turbulent flow into three regimes. In the first regime, if $t_p \gg t_f$, a particle will not respond to fluctuations in the flow. For example, paths of heavy large steel balls dropping through air will not be affected by turbulent eddies. In the second regime, if $t_p \ll t_f$, a particle will completely follow the flow including any fluctuations. The seed particles used in Laser Doppler Anemometry (LDA) measurements to obtain flow velocities are assumed to behave in such a manner. The third possible regime occurs when both t_p and t_f are of the same order of magnitude. In such a case particles respond partially to the fluctuations in the flow. Here, the particles are not able to follow the fluid elements exactly, but their paths are altered by fluid fluctuations. The flow in this regime is most poorly understood and is very difficult to model. This regime may also encompass the induct injection processes. The injection of the particle-laden jet into cocurrent flow further complicates the process. The wetting of the sorbent particles with water spray appears to enhance sorbent utilization. This makes the flow solid-liquid-gas multiphase flow with all the associated complexities.

A thorough review of literature was undertaken in this area and was reported by Kadambi et. al (3,4) in the first year and second year reports to the Coal Research Consortium of Ohio Coal Development Office.

Work in the area of particle laden flows covering turbulent

free jets, concentric jet flows, pipe flows areas were reviewed and more than 30 papers were reviewed. However no paper in the area of interaction of water spray and particles in cocurrent flow relevant to dry FGD processes was obtained. The following conclusions were drawn from the review.

Though there have been some studies of two phase mixing problems and particle laden jets, so far, many of the fundamental questions involved in the two and three phase flows, especially relevant to FGD processes, have not been resolved. In addition, the mixing of the sorbent particles in FGD processes can possess different features because of different particle sizes, jet Reynolds number, particle loading, and agglomeration properties. The information required to develop a better understanding of the phenomenon of mixing relevant to FGD processes where two or three phase, gas-solid, gas-solid-liquid, turbulent, horizontal jet issues into a cocurrent flow with relatively smaller diameter particles is not available.

Injection of fine spray of water into the duct appears to enhance the sorbent utilization. However, the residence time of the droplets (e.g. 30 micron diameter) is about 2.5 seconds to 3.0 seconds before evaporation, and the interaction between the water droplet has to take place before that. The interaction between the water droplet and sorbent has to be improved so as to enhance wetting and mixing. The scavenging has also to be improved. There is need for experimental data to validate, develop and improve water spray and two phase slurry models. The emphasis being on mixing, dispersion and increasing turbulence. Another issue of interest is the location of water spray

and sorbent injection location relative to one another along the axial direction. Additionally, for certain ratios of spray velocity to flue gas velocity regions of negative flow appear and there is a need to define onset of such negative flows to avoid such flow conditions in FGD process.

1.1 Five Year Plan Objectives :

A five year plan was developed to improve our understanding of such flows involved in dry FGD processes.

The objectives of this five year plan of study is to experimentally obtain a basic understanding of (1) turbulent flow structure of the mixing zone and its influence on particle dispersion, (2) the effect of particle loading on turbulent properties and mixing, (3) the effect of jet entrainment, (4) water spray-sorbent interaction, sorbent wetting and mixing, (5) investigate the flow field where certain ratios of jet velocity to flue gas velocity result in regions of negative flow and define onset of negative flow , (6) sorbent reactivity in immediate mixing zone and (7) effect of particle agglomeration .

2. BRIEF REVIEW OF WORK DONE IN FIRST TWO YEARS (9/90-8/92)

To properly simulate the conditions encountered in induct sorbent injection FGD process set ups, geometric, dynamic and kinematic similarity parameters were considered (Kadambi and Chinnapalaniandi, 4). The tube size for the jet and the cocurrent flow duct wall did not interact with the jet for at least 35 diameters downstream of the tube exit ensuring no wall interaction effect on the mixing and entrainment characteristics. The duct design also allows for an easy increase in the duct cross sectional area. To obtain dynamic and kinematic similarity the range of Reynolds number, Stokes number, Froude number, the particle laden jet to cocurrent stream momentum flux ratio and the mass loading ratio encountered in FGD processes were duplicated. This criteria was used in designing and building the test facility and details are provided in Reference 4.

The schematic diagram of the sorbent injection test facility is shown in Figure 1(Please note that the figures are provided at the end of the Report). A 7.3 mm diameter tube is used for injecting the solid particle laden jet into a 88.6 mm by 88.6 mm square duct. The duct(7) is made up of transparent plexiglass walls except for the 300 mm long test section which is made up of pyrex glass. The 7.3 mm tube protrudes slightly into the test section. The glass sides and the square configuration of the duct facilitates the use of laser based non-intrusive Particle Dynamics Analyzer (PDA) for obtaining particle size and velocity simultaneously. The particle material used in the tests are glass, and lime particles in the size range of 5 to 100 micrometer diameter. The glass particles are spherical while the lime particles

are not spherical. Since the PDA performance depends upon the particle sphericity, in the first series of tests (in the second year) spherical glass particles were used. To ensure proper mixing of the particles and the jet air stream, the particles were added at a location far upstream ($x/d=100$) of the particle laden jet exit into the duct. The particle laden flow is then led into the 7.3 mm diameter jet tube. A range of mass loading (0 to 10) was obtained. The interaction between the particle laden jet and cocurrent duct flow occurs in the test section. A seeder to seed the duct flow for obtaining duct velocity was also developed. The seeder is a cyclone separator in reverse. Micronized talc powder is used as the seed. The air flow rates in the duct and the particle feeder jet were monitored using a turbine flowmeter and a flowrator. Details of the sorbent injection test facility are provided in Reference 4.

The major instrumentation used is the Particle Dynamics Analyzer (PDA). The PDA manufactured by Dantec Electronics utilizes a 2 watt Argon-ion laser. The PDA simultaneously measures the size, velocity and concentration of the spherical particles. It is based upon Laser Doppler Anemometry and Phase Doppler Interferometry.

Details of PDA/LDA theory and operations are provided in our second year report as well as Bachalo(5), Saffman(6), and Dantec Manual(7). The PDA transmitting and receiving optics are mounted on a three dimensional traverse. This allows the mapping of the particle laden jet flow in the duct. The PDA is operated in the back scatter second order refraction mode at an angle of 158° , as recommended in the Dantec's instruction manual. At each measurement point 3000 PDA/LDA measurements

were made.

In complex two phase solid gas flows with high particle loading, it is important to measure the velocity of continuous phase in the presence of the dispersed phase in addition to the size of particles. By seeding the flow, sizing all particles and then extracting the particles which are small enough to track the flow (particles less than 3 micron were used in this study), the velocity of gas phase within the particle-laden jet flow field were deduced. For single phase measurement in the jet flow, that is at $m=0$ loading talc powder seeder was also used in the jet and the PDA was operated in LDA mode.

The uncertainties in the measurements were as follows. For PDA/LDA measurements: Traverse accuracy ± 0.01 mm, Velocity measurements $\pm 1.5\%$, Particle diameter $\pm 8\%$, and concentration $\pm 4\%$. For turbine flowmeter $\pm 1\%$, Flowrator $\pm 2\%$, and particle mass loading $\pm 1.0\%$.

The test details and detailed description of the test results and discussions are provided in our second year report. However, some important conclusions regarding Particle laden flows from the work done in second year, which led to third year work definition, follow:

- Phase Doppler Anemometry was successfully utilized for studying particle-laden flows. Particle size and velocity and flow velocities were obtained allowing us to discriminate between the phases.
- The particle velocities were less than the single phase fluid velocities along the centerline near the exit of the jet. At downstream locations greater than $x/d = 10$ the situation reversed with the particle velocities being greater than the fluid

velocities, since, the axial velocity decay is faster for single phase than that for particle phase due to higher spreading of shear layer in single phase. This phenomenon is further enhanced with the increase in particle loading due to inertia.

- The slip velocity was nearly constant for all mass loadings.
- Addition of the particles to the flow resulted in an increase in the gas-phase mean velocities.
- Particle mass loading has a significant effect on the development of the particle laden jet. These include the following. (a) In the radial direction along the width the particle mean velocities and the fluctuating components are dependent upon the mass loading. Larger mass loading results in higher mean velocity and smaller fluctuating component, (b) the presence of particles was found to suppress turbulent fluctuations, since $Re_p = O(1)$. This is also known as turbulence modulation and results in the reduction in the turbulence intensity and shear stress. These effects became more pronounced when mass loading was increased, and (c) Jet spreading rate decreases with increasing mass loading, which results from the reduction in the radial fluctuation velocity.
- It was found that particle laden jet entrainment depends upon the jet velocity, mass loading, and axial distance. Entrainment increase with higher jet velocity and lower mass loading.
- Since, the higher mass loading results in a lesser spreading rate, the particles are concentrated in a smaller radial distance and there is a resulting reduction in the particle dispersion and mixing.

- Mass loadings greater than 5, result in the reduction in turbulence intensity, Reynolds stress, jet entrainment and spreading rate. That is, the mixing is reduced. Lower mass loadings, $m < 5$, show better mixing characteristics and therefore may be beneficial for induct injection processes.

3. THE THIRD YEAR WORK (9/92-8/93)

3.1 The Third Year Tasks;

Based upon the successful development of the facility and implementation of measurement and analysis techniques has allowed us to investigate particle laden jet flow in cocurrent flow as indicated in the second year report, the third year tasks involved the following.

- (a) Conducting tests with lime laden jet flow ,COOLSIDE Configuration, (Task 1)
- (b) Investigating better sorbent injection schemes (Task 2)
- (c) Develop technique to study particulate droplet interactions and conduct tests (Tasks 3 and 4)
- (d) Investigating jet to cocurrent flow velocity ratio ranges which result in region of negative flow (Task 5)
- (e) Develop optimized sorbent injection scheme plan tests (Task 6)

The task number in parenthesis identify the tasks as identified in the proposal. These tasks formed a very ambitious and challenging program for the third year.

3.2 Lime Laden Jet Flow (Task 1)

3.2.1 The Transit Time-LDV(TTLDV) Technique

Since the PDA technique cannot be used for obtaining irregular shaped

lime particle size, we have concentrated upon developing the combination of Transit Time Technique and Laser Doppler Velocimetry (LDV) for simultaneously measurement of lime particle size and velocity. We call the technique "TTLDV" technique. The technique utilizes the particle transit time in the measurement volume and the velocity obtained by the LDV technique. The operating principles of LDA can be explained by using a simple fringe model. The laser beam from a continuous wave laser is split into two parallel beams which then pass through a focusing lens causing the beams to intersect at the focal point which is also the measurement location. A set of plane parallel interference fringes are formed at the intersection, with the fringe spacing determined by the laser wavelength and the angle between the two beams. A particle passing through the measurement volume scatters light as it passes through the fringe pattern. The scattered light is collected and converted into an electric signal by a high speed photodetector. The frequency of the electrical signal is directly proportional to the velocity perpendicular to fringe direction. This simple model describes the LDA operation and the various parameters are shown in Figure 2 . The fringe pattern produced at the crossing point of the beams will be stationary resulting in directional ambiguity. This directional ambiguity is removed by utilizing a Bragg cell in one of the beams to provide a frequency shift, consequently the fringes are no longer stationary and the directional ambiguity is thus removed.

With the covariance processor (Model #58N10 Dantec Electronics) available with the PDA and the processing software, we can also obtain

the transit time of the particle through the measurement volume. The transit time is obtained by analyzing the intensity of the laser beam light scattered by the particle. The intensity distribution will be gaussian. If the transit time, for a particle whose dimension in the direction of fringes is 'd', to cross the measurement volume major diameter of length D (see Figure 3 a) is t, then we have:

$$tv = (d + D) \quad (1)$$

where v is the velocity of the particle obtained from LDV measurement. Length D of the measurement volume is fixed by the laser beam wavelength and the beam crossing angle. Thus if the transit time and velocity of the particle are known, the linear dimension of the particle crossing the measurement volume can be obtained. The covariance signal processor and the associated software can be utilized to simultaneously obtain the transit time and the velocity of the particle crossing the measurement volume. The technique appears to be simple and easy to apply. However, there are difficulties associated in the application of the technique, which have to be overcome.

One major problem area is if the particle is passing through the edge of the measurement volume, it will not cross the diameter D but a relatively smaller length. This problem can be addressed by ascertaining that the data from those particles which cross a fixed number of fringes whose total spacing corresponds to or is very close to D are used. The size of the measurement volume relative to the particle size (linear dimension crossing the measurement volume) is also very important. A substantially larger particle can tend to block the two laser beams and thus not allow the laser beams to intersect at the

measurement location and will get rid of the LDV Doppler signal. Thus a judicious selection of measurement size is very important and has to be based upon the range of the size of particles involved. Another problem stems from the fact that the intensity of the scattered light is a function of particle surface, the laser beam intensity, the PMT voltage and gain and particle size. Out of these factors the laser beam intensity, photomultiplier voltage and gain can be preset and kept constant. Particle surface depends upon the type of particle and particle size is of course an unknown we want to obtain. Having an idea of the variation in the size of particles in the flow will allow us to select a measurement size and number of fringes which will accommodate the range of particle size to be encountered. Surface effects can be taken care of by conducting calibration experiments to obtain a relationship between the particle size and the product of particle velocity and transit time (Vt).

3.2.2 Rotating Wire Calibration Tests:

Feasibility calibration tests were conducted with known size wires which were attached radially to a rotating wheel. Each wire crossed the LDV probe volume once per revolution. The rotational speed of the wheel was monitored and kept constant. The different size wires were mounted in such a way so as to cross the probe volume as close as possible to the probe volume's centerline(i.e.D). Figure 3 b shows the rotating wheel and the wires. Wires of diameters 1150 microns and 250 microns were used. The LDV set up included a 5w Argon ion Laser, LDA/PDA receiving and transmitting optics. Green beams of wave length 514.5nm were used. For the test configuration the measurement volume had a

major diameter of 90 microns.

Figures 4,5 and 6 show the results from a representative calibration test where two wires of diameters 1150 and 250 microns were used. Figure 4 shows the histogram of the two wire velocities which are same (1.7 m/s) and is within $\pm 0.5\%$ of the velocity obtained from the wheel speed. Figure 5 shows the transit time histograms for the two wires. The histogram of the product Vt is shown in Figure 6. The mean values associated with the histograms for the two wires are 310 and 1130, and if one subtracts the length of the measurement volume (90 microns) the wire size we get are 220 and 1040 as compared to measured values of 250 and 1150 microns. These values are within 12% and indicate that it may be feasible to use this technique to obtain the particle size and velocities simultaneously in solid fluid two phase flows.

The differences in the wire sizes obtained in these tests and the measured values can be attributed to (i) slight bending of the wires (not of any consequence in two phase flows), (ii) variation in the surface of the wire effecting the light scattering, and (iii) the wire not crossing exactly at the center of the measurement volume. Items (ii) and (iii) have to be addressed in solid-fluid flows. To take care of the surface scattering characteristic effects, one needs to obtain a calibration curve to relate the parameter Vt with the particle size, i.e the linear dimension of the particle crossing the measurement volume. One will also have to obtain the optimum measurement volume size for a given range of particle sizes. The third issue of particles not crossing in the middle of the measurement volume can be addressed by ensuring that only signals from particles that cross a given number of

fringes in the measurement volume are accepted. Some of these issues have been discussed by Saffman [9].

3.2.3 TTLDV Tests With Glass Particle Laden Jet:

Next set of tests were conducted in the sorbent injection test facility using micron size glass beads. Particle sizes were obtained using PDA and TTLDV methods. Focusing lenses of focal lengths 310 mm and 160 mm were used in the transmitting optics. The beam separation was 36 mm. Off axis back scattering on the second order refraction mode was used for the PDA measurements.

The tests were carried out at a location 2.5 cm downstream of the jet centerline. Mean particle velocities were varied from 9.3 m/s to 18 m/s. Particle sizes were obtained for different fringe count ranges and spherical glass beads of mean diameters 48 microns and 59 microns were used. Some test results are shown in Table 1, where the diameters obtained by PDA and TTLDV technique are compared. As can be observed from the table, the number of fringes play an important role in the accuracy of the results. It was observed that the TTLDV approach produces smaller mean sizes if the fringe count is smaller than an optimum and larger sizes if the fringe count is larger than the optimum. For the given LDA parameters, fringe count of 35 ensures that the measurement volume size is crossed. TTLDV method results compare well with the PDA results and are within 25% to those results obtained by PDA. The optimum fringe count corresponds to the number of fringes calculated from the optical configuration. The lower limit fringe value is the parameter most effecting the results of this experiment.

Experiment #	Number of Fringes	Velocity m/s	Size Range μm	Mean Particle Size μm		% Difference
				TTLDV	PDA	
1	≥ 35	9.3	1-150	51.1	49.2	4.9
2	≥ 35	9.6	1-150	49.2	47.1	4.4
3	≥ 35	18	1-150	53.0	48.2	9.9
4	35-50	13.6	1-75	38.4	38.8	1.0
5	35-50	13.6	1-75	31.8	41.0	22.0
6	≥ 40	9.3	1-150	62.9	51.1	23.0
7	≥ 40	9.6	1-150	59.6	50.0	19.2
8	≥ 40	12	1-150	57.2	54.4	5.0
9	≥ 40	13.6	1-75	43.2	41.0	5.4
10	≥ 40	13.6	1-75	43.3	41.0	5.6
11	≥ 40	18	1-150	62.5	49.9	25.0
12	40-45	9.6	1-150	41.4	45.6	9.2
13	40-50	12	1-150	52.7	48.3	9.1

Table 1. TTLDV Results

However, as the upper fringe limit is increased data validation rate increases with a decrease in accuracy. Figures 7,8 and 9 show the comparison of particle diameter sizes obtained from PDA and TTLDV data for different test conditions and reinforce the preceding observations. The development of the TTLDV Technique is a substantial achievement and provides a very useful tool to study solid gas flow with irregular shaped particles.

3.2.4 Hydrated Lime Laden Jet Flow Tests :

Based upon the TTLDV technique's success as indicated in the preceding section , tests were started in lime laden jet . A fringe count of 35 was maintained in the TTLDV mode . A test matrix similar to the test matrix for the glass beads test was planned as shown in Table 2 .

Hydrated lime was obtained from Dravo Corporation (courtesy Mr. M. Babu) which is similar to the lime used in COOLSIDE tests . On our request ,Mr. D. Wildman of USDOE's Pittsburgh Energy Technology Center, Pittsburgh , Pa. got the lime particles size analyzed in Leeds and Northrup Microtrack Standard Range Analyzer (SRA) . The SRA utilizes Franhofer diffraction technique to obtain particle size . The scattering angle is inversely proportional to the size of the particle . In addition of the lime particles , the glass beads used in the second year tests were also analyzed . The results for lime as well as glass beads are presented in Table 3. The lime particle size varied between 1.9 microns to 22 microns with the volumetric mean diameter being 7.9 microns . Seventy two percent of the lime particles were 9.4 micron size or smaller . In comparison to the lime particles the volumetric mean

diameter of the glass particles was 42.6 microns . Flow ability of the lime from the bin to the nozzle injector posed a few problems . This was taken care of by grounding the valve nozzle assembly and using

TABLE 2. TEST MATRIX FOR HYDRATED LIME

Single Phase :

Center line jet velocity, U_o (m/s)	35, 30
Mass flow rate of jet flow m_a (kg/s)	1.7×10^{-3} , 1.5×10^{-3}
Reynolds number of jet $\rho U_o / \mu$	1.7×10^4 , 1.5×10^4
Cocurrent Velocity , U_{df} (m/s)	20, 15, 10

Particle - Phase (Hydrated lime) :

Particle Diameter (microns)	1 - 20
Particle Density, ρ_p (kg/m ³)	2240

<u>Velocity Ratio</u> U_o/U_{df}	<u>mass loading</u>
Case 1: 35/20	2,5,7
Case 2: 35/15	2,5,7
Case 3: 35/10	2,5,7
Case 4: 30/10	2,5,7

Lignosulfates and other additives to improve lime flowability . Suggestions from PETC (Dr.Wildman) , Dr. Babu and Dr. Statnick were useful in overcoming this problem .

The first set of tests were conducted at a mass loading (ratio of lime particle mass flow rate to air flow mass rate) of 2 .The results showed axisymmetric flow profile as shown in Figure 10 . Measurements were made along the mutually perpendicular horizontal and vertical axes . Particle size , velocity and concentration were obtained at a mass loading of 2 . Further increase in the loading resulted in substantial difficulties in making measurements. Since the average lime particle size is substantially smaller 7.9 microns as compared to 42.6 microns for glass beads , the number of lime particles are nearly 140 times the glass beads for the same loading . This tremendous increase in the number density causes the lime jet to be very dense and nearly opaque as was observed when the loading was increased to 5. The laser beams were practically blocked and it was not possible to use the TTLDV technique . We are planning to borrow a Malvern Particle Size Analyzer, which works on the Franhofer diffraction principle, from PETC and try it also. However it appears that the use of optical laser based techniques may not be possible for hydrated lime loadings of 5 and greater . This problem is being discussed with URC project monitors and are looking into the possibilities of using larger size limestone particles or to get relevant high loading test data .

Table 3. Hydrated Lime and Glass Particle Size Distribution and Mean Values

LIME CA(OH)₂
 SAMPLE #1
 SAMP. TIME = 40 SEC
 AVERAGE OF 3 RUNS
 SRA DATA

DV = 0.2333
 X18 = 2.41
 X50 = 6.03
 X90 = 16.99
 MV = 7.93
 CS = 1.267

PERCENT PASSING	CHAN.	CUM.	VOL.
300	100.0	0.0	
212	100.0	0.0	
150	100.0	0.0	
106	100.0	0.0	
75	100.0	0.0	
53	100.0	0.2	
38	99.8	2.5	
27	97.2	4.5	
19	92.8	8.2	
13	84.6	12.6	
9.4	72.0	18.1	
6.6	53.9	13.1	
4.7	40.8	17.4	
3.3	23.4	13.6	
2.4	9.8	9.8	

RELATIVE VOL. GRAPH

250	0
176	0
125	0
80	0
62	0
44	0
31	*2
22	***4
16	*****8
11	*****12
7.8	*****18
5.5	*****13
3.9	*****17
2.8	*****13
1.9	*****9

CUMMULATIVE GRAPH

300	*****100
212	*****100
150	*****100
106	*****100
75	*****100
53	*****99
38	*****99
27	*****97
19	*****92
13	*****84
9.4	*****72
6.6	*****53

LIME CA(OH)₂
 SAMPLE #1
 SAMP. TIME = 40 SEC
 AVERAGE OF 3 RUNS
 SRA DATA

DV = 0.2329
 X18 = 2.44
 X50 = 5.98
 X90 = 16.56
 MV = 7.80
 CS = 1.260

PERCENT PASSING	CHAN.	CUM.	VOL.
300	100.0	0.0	
212	100.0	0.0	
150	100.0	0.0	
106	100.0	0.0	
75	100.0	0.0	
53	100.0	0.0	
38	100.0	2.9	
27	97.1	3.5	
19	93.6	8.9	
13	84.7	11.6	
9.4	73.1	17.6	
6.6	53.5	14.9	
4.7	40.7	17.8	
3.3	22.9	13.5	
2.4	9.4	9.4	

RELATIVE VOL. GRAPH

250	0
176	0
125	0
80	0
62	0
44	0
31	*2
22	*3
16	*****8
11	*****11
7.8	*****17
5.5	*****14
3.9	*****17
2.8	*****13
1.9	*****9

CUMMULATIVE GRAPH

300	*****100
212	*****100
150	*****100
106	*****100
75	*****100
53	*****100
38	*****100
27	*****97
19	*****93
13	*****84
9.4	*****73
6.6	*****55

(A) Lime Particles Size

GLASS BEADS

SAMP. TIME = 100 SEC
AVERAGE OF 3 RUNS
SRA DATA

DV = 0.2937
X10 = 26.31
X50 = 42.79
X90 = 66.94
MV = 42.64
CS = 0.163

PERCENT PASSING

CHAN.	CUM.	VOL.
300	100.0	0.0
212	100.0	0.0
150	100.0	0.0
106	100.0	1.6
75	98.4	23.1
53	75.4	37.3
38	38.1	27.5
27	10.6	6.0
19	3.8	2.6
13	1.2	0.9
9.4	0.2	0.2
6.6	0.0	0.0
4.7	0.0	0.0
3.3	0.0	0.0
2.4	.0	0.0

RELATIVE VOL. GRAPH

250 0
176 0
125 0
88 1
62 *****23
44 *****37
31 *****27
22 *6
16 2
11 0
7.8 3
5.5 0
3.9 0
2.8 0
1.9 0

CUMMULATIVE GRAPH

300 *****100
212 *****100
150 *****100
106 *****100
75 *****98
53 *****75
38 ***38
27 *10
19 3
13 1
9.4 A

GLASS BEADS

SAMP. TIME = 100 SEC
AVERAGE OF 3 RUNS
SRA DATA

DV = 0.2849
X10 = 26.25
X50 = 42.78
X90 = 66.73
MV = 42.51
CS = 0.165

PERCENT PASSING

CHAN.	CUM.	VOL.
300	100.0	0.0
212	100.0	0.0
150	100.0	0.0
106	100.0	1.3
75	98.7	23.2
53	75.5	37.4
38	38.1	27.4
27	10.6	6.7
19	3.9	2.5
13	1.4	0.7
9.4	0.6	0.6
6.6	0.0	0.0
4.7	0.0	0.0
3.3	0	0.0
2.4	0	0.0

RELATIVE L. GRAPH

250 0
176 0
125 0
88 1
62 *****23
44 *****37
31 *****27
22 06
16 2
11 0
7.8 0
5.5 0
3.9 0
2.8 0
1.9 0

CUMMULATIVE GRAPH

300 *****100
212 *****100
150 *****100
106 *****100
75 *****98
53 *****75
38 ***38
27 *10
19 3
13 1

(B) Glass Beads Size

Hydrated lime particle size distribution(microns)
from Table 3.

Glass beads particle size distribution(microns)
from Table 3.

3.3 Investigation of Better Sorbent Injection Methods and Develop Optimized Sorbent Injection schemes. (Tasks 2 and 6)

This task deals with optimization of particles and cocurrent flow mixing processes and design and /or development of new schemes. The particle laden jet tests (2nd year tests ,also see section 2) showed that the spreading rate of the jet reduces as the loading is increased and that the larger diameter particles tend to stay in the center . The spray characterization tests showed that larger droplets tend to be around the edges of the spray and the smaller droplets stay close to the center . For improved mixing of the sorbent particles with the cocurrent flowing flue gases we have to (a) increase the spreading rate of the jet at higher particle loadings , (b) mix up the particle size distribution making it more uniform and (c) enhance turbulence especially in the radial direction . One additional constraint is that no additional energy be used so that the process can stay commercially viable . With this criteria literature was surveyed . Most of the work in this area has been conducted from the point of view of combustion , especially sprays in combustors where proper mixing of fuel and air (Oxygen) is very important from combustion efficiency . Some of the requirements are similar to our requirements . In this survey we found two concepts of interest. One was the use of coaxial atomizer investigated by Shavit , Chagier et al (10) .The atomizer is shown in Figure 11. By varying the cross jet air velocity normal to the coaxial jet , turbulence levels as high as 34 % were obtained . Since turbulence plays a very important role in mixing increased turbulence resulting from a cross jet air flow

scheme has some potential for increasing sorbent mixing with cocurrent flow . However , this geometry requires relatively complex flow nozzle and blockage of the cross flow hole from the particulates could cause the atomizer to fail . In addition more air will be needed for the cross flow path , thus increasing the energy requirements , and therefore for these reasons this geometry was not considered for use .

Another type of atomizer of interest is the swirling co-flow atomizer which was investigated by McDonnell and Samuelsen (11) utilizing Phase Doppler Interferometry i.e. PDA technique . They studied (1) the dispersion of droplets due to aerodynamic swirl, (2) and assessment of spray symmetry. For them the understanding the role of swirl in the dispersion of droplets is important in the design and operational procedures of burners for liquid combustion systems. Figure 12 shows the geometry used in their study which examines the effect of swirling and non-swirling co-flow on the dispersion of drops in a non-reacting spray. Such information is useful in the design of burners for liquid combustion system and questions about swirler design and atomizer design may be addressed with knowledge of the interaction between the aerodynamics and the droplets. Figure 13 presents radial profiles of the droplet size distribution (SMD) at 3 axial positions from the atomizer obtained by them . With no swirl, small drops remain at the centerline of the flow, and large drops remain away from the centerline. With the addition of swirl, the droplet size becomes uniform across the spray. Even 75 mm downstream of the atomizer, the case without swirl shows strong segregation of droplets, with large drops present at the outside of the spray, and small drops present at the center.

In Figure 14 they present vector plots of the axial/radial velocity of two different drops size classes. With the addition of swirl, 11-20 μm drops at the edge of the spray are moving away from centerline with much greater velocity than are the drops with non-swirling co-flow. In contrast, the 61-75 μm drops exhibit similar behavior for either the swirling or non-swirling case. A modest increase in the radial spread is observed for the larger drops. It was also noted that the larger drops travel significantly faster at the edge of the spray in the case with swirl. Their results indicate that the addition of swirl concentric to the atomizer results in a more uniform distribution of drop sizes, which is caused by variation in the trajectories of the drops. The addition of swirl, although reducing the axial/radial velocities of drops at the centerline, increases these velocity components of drops at the outer edge. One implication of the measurements is that small drops and large drops will be more likely to collide in the swirling case. Though their study was limited to droplets, it has implications for the mixing of particle laden jet in cocurrent flows. We also desire better mixing of the particles with cocurrent flow and obtain a better homogenous particle size distribution as well as a broadening of the particle laden jet. In addition when water spray is also involved it appears that this type of atomizer may also improve the droplet sorbent particle interactions.

This swirling co-flow atomizer seems to hold potential for our application as discussed in the preceding paragraphs. In addition since all that has to be done is to provide a relatively simple small larger

diameter pipe over the jet tube and connect the pipe with small swirl plate to the jet tube(as shown in Figure 12) . As per the recommendation in the CRC Report of August 9 , 1993 the CRC mentor ,Dr. R. Statnick 's opinion is being sought regarding the applicability of the swirling co-flow atomizer for injecting sorbent particles into cocurrent flue gas flow prior to running tests in the sorbent injection test facility.

3.4 Develop Technique to Study Particulate Droplet Interactions and Conduct Tests. (Tasks 3 and 4)

This work was started after the investigation of flow reversal phenomena was completed . Since the spray nozzle to be used for this study was the same i.e. Spraying Systems SU 1/8 JJ nozzle the nozzle spray characteristics required were obtained . The flow reversal tests also provided us with the information of the spray flow behavior in the duct which would be useful in deciding the particle laden jet location . The relative location of the particle jet tube and the spray nozzle will be fixed after consultations with the CRC monitor. Earlier tests with lime were planned , however with the problems associated with higher lime loading (>2) it is felt that glass particles may be a better alternative .A multiphase data acquisition and analysis system was procured from the PDA manufacturer Dantec Inc. This software was tried and it appears that the software works well when one set of particles is opaque and the other clear . For the case when we use glass beads and water droplets there may be some problems . In addition when water impinges on particle , the water envelope over the particle will have a different refractive index . It is felt that the TTLDV technique may

provide better results for droplet particle interactions . Though progress was made in this tasks the task was not completed because of the preceding difficulties. In addition in the CRC's August 9 Report it was suggested that the tests in room temperature air do not reflect the COOLSIDE conditions where the relatively hotter flue gas vaporize the fine droplets and thus the effect of fine droplets are eliminated . Thus there is a need to modify the test facility to provide heated air. This concern will be discussed with the CRC monitors and addressed when these tests will be in early part of the fourth year work.

3.5 Investigation of jet to Cocurrent flow velocity ratio ranges which result in region of negative flows (Task 5) :

In this task, our objective was to investigate water atomizer jet velocity to cocurrent gas velocity ratio ranges which result in region of negative flow and define onset of negative flow. The sorbent injection test facility was modified to allow these tests. The particle jet tube was removed and replaced by SU 1/8 JJ air atomizing nozzle manufactured by Spraying System Co. The use of this nozzle was suggested by URC project monitor Dr. R. Statnick, since a same model nozzle were used in FGD processes earlier. Provision was made to supply compressed air and water to the nozzle. The nozzle was placed close to the start of the test section. The cocurrent duct air flow rates were varied from 0.5 to 2.0 scfh, while the nozzle water flow rate and air pressure were varied between 20 cc/min to 70 cc/min and 20 psig to 50 psig respectively. The water droplet size and velocities were measured

5,10, 20 and 30 cm downstream of the nozzle. PDA was used for droplet size and velocity measurements. Tests were conducted for 36 condition. Table 4 provides details of test data which includes water flow condition (water flow rate, atomizer air pressure). Duct flow conditions (air flow velocities), spray center line velocity at nozzle exit, average droplet size (at 5 cm location), particle to duct velocity ratio and location of the flow reversal.

The initial test was conducted to ascertain that the atomizer flow was axisymmetric. A water flow rate of 50 cc/min was chosen and the velocity profiles for an air pressure of 50 psig and a duct flow rate of 0.75 scfh were obtained. In order to do this measurements were made from the top center of the duct at 1 mm intervals until the bottom of the duct was reached. This was the measurement in the x-z plane. Then measurements were made from the back wall of the duct along the center. Again measurements were made at 1 mm intervals until the front wall was reached. This is the x-y plane. The center of the spray was traversed both times. Measurements were made 5,10 and 20 cm from the atomizer. Each measurement point consisted of 4000 PDA measurements. Measurements included droplet diameters as well as velocities.

The velocity profiles for the x-z and x-y planes were plotted. These plots indicate that the nozzle is indeed axisymmetric, as shown in Figure 15. The velocities do not match exactly very close to the wall because of the low particle seeding rate in this region. Once axisymmetry was ascertained measurements were made for half the duct width only.

Velocity and droplet diameter measurements of the spray were made

TABLE 4. DETAILS OF FLOW REVERSAL TEST DATA

ATOMIZER CONDITIONS		DUCT FLOW CONDITIONS		RESULTS				
WATER FLOW RATE (cc/min.)	ATOMIZING AIR PRESSURE (psig)	AIR FLOW RATE (scfm)	AIR FLOW VELOCITY (m/s)	TEST NO.	CENTERLINE VELOCITY AT NOZZLE EXIT 5cm (m/s)	AVG. DROPLET SIZE AT 5cm (µm)	RATIO OF CNTR. LN. VEL. AIR FLOW VEL. AT 5cm	APPROX. LOCATION OF FLOW REVERSAL (cm)
50	50	122.99	24.25	1	108.86	27.205	4.49	
		85.60	16.89	2	111.47	27.242	6.60	30
		53.89	10.63	3	108.96	25.926	10.25	30,20
	40	119.60	23.60	4	95.056	15.832	4.03	
		90.94	17.95	5	95.804	15.796	5.34	
		59.58	11.76	6	96.195	14.965	8.18	30
	30	113.20	22.34	7	84.946	20.659	3.80	
		82.18	16.22	8	80.820	19.443	4.98	
		60.48	11.93	9	82.390	18.624	6.91	30
		43.42	8.57	10	82.517	17.620	9.63	30,20

TABLE 4. (CONTD.)

ATOMIZER CONDITIONS		DUCT FLOW CONDITIONS			RESULTS			
WATER FLOW RATE (cc/min.)	ATOMIZING AIR PRESSURE (psig)	AIR FLOW RATE (scfm)	AIR FLOW VELOCITY (m/s)	TEST NO.	CENTERLINE VELOCITY AT NOZZLE EXIT 5cm (m/s)	AVG. DROPLET SIZE AT 5cm (μm)	RATIO OF CNTR. LN. VEL. AIR FLOW VEL. AT 5cm	APPROX. LOCATION OF FLOW REVERSAL (cm)
20	50	119.40	23.56	11	89.005	18.217	3.78	
		81.13	16.01	12	91.292	19.000	5.74	
		53.57	10.57	13	90.609	16.567	8.57	30
		13.77	2.72	14	88.735	18.990	32.62	30,20
	40	124.95	24.66	15	76.410	18.328	3.10	
		87.75	17.32	16	75.662	19.551	4.37	
		55.42	10.94	17	76.715	21.021	7.01	30
		12.32	2.43	18	76.353	24.979	31.42	30,20
	30	119.42	23.57	19	57.843	17.496	2.45	
		84.21	16.62	20	59.903	20.659	3.60	
		47.46	9.37	21	59.486	21.283	6.35	30
		12.25	2.42	22	58.818	21.825	24.30	30,20
	20	118.54	23.39	23	51.235	15.609	2.19	
		86.05	16.98	24	51.453	15.044	3.03	
		51.27	10.12	25	52.554	19.767	5.19	30
		4.71	0.93	26	51.407	20.347	55.28	30,20

TABLE 4. (CONTD.)

<u>ATOMIZER CONDITIONS</u>		<u>DUCT FLOW CONDITIONS</u>			<u>RESULTS</u>			
<u>WATER FLOW RATE</u> (cc/min.)	<u>ATOMIZING AIR PRESSURE</u> (psig)	<u>AIR FLOW RATE</u> (scfm)	<u>AIR FLOW VELOCITY</u> (m/s)	<u>TEST NO.</u>	<u>CENTERLINE VELOCITY AT NOZZLE EXIT</u> 5cm (m/s)	<u>AVG. DROPLET SIZE AT 5cm (µm)</u>	<u>RATIO OF CNTR. LN. VEL. AIR FLOW VEL. AT 5cm</u>	<u>APPROX. LOCATION OF FLOW REVERSAL</u> (cm)
70	50	112.25	22.15	27	89.411	16.970	4.04	
		88.39	17.44	28	93.248	15.065	5.35	30,20
		47.03	9.28	29	91.812	17.129	9.89	30,20
	40	118.93	23.47	30	87.414	14.517	3.72	
		87.26	17.21	31	85.471	14.135	4.97	
		45.13	8.91	32	88.849	18.467	9.97	30,20
	30	120.21	23.72	33	72.865	13.769	3.07	
		87.59	17.28	34	73.347	14.506	4.24	
		46.61	9.20	35	75.565	16.580	8.21	30,20

5, 10, 20 and 30 cm downstream of the atomizer. Water flow rate and atomizing air pressure were held constant while the duct velocity behind the nozzle was parameterized. The experiment was conducted for three different duct air flow rates. Upon completion the air pressure for the atomizer was lowered and the experiment was repeated.

As expected the velocity profile near the atomizer exit was parabolic in nature. Moving further downstream the velocity profile began to flatten out with the maximum velocity decreasing significantly. At the point of furthest measurement, 30 cm downstream, the velocity profile is virtually flat (See Figure 16 a,b), as can be expected since the momentum is dispersed in the expansion of the spray moving downstream. In most cases the maximum axial velocity at 30cm was approximately one fourth of the value at the 5mm downstream location.

As the duct velocity was reduced one could observe the reversal of flow for each atomizer air pressure setting. Figure 17 shows the velocity profiles along with the flow reversal. This figure is representative of the data. This flow reversal in the duct was visible to the observer. We have taken movies of these conditions and the VHS tape is available with the P I. Unfortunately as this phenomenon became more prominent the wall of the test section began to get wet. This first happens far downstream of the atomizer and spreads back towards the nozzle. Flow reversal that occurs downstream of the test section is not relevant because in FGD process several atomizers are lined up next to each other and interact at a certain distance downstream (nearly a distance equal to the test section length). Our objective in this task was to study the flow reversal and identify parameters useful in

eliminating such reversal in spray which lead to collection of water on duct walls in FGD processes.

As stated earlier, the experiments were performed at atomizer air pressures of 50, 40, 30 and 20 psig. At each air pressure the duct velocity was first set at approximately 120 scfm, then reduced to 85, 60, and 40 scfm. For each case the flow reversal begins at a fixed point in the spray and continues until the spray hits the wall. The duct flow is entrained upstream of the initial point of reversal, but recirculation eddies are formed between this point and the downstream limit at which the spray hits the duct. Flow reversal became evident in most cases for nozzle centerline air velocity to duct air velocity ratios larger than 6. At ratios greater than 6 the flow reversal became more vigorous as entrainment diminished and the upstream boundary of reversal was pushed towards the spray inlet. The water layer on the test section wall grew towards the atomizer (See Figure 17). Once the test section was wet it was not possible to make measurements at that location. The test data (Table 4) also provides the reversal parameters. This work is part of V. Kadaba's M.S. Thesis and he is in midst of analyzing the data and trying to correlate the nondimensional parameters to obtain quantitative information regarding velocity ratios and obtain correlations for flow reversal conditions and its locations.

In addition to velocity measurements, particle sizes were also obtained using PDA. The sauter mean diameter, a ratio of particle volume to surface area, was measured at several locations. As seen in Figures 18 and 19, at locations near the atomizer, the smaller droplets remain close to the centerline of the spray while the larger droplets

move to the edge of the spray. Further downstream of the spray the particle diameters seem to be virtually uniform, this is largely due to evaporation due to mass transfer between the duct airflow and the atomizer spray.

4. SUMMARY AND STATUS

Satisfactory progress has been made in the project and the third year tasks have been addressed.

For task 1 (Lime Laden Jet Flow), since no existing technique was capable of providing the simultaneous measurement of irregular shaped particle size and velocity, a new technique, TTLDV which utilizes the transit time in LDV measurement volume and the LDV velocity measurements to obtain simultaneous particle size and velocity measurements was developed. The techniques applicability was ascertained using known size glass beads. The technique was then successfully tried on lime laden jet flow. Development of the TTLDV technique is a substantial achievement and provides a very useful tool for studying solid gas flows. Some difficulties were faced with lime loadings higher than 2 (5 or more) since, the smaller size of lime particles (7.9 microns average size) resulted in optically very dense jets for such loadings. This issue of higher loading is being discussed with URC monitors. Data analysis for lime jet flow is being performed.

Investigation of Better Sorbent Injection Methods and Optimized Injection Schemes (Task 2 and 6) have been addressed. Swirling atomizer (injector) seems to be an appropriate choice. URC mentors suggestions are being sought before conducting tests in the sorbent injection facility as per the recommendation of the URC Report of August 9.

Progress was made in the development of Technique to Study Particulate Droplet Interactions, (Task 3 & 4) could not be completed because of reasons cited in the report. In addition URC Report recommends that tests be conducted in heated air to simulate COOLSIDE operating conditions. This requires facility modifications and the associated difficulties will be discussed with URC mentors. Completion of task (4) will be undertaken in early part of the fourth year in consultation with URC mentors and OCDO.

The investigations of flow reversal resulting from spray jet cocurrent flow interactions (task 5) was completed. A 36 set data (about 144 axial measurement locations) was taken. Spray velocity to duct air velocity ratio greater than 6.0 results in flow reversals. The data is now being further analyzed to obtain correlations using nondimensional parameters to obtain the flow reversal locations as a function of parameters of interest. The characterization of SU 1/8 JJ nozzle is also useful for Task 3 and 4 tests. We are ready to continue on the fourth year tasks as outlined in the continuation proposal in consultation with URC mentor and OCDO.

Publications:

Papers on the TTLDV technique were presented at two different symposia. These were:

"Transit Time Technique for Simultaneous Measurement of Particle Size and Velocity in Two Phase Flows", authored by C. Yurteri, V. Kadaba, M. Assar and J. Kadambi, American Filtration Society's Annual Meeting, Multiphase Flow Symposium; Chicago, May, 1993.

'A Simultaneous Measurement of Irregular Particle Size and Velocity using Transit Time and LDV', Flow Instrumentation Forum, authored by J. Kadambi, C. Yurteri, M. Assar and V. Kadaba. Fluids Engineering Division Meeting, FED vol. ASME, Washington D.C. June, 1993.

A full length paper on the TTLDV technique is now being prepared to ASME's Fluid Engineering Division Symposium to be held at Lake Tahoe in June, 1994 and will be considered for publication in Journal of Fluids Engineering.

5. LITERATURE REFERENCES

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Figure 1. Schematic of Sorbent Injection Facility

Figure 2. LDA Parameters

Schematic of Probe Volume

3a. Measurement Volume Details

The Wire Disk Assembly

3b. Wire Disk Assembly

Figure 3. Wire Disk Assembly Setup

Figure 4 :Histogram for two rotating wire velocities

Figure 5 :Histogram of the two rotating wire transit time ,the larger value is for the 1150 micron wire

Figure 6 :Histogram of product vt for the two rotating wires ,the larger value is for the 1150 micron wire

Figure 7 Particle size histograms. Lens focal length is 160 mm. (LDA mode)
Fringe count is 40-200. (TTLDV mean; 43.2 μm and PDA mean; 41 μm)

Figure 8 Particle size histograms. Lens focal length 310 mm. (PDA mode)
Fringe count is 35-50. (TTLDV mean; 38.4 μm and PDA mean; 38.7 μm)

Figure 9 Particle size histograms. Focal length is 310 mm. (PDA mode)
Fringe count is 35-200. (TTLDV mean; 49.2 μm and PDA mean; 47.1 μm)

Figure 10. Axial velocity profile showing symmetry of flow for line Laden Jet ($m = 2$)

Figure 11. Sketch of Coaxial Flow Injector

Figure 12. Swirl Atomizer (from reference 11)

Figure 13. Radial Profiles of Size Distribution in Swirl Atomizer (from reference 11)

(a) 11-20 μm

(b) 61-75 μm

Figure 14. Vector Representation of Droplet Velocities
(from reference 11)

Figure 15. Droplet axial Velocities Along the Horizontal and Vertical Axis Showing Axisymmetric Spray.

Figure 16. Normalized Droplet Axial Velocity Profiles (U/U_0) at Different Axial Locations (no flow reversal).

Duct velocity of 3 m/s

Figure 17. Droplet Axial Velocities at Different Axial Locations (flow reversal, test # 15)

Figure 18. Droplet Size (SMD) Profiles at Different Axial Locations (test # 12)

Figure 19. Droplet Size (SMD) Profiles at Different Axial Locations (test# 27)

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