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INVESTIGATION OF TRANSPORT PROCESS
INVOLVED IN FGD

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For the Fifth Year
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EXECUTIVE SUMMARY

This report describes the work done in the fifth year of the project " Investigation of Transport Processes Involved in FGD".The objectives of this five year plan of study were 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 , and (6) sorbent reactivity in immediate mixing zone.

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 were used for flow characterization of particle laden jet in cocurrent flows . In the third year a new technique called TTLDV which combines particle transit time in measurement volume of LDV and LDV velocity measurements to simultaneously obtain non-spherical lime particle size and velocity was developed. Better sorbent injection schemes were investigated .In the fourth year the spray cocurrent flow interaction was investigated and a criterion was developed for predicting the flow reversal. Reversal results in deposition of water droplets on the duct wall and occurs when the spray has entrained all the cocurrent flowing stream . Tests on the swirl nozzles in air were conducted and the results indicated that

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the mixing is enhanced and the turbulence intensities in the radial direction show an increase of 10 to 30 %.

The following was accomplished in the fifth year. The sorbent injection facility was modified by adding a heater so as to obtain cocurrent flowing air at temperatures (upto 160°F) to simulate the higher flue gas temperatures. Spray cocurrent flow interaction tests were conducted at the higher temperatures . Larger size droplets survived the higher temperature cocurrent flow resulting in larger size droplets downstream of the spray nozzle in the test section. The flow reversal criterion, developed in the fourth year report, successfully predicted the flow reversal for these test conditions also. Tests were conducted with particle laden jet to understand the cocurrent flow particle interactions and flow reversals. A new correlation for potential core length for the particle laden jet was developed from the test data. The criterion for spray reversal was used with the new potential core relation. The criterion successfully predicted the flow reversal for particle laden flows. These criteria will allow the designer to avoid the flow conditions which will result in flow reversal and deposition of droplet and sorbent particles on the duct wall and floor which can lead to poor sorbent utilization. Tests were conducted on two new swirl nozzles and the simple nozzle. The test data indicated better mixing characteristics for the swirl nozzles. A set up for conducting tests with the swirl and simple nozzles in simulated flue gas containing sulfur dioxide in University of Cincinnati's Sprayer Dryer facility was designed and constructed.

Tests were then conducted with simulated flue gas at University of Cincinnati. The help and cooperation of Dr.T.Keener and his graduate students in conducting the tests and in the analysis of the lime sorbent used is very much appreciated. The test results are very encouraging and indicate substantial improvement, upto 140 % ,in sulfur capture by lime when swirl nozzle 1 is used over the results obtained for the simple nozzle. The swirl nozzle has 4 blades mounted on its outer diameter which swirl the flow. No additional energy is required . The improved mixing resulting from the swirl nozzle has enhanced the sorbent utilization during these tests. Further optimization and improvement in nozzle design is recommended which may be very useful in enhancing sorbent utilization in dry FGD methods.

The chapter on " Transport Processes involved in FGD " for the OCDO manuscript was completed and sent to Dr. Sampson. All the fifth year tasks were addressed and completed .

Two participants Ms.A.Plantner (B.S. Mechanical Engineering) and Mr.M.Assar (Ph.D, Mechanical Engineering) graduated in 1995. Following articles were written and presented in 1995.

1. "Particle Laden Jet and Spray Interaction and Reversal in Cocurrent flow", C.Yurteri, J.R.Kadambi and V.Kadaba, accepted for the 9th International Symposium on Transport Phenomena(ISTP-9) in Thermal-Fluids Engineering ,Singapore 1996/ International Journal of Transport Phenomena, December, 1995.

2. "Spray Reversal in Cocurrent Air Flow in a Horizontal Duct", V.P. Kadaba, C.Yurteri and J.R. Kadambi ,Gas Liquid Flows-1995-FED- Vol.225 , American Society of Mechanical Engineers, New York,NY , 1995 , and also presented at the Summer Annual Fluids

Engineering Conference at Hilton Head, S.C. August 1995.

3. Submitted a chapter on "Transport Processes in FGD" in Dry Sorbent Injection Technology for Sulfur dioxide emission control being published by OCRC for OCDO . December, 1995.

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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

$$t_p = \rho_p (d_p)^2 / (18 \mu) \quad (1)$$

Where ρ_p = particle density , d_p = particle diameter and μ = the fluid viscosity. A fluid time scale t_f based upon a given eddy can be defined as:

$$t_f = L/U \quad (2)$$

Where L is the eddy length scale and U is the 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 review of literature was undertaken in this area of spray cocurrent flow and was reported by Kadambi et. al (3,5). 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 has to be developed.

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 , and (6) sorbent reactivity in immediate mixing zone. Some of these objectives have been addressed in this investigation. The first four years work will be briefly discussed and then the results of the final fifth year work will be presented.

2. PREVIOUS ACCOMPLISHMENTS

2.1. Work Accomplished in the 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 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 (Reference 3).

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(Figure 1). The duct is made up of transparent plexiglass walls except for the 300 mm long test section which is made up of pyrex glass. 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

Figure 1 Schematic of Test Facility

interaction between the particle laden jet and cocurrent duct flow occurs in the test section. Details of the sorbent injection test facility are provided in by Kadambi et al. in Reference 3.

The major instrumentation used is the Particle Dynamics Analyzer (PDA). The PDA manufactured by Dantec Electronics utilizes a 4 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. The details and principle of operation of PDA/LDA are provided in Reference 4 (Dantec Manual).

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 are provided in our second year report (Reference 3). Some important conclusions from the first 2 years were:

- 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.

2.2 Work Accomplished in third year (9-92 to 8-93)

The third year tasks involved (a) conducting tests with lime laden jet flow , (COOLSIDE Configuration), (b) Investigation of spray to cocurrent flow velocity ratio ranges and which result in region of negative flow, (c) investigate better sorbent injection schemes and (d) develop techniques to study particulate droplet interaction.

(a) TTLDV Technique:

The PDA technique can obtain simultaneous measurement of particle velocity and size for spherical particles (droplets) only. Lime particles are not spherical and therefore, PDA could not be used for irregular shaped lime particles. We therefore concentrated upon developing a technique 'TTLDV' for simultaneous measured of lime particle size and velocity. The TTLDV technique is based upon the measurement of the transit time of the irregular shaped particle to cross the known size of the measurement volume formed by the crossing of the two laser beams of the Laser Doppler Velocimeter (LDV), and the particle velocity obtained by LDV. The applicability of the TTLDV technique was ascertained by (a) using

Figure 2 Glass particle size distribution obtained from PDA and TTLDV (160mm lens), (TTLDV mean = 41.0 μm , PDA mean = 43.2 μm).

Figure 3 Comparison of lime particle size distribution obtained from TTLDV and PDA tests, and Microtrak results. (Cumulative results)

known size spherical glass beads and comparing PDA and TTLDV data as shown in Figure 2 and (b) using known size lime particles and comparing the TTLDV results with the known sizes. The lime particle size was obtained independently using Microtrac which utilizes Franhofer light scattering technique. The comparison of TTLDV, Microtrac and PDA results for lime tests are shown in Figures 3. As can be observed from the figure, TTLDV and Microtrac results compare favorably but the PDA results are off by a factor of 4. Details of the TTLDV technique are provided in Reference 5 and 6.

(b) Investigation of spray - cocurrent flow interactions.

Flow reversal resulting from spray jet cocurrent flow interaction was investigated. Again, non-intrusive PDA/LDV technique were used for measuring the droplet velocity and diameter. SS 1/8 JJ atomizing nozzle was used. It was installed into the sorbent injection facility in the place of the particle laden jet tube in the 88 mm x 88mm duct. The characteristics of the atomizing nozzle were obtained. The complete test data included 36 sets (about 144 axial locations). The test data analyzes was started near the end of third year and was completed in the early part of fourth year and will be discussed in the section dealing with the fourth year work.

(c) Swirling co-flow atomizer (injector) was selected for obtaining better mixing of the droplets with the cocurrent flowing air. The swirl atomizers requires relatively simple arrangement of swirl generator (blades), without additional energy requirements.

(d) A multiphase data acquisition program which was acquired and was used to investigate droplet-glass particle interaction felt that this technique TTLDV technique may be useful in the droplet-particle interactions.

2.3. Work Accomplished in the fourth year (1994-95)

The fourth year tasks included:

- Investigation of spray cocurrent flow interaction and development of a criterion to predict flow reversal.
- Development of swirl nozzle configuration for improved sorbent cocurrent flow mixing, and
- Design a test leg to fit into the University of Cincinnati's Sprayer Dryer facility to conduct tests and evaluate the swirl nozzle configuration in simulated SO_2 containing flue gas flow.

Spray Cocurrent flow interaction and flow reversal.

Test were conducted with spraying system's Ss 1/8 JJ nozzle in the sorbent injection test facility. PDA was utilized for measuring droplet and flow velocities the following was achieved.

A cosine model was developed to predict the velocity profiles. The agreement between the model and the experimental results in regions of $x/d_0 > 80$ is within 5%. An equation for centerline velocity decay was developed and the agreement with experimental results is within 3%.

A criterion for predicting the onset of flow reversal was developed. Flow reversal is defined as the negative flow arising beyond the point where all the cocurrent air mass flow is entrained by the spray. This criterion successfully predicted flow reversal

Table 1

(a) Procedure for Determination of Flow Reversal for spray

<i>Parameter Calculated</i>	<i>Equation For the Parameter</i>
Mass Flow Ratio of Two Phases	$\lambda = \frac{\rho u}{\rho_0 u_0}$
Potential Core Length	$\frac{x_p}{d_o} = 4 + 55\lambda$
Modified Thring-Newby Parameter	$\theta = \frac{\dot{m} + \dot{m}_o}{\dot{m}_o} \frac{d_o}{2L} \left(\frac{\rho_o}{\rho} \right)^{1/2}$
Location of Flow Reversal Initiation	$X_N = 6.25\theta L$
Axial Distance from Nozzle Exit to Spray Interaction with Wall	$\frac{L}{X_W} = \frac{1}{4 + 55\lambda}$
Existence of Flow Reversal	If $X_N < X_W$
Mass Flow of Recirculation	$\frac{\dot{m}_e}{\dot{m}_o + \dot{m}} = \frac{0.47}{\theta'} - 0.5$

(b) Procedure for Determination of Flow Reversal for particle laden jet.

<i>Parameter Calculated</i>	<i>Equation For the Parameter</i>
Mass Flow Ratio of Two Phases	$\lambda = \frac{\rho u}{\rho_0 u_0}$
Potential Core Length	$\frac{x_p}{d_o} = 6 + 30\lambda$
Modified Thring-Newby Parameter	$\theta = \frac{\dot{m} + \dot{m}_o}{\dot{m}_o} \frac{d_o}{2L} \left(\frac{\rho_o}{\rho} \right)^{1/2}$
Location of Flow Reversal Initiation	$X_N = 6.25\theta L$
Axial Distance from Nozzle Exit to Spray Interaction with Wall	$\frac{L}{X_W} = \frac{1}{6 + 30\lambda}$
Existence of Flow Reversal	If $X_N < X_W$
Mass Flow of Recirculation	$\frac{\dot{m}_e}{\dot{m}_o + \dot{m}} = \frac{0.47}{\theta'} - 0.5$

for all test conditions in which flow reversal was observed. The procedure to determine the existence of flow reversal is outlined in Table 1(a). An equation is developed which predicts the ratio of recirculating mass flow to total mass flow for flow reversal conditions.

Tests on new Swirl Nozzles.

Tests on the new swirl nozzle configurations were conducted. The swirl nozzle is shown in Figure 4. The length 'l' and height 'h' and the twist angle can be varied. The design allows the cocurrent flow to be swirled so as to enhance the mixing of the cocurrent flow with the particle laden jet. There is no need to spend any extra energy to enhance the mixing. PDA (Particle Dynamics Analyzer) and LDA (Laser Doppler Anemometer) were utilized to characterize the flow. Axial, radial mean velocities and the turbulent fluctuating components were obtained. The data have been compared with the Coolside configuration (which is a straight tube). Data analysis indicates that the flow emanating from the swirl nozzle has higher fluctuating components (turbulent intensities) of velocity in the radial as well as the axial direction as compared to the Coolside configuration. An increase of more than 15% is observed in the fluctuating components of the axial velocity. The increase in the fluctuating component of the radial velocity is greater than 10%. The level of increase is dependent upon the axial location and generally increases as one moves away from the nozzle. Increase in turbulent intensities, especially in the radial direction, implies better diffusion and

Swirl Nozzle 1: $l=10$ cm, $h=1$ cm, and $\varnothing = 15^\circ$
 Swirl Nozzle 2: $l=5$ cm, $h=1$ cm, and $\varnothing = 15^\circ$
 Simple Nozzle is just the tube without blades.

OCDO _ FLUE GAS DESULFRIZATION PROCESS

SWIRL NOZZLE DESIGN

$\varnothing$ Blade Swirl Angle and h blade height
 l Blade length

Figure 4 The Swirl Nozzle

consequently better mixing rates. A setup for installing the swirl nozzle and simple nozzle arrangement in the Sprayer Dryer facility was designed. The arrangement goes between the Spray Dryer and the Fabric Filter. Provision to obtain spent lime samples immediately upstream of the Fabric Filter was provided. The lime sample will then be evaluated to assess its utilization. The setup and tests are explained in the fifth year work. The details of the fourth year work is provided in Reference 7.

3. WORK ACCOMPLISHED IN THE FIFTH YEAR (1994-95)

3.1. Fifth Year Objectives:

1. Complete the tasks associated with enhanced mixing, optimization, droplet and particle interactions with cocurrent duct flow.
2. Investigate spatial distribution of injected reagents on flue gas (cocurrent flow) recirculation zones with emphasis on sulfurdioxide control and flue gas humidification for ESP performance enhancement. The tests will include investigation of recirculation zones for spray droplets with cocurrent flow temperature around 160°F. This will simulate the flue gas duct conditions. This work will build upon the results of spray droplet cocurrent flow interactions resulting in separation and recirculation zones.
3. Fabricate the set up for the swirl nozzle and simple nozzle for conducting simulated SO₂ tests in University of Cincinnati's Sprayer Dryer Facility.

4. Conduct tests on the swirl nozzles and simple nozzle in University of Cincinnati's Sprayer Dryer Facility using the COOLSIDE configuration and the optimized swirl nozzle configurations and compare the lime utilization i.e. sulfur capture for the nozzles. Assess the improvements , if any, obtained by better mixing resulting from the swirl nozzles.

5. Completion of the chapter on "Transport Processes in FGD" for the OCDO Manuscript.

6. Document the results.

It should be noted that the preceding objectives were modified after consultations with the CRC mentors (Dr. Statnick) and were reported in the Fourth year final report and the quarterly report covering the time period 9-1-1994 to 11-30-1994.

3.2. Enhanced mixing, optimization, droplet and particle interactions with cocurrent duct flow.

To conduct the cocurrent flow droplet and particle interactions at temperatures relevant to FGD processes, a heating system was added. The sorbent injection test facility was modified by incorporating Chromolox's duct electric heater (Model# CABB-1211) into the inlet duct. The heater regulates the air temperature between 60°F to 250°F (i.e 15 to 120°C). However, since the duct walls are made of Lexan, the maximum operational air temperature was limited to 140°F (60°C). Spraying systems JJ 1/8 spray nozzle was used for generating water spray. The same nozzle was utilized in earlier tests at room temperature. The test

conditions and parameters are provided in Table # 2. The cocurrent air temperature was varied between 112°F and 140°F (50 to 60°C). The earlier experiments reported in the 1993/94 final reports (Reference 5 and 7) were conducted with cocurrent flowing air at room temperature (20-30°C). These tests were conducted at test section Reynolds numbers similar to those encountered in the FGD process as was the case in the earlier room temperature air tests. The PDA was used for measuring the droplet velocity and size simultaneously. The PDA receiving optics were set at 149° in the off axis back scatter mode to utilize the 2nd order refraction mode. The flow was mapped in one half of the duct, since it was axisymmetric, at different axial locations. The water flow rate was maintained at 50 cc/min. The duct flow rate was varied from 4 to 11.6 m/s. The air pressure for the spray nozzle was varied from 20 to 40 psia. Figure 5 shows the axial droplet velocity distribution in the radial direction at axial locations 5, 10, 15, 20 and 25 cm downstream of the spray nozzle exit. The axial velocity profiles shown in this figure at different axial locations are typical of the data and the profiles are similar to those obtained with the room temperature air tests reported earlier in the 1993-94 final report. As one moves away from the nozzle the velocity profile becomes flatter with an appreciable decrease in the centerline velocity. This is to be expected because of the dispersion of the momentum as the spray expands. Figure 6 shows the Sauter mean diameter (SMD) profile in the radial direction at different axial locations. Larger droplets tend to move to the

Table 2

Test Facility Parameters and Specifications

Nozzle Orifice Diameter	1.3 mm
Inside Dimensions of Square Duct	88.6 x 88.6 mm ²
Test Section Length	300 mm
Mean Concurrent air Velocity	4.65 - 11.60 m/s
Centerline Spray Velocity (5 cm)	50 - 110 m/s
Temperature of Concurrent Air	50 - 60 C

Test Conditions

Volumetric Flow Rate of Water in Atomizer(cc/min)	50
Volumetric Flow Rate of Air in Atomizer (scfm)	1.4 / 1.02 / 0.72
Axial Measurement Locations (cm)	5 / 10 / 15 / 20 / 25
Non Dimensional Measurement Locations (x/d _o)	38.5 / 76.92 / 115.39 / 153.85 / 192.31
Air Density, ρ (kg/m ³)	0.9950 - 1.08

	<i>Water Rate (ccm)</i>	<i>Air Pressure (psi)</i>	<i>Measurement locations (x/d_o)</i>	<i>Duct Temperature (C)</i>
<i>Case 1</i>	50	40	38.5 / 76.92 / 115.39 / 153.85 / 192.31	50
<i>Case 2</i>	50	30	38.5 / 76.92 / 115.39 / 153.85 / 192.31	50
<i>Case 3</i>	50	20	38.5 / 76.92 / 115.39 / 153.85 / 192.31	50
<i>Case 4</i>	50	40	76/92 / 115.39	60

Figure 5 Axial velocity profile at Locations 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm downstream of the nozzle exit.

Figure 6 The spray droplet size (Sauter Mean Diameter) distribution at various locations for test data shown in Figure 5.

edge of the spray while the smaller ones stay near the centerline. As one moves away from the nozzle exit, nearly all of the smaller droplets evaporate leaving the larger ones (around 22 micron diameter). Because of the higher temperature of the air the smaller particles are evaporated quickly and one observes that the particle size at axial locations 20 cm and 25 cm downstream of the nozzle are nearly uniform and similar in size. Figure 7 shows the histogram at an axial location 10 cm downstream of the nozzle and indicates that due to higher temperature air, that all particles smaller than 5 microns have been evaporated. In the earlier room temperature air tests smaller size droplets were encountered. The flow reversal criteria, developed earlier, predicted the flow reversals correctly at the higher temperature flows.

Additional tests were conducted to obtain more data for particle laden jets in cocurrent flow to develop a more accurate correlation for the potential core length based upon the data. These results are discussed in section 3.3.

Swirl nozzle tests for optimization:

Tests were conducted with two swirl nozzle designs as indicated in Figure 4 with blade lengths 100 mm and 50 mm. The number of blades used was 4. The mixing characteristics of these swirl nozzles were compared with the simple nozzle used in the COOLSIDE tests (Figure 8. As was reported earlier in the single phase tests, the particle laden jet test indicated enhancement of the turbulent intensities and an increase in u' and v' of 10 to 15%.

Figure 7 The histogram of spray droplet size distribution at an axial location 10 cm downstream of the nozzle for test data shown in Figure 5.

Figure 8 Comparison of single and particle phase velocities, $x/D=0.1$, for simple and swirl nozzle. $U_d = 10$ m/s, $U_o = 35$ m/s.

The larger blade length (10 cm) swirl nozzle indicated better mixing than the shorter blade length (10 cm) swirl nozzle . The improvement in mixing was higher for nozzle exit velocity/cocurrent velocity ratios of 30/20 and 35/20 as compared to lower duct velocities of 15 m/s. The particle loadings of 2.5 and 5.0 were tried for these tests. Since loadings greater than 5.0 resulted in damping the turbulent intensities as indicated in our 1992-93 report tests were not conducted at loadings higher than 5. The performance of the two swirl nozzles was encouraging and these configurations were selected for the tests conducted for the fifth year objective 4 in University of Cincinnati's Sprayer Dryer facility which simulates SO₂ laden flue gas.

3.3 Particle Laden Jet - Cocurrent flow interaction

The tests to study particle cocurrent flow interactions resulting in flow reversal were also conducted and Spherical glass particle of average diameter 40 microns were used. Ms. Anita Plantner , an undergraduate student (senior) was also involved in these tests and the work formed a part of her senior thesis . She graduated in December 1995. PDA measurements of velocity profiles were made at normalized axial distances (x/d) of 0.1, 5.0, 10.0, 15.0 and 20.0. The mass loading was varied up to 2.5. The duct mean velocity U duct, i.e. the cocurrent velocity was reduced from 10 m/s to a value where flow reversal occurred. The values were 10 m/s, 6 m/s, 4.16 m/s and 1.66 m/s.

The cosine power law was modified slightly by considering the particle velocity at the edge of jet i.e. at the boundary for the

axial location instead of the average duct velocity. The modified equation is:

$$\frac{U - U_{edge}}{U_c - U_{edge}} = \frac{1}{2} [1 + \cos(\frac{\pi r}{Y_{05}})] \quad (3)$$

where Y_{05} is the radial distance where the velocity = $\frac{U_c + U_{edge}}{2}$

Here U is the particle velocity, U_{edge} the velocity at the edge of the jet and U_c is the centerline velocity. The comparison between data and modified cosine law is good (Figures 9a and 9b). The data were utilized to develop a new correlation for the potential core length for the particle laden jet. The new correlation is given by Equation 4.

$$X_p/d_0 = 6.0 + 30\lambda \quad (4)$$

Where X_p = potential core length, d_0 = diameter of nozzle, $\lambda = (\rho u / \rho_0 u_0)$. The potential core length X_p for the particle laden jet is different than that for the spray. However the value of the core length obtained using the two equations were similar. However, the error band for spray correlation length was 14 % while for the particle laden jet correlation was 2.5%. The criteria developed for predicting flow reversal for the spray was also used for predicting flow reversal for the particle laden jet. The criteria, successfully predicts the flow reversal for the particle laden jet. The particle axial velocity distribution along the jet as it expands into the duct in cocurrent flow was also plotted. Figures

Figure 9(a)

Figure 9(b)

Figure 9 Comparison of the experimental velocity profile with modified cosine law profile. (Mean duct velocity: 10 m/s, (a) $x/d=10$, (b) $x/d=15$)

10 and 11 show the distribution for tests where the particle jet velocity at nozzle exit was 35 m/s while the duct velocities were 10 m/s and 1.66 m/s respectively. In Figure 10 at the higher duct velocity the jet expansion is not that robust. At the lower duct velocity of 1.66 m/s flow reversal was observed. Figure 11 shows the axial velocity distribution for this case and one can observe the reduction in the axial velocity along the constant velocity contours. The deposition of the particles on the walls prevented us from making measurements of the negative velocities as the PDA laser beams were blocked by the particles deposited on the wall.

3.4 Swirl Nozzle tests at U.C.'s Sprayer Dryer Facility(Task 3 & 4)

The simple arrangement for incorporating the simple and swirl nozzles in University of Cincinnati's Sprayer Dryer facility is shown in Figure 12. Higher temperature resistive PVC ducting was used for the arrangement. This addition was built in such a way so that it could be easily assembled and incorporated into U.C.'s Sprayer Dryer facility. Graduate student, Mr. C. Yurteri, assembled the unit into the facility and conducted the SO₂ laden flue gas tests. The lime injected through the nozzles was supplied by Dravo (courtesy of Dr. Manyam Babu). The objective of task 4 was to investigate the effect of improved mixing characteristics of the swirling nozzle jet in enhancing the capture of sulfur by the sorbent and improving the sorbent (lime) utilization. Experiments were performed using the simple nozzle and two swirl nozzles. The swirl nozzle jet design enhances the mixing characteristics without expending any additional energy. The test setup is shown in

Figure 10 Particle Axial Velocity Distribution in the Jet. Mean duct velocity $U_d=10\text{m/s}$, Particle jet exit velocity $U_o=35\text{m/s}$, axial location $x/d=0.1$, mass loading $m \ll 1$

Figure 11 Particle Axial Velocity Distribution in the jet. Mean duct velocity $U_d=1.66\text{ m/s}$, Particle jet exit velocity $U_o=35\text{m/s}$, axial location $x/d=0.1$, mass loading $m=2.5$

Figure 12 Simple arrangement for straight and swirl nozzle sulfur dioxide tests in University of Cincinnati's spray dryer facility.

photographs in Figure 13. The swirl nozzles are shown in Figure 4. The Nozzle specification, test conditions and the test matrix is provided in Table 3. The sorbent mass loading was varied between 2.5 and 5.0. No attempt was made to run tests at higher loading since earlier tests (Reference 5) showed the loading higher than 5 results in reduction in mixing. The mean SO₂ laden air velocity was varied between 15 m/s and 20m/s. The system capabilities did not allow for any higher air velocity. Mean nozzle velocity was varied between 30 m/s and 35 m/s. The air temperature was maintained at an average temperature of 170°F, with a variation of 10 degrees. Figure 14 shows the variation in the temperatures at spray dryer inlet, duct and the bag house outlet during a span of 75 minutes. The figure indicates that steady state conditions were reached during the tests. The sulfur dioxide concentration at the inlet of the sprayer dryer is shown in Figure 15 during a time span of 55 minutes. An average concentration of 2409 ppm was maintained during the tests as shown in Figure 16. The SO₂ concentration was monitored with HORIBA PIR-2000 gas analyzer. The samples of injected lime particles were collected 50 diameters downstream of the nozzle tip upstream of the bag house inlet. The samples were obtained using a sampling probe-vacuum pump combination and a particle trap. The cooperation and help of Dr. Keener and his graduate students, especially Mr. Jun Wang is running these tests

Table 3 Test Parameters and Specifications

Nozzle Specifications;

Nozzle type	Orifice Diameter	# of Blades	blade length	blade height
Simple	7.3 mm	none	-	-
Swirling 1	7.3 mm	4	100 mm	10 mm
Swirling 2	7.3 mm	4	50 mm	10 mm

ID. of Circular Duct	72 .0 mm
Flow Velocity In Duct (co-current) (U_d)	15 - 25 m/s
Flow Velocity at Nozzle Exit (U_o)	30 - 35 m/s
Jet Reynolds Number based on diameter	1.5E+4, 1.8E+4
Duct Reynolds Number based on diameter	30.E+4, 95.E+4
particle Density	2240 kg/m ³
Particle material	lime, Ca(OH) ₂
Particle Diameter (non-spherical)	1-30 μ m (26 μ m mean size)
Mass Loading (m)	2.5 , 5.0
Flow Temperature at Duct	~170 °F
Air Density	~1 kg/m ³
SO2 Concentration	2400 ppm

Table 4 Test Results

TEST RESULTS		Test number, and % Sulfur capture (with weight)					
Test Conditions		Simple		Swirl 1		Swirl 2	
U_o/U_d	m	No	% Sulfur	No	% Sulfur	No	% Sulfur
30/20	2.5	1	0.584	9	0.905	17	0.794
30/20	5	2	0.525	10	1.194	18	1.132
35/20	2.5	3	0.586	11	0.828	19	0.824
35/20	5	4	0.621	12	0.970	20	0.809
30/15	2.5	5	0.635	13	0.641	21	0.700
30/15	5	6	0.865	14	0.661	22	0.760
35/15	2.5	7	0.808	15	0.887	23	0.714
35/15	5	8	0.915	16	0.862	24	0.575

Figure 13 Two pictures of the test setup at University of Cincinnati's spray dryer facility

Figure 14 Temperature variation during the spray dryer facility test.

Figure 15 SO₂ concentration during the spray dryer facility test.

Figure 16 SO₂ Concentration distribution statistics for a test span.

is very much appreciated. The analysis of the lime samples (sulfur capture by weight %) was also conducted by Dr. Keener's graduate student. The percentage of sulfur absorbed by the injected lime was obtained for various test conditions.

The results of the tests are reported in Table #4. The table provides the test conditions including jet exit to duct velocity, mass loading, nozzle configuration simple (i.e no blades), swirl nozzle 1 and swirl nozzle 2, sample number and % of sulfur absorbed (by weight) by lime.

The results are also plotted in Figure 17 which provides the % of sulfur captured as a function of duct velocity U_d , nozzle exit velocity U_0 and mass loading. The results show the effect of the improved mixing resulting from the swirl nozzles, especially #1 which has longer blade length (100 mm). As can be observed from the figure, at lower duct velocity of 15 m/s, the performance of the simple nozzle and swirl nozzles is relatively similar with the swirl nozzle performing better for two cases and the simple nozzle performing better in two cases. However when the duct velocity is increased to 20 m/s, the improvement observed in the capture of sulfur by lime injected with swirl nozzle #1 over the simple nozzle is substantial with the sulfur capture percentage increasing in the range of 41% to 127%. For swirl nozzle #2 the increase is in the range of 30 % to 116%. The longer length of the blade (100 mm) for Swirl Nozzle #1 as compared to swirl nozzle #2 (50 mm) seems to more effective in improving mixing and thus increasing the sulfur capture by the lime sorbent. These results are very encouraging

Figure 17 Sulfur capture in University of Cincinnati's spray dryer facility tests by simple and swirl nozzles. Swirl Nozzle 1 ($l=10\text{cm}, h=1\text{cm}$), Swirl nozzle 2 ($l=5\text{cm}, h=1\text{cm}$), U_d = Mean Duct Velocity, U_o = Particle Jet Velocity at Nozzle Exit, mass loading = Particle to air mass ratio

and indicate that improved mixing of the injected lime with the flue gas will substantially enhance the sorbent utilization. The swirl nozzle design can be further optimized .

3.5 Chapter for Monograph.

The chapter on "Transport Processes Involved in FGD" was completed and sent to Dr. K. Sampson. The chapter was reviewed and changes have been made.

4. SUMMARY:

All the fifth year tasks were addressed and completed . The sorbent injection facility was modified by adding a heater so as to obtain cocurrent flowing air at higher temperatures (upto 160°F) to simulate the higher flue gas temperatures. Spray cocurrent flow interaction tests were conducted at the higher temperatures . Larger size droplets survived the higher temperature cocurrent flow resulting in larger size droplets downstream of the spray nozzle in the test section. The flow reversal criterion developed in the fourth year report successfully predicted the flow reversal for these test conditions also. Tests were conducted with particle laden jet to understand the cocurrent particle interactions and flow reversals. A new correlation for potential core length for the particle laden jet was developed from the test data. The criterion for spray reversal was used with the new potential core relation. The criterion successfully predicted the flow reversal for particle laden flows. These criteria will allow the designer to avoid the flow conditions which will result in flow reversal and deposition of droplet and sorbent particles on the duct wall and floor which

lead to poor sorbent utilization. Tests were conducted with two new swirl nozzles and the simple nozzle. The test data indicated better mixing characteristics for the swirl nozzles. The swirl nozzles have 4 twisted blades mounted on the outer diameter of the nozzle tube and do not require any extra energy for enhancing the mixing. A set up for conducting tests with the swirl and simple nozzles in simulated flue gas containing sulfur dioxide in University of Cincinnati's Sprayer Dryer facility was designed and constructed. Tests were then conducted with simulated flue gas at Cincinnati. The help and cooperation of Dr.T.Keener and his graduate students in conducting the and analysis of the lime sorbents is very much appreciated. The test results are very encouraging and indicate substantial improvement in sulfur capture of upto 140% by lime when swirl nozzle 1 is used as compared to the results obtained with the simple nozzle . The improved mixing resulting from the swirl nozzle appears to enhance the sorbent utilization. These tests indicate that further optimization and improvement in nozzle design could be very useful in enhancing sorbent utilization.

Two participants Ms. A. Plantner (B.S. Mechanical Engineering) and Mr. M. Assar (Ph.D. Mechanical Engineering) graduated in 1995.

Following are the articles and presentations for 1995.

1. "Particle Laden Jet and Spray Interaction and Reversal in Cocurrent flow", C.Yurteri, J.R.Kadambi and V.Kadaba, accepted for the 9th International Symposium on Transport Phenomena(ISTP-9) in

Thermal-Fluids Engineering ,Singapore 1996/ International Journal of Transport Phenomena, December, 1995.

2. "Spray Reversal in Cocurrent Air Flow in a Horizontal Duct", V.P. Kadaba, C.Yurteri and J.R. Kadambi ,Gas Liquid Flows-1995-FED- Vol.225 , American Society of Mechanical Engineers, New York,NY , 1995 , and also presented at the Summer Annual Fluids Engineering Conference at Hilton Head,S.C. August 1995.

3. Submitted a chapter on "Transport Processes in FGD" in **Dry Sorbent Injection Technology for Sulfur dioxide emission control** being published by Ohio Coal Research Consortium for Ohio Coal Development Office ,Columbus.December, 1995.

5. LITERATURE REFERENCES

1. Drummond, C., Babu, M., et al., "Duct Injection Technologies for SO₂ Control", Proceedings of First Combined Flue Gas Desulfurization and Dry SO₂ Control Symposium, EPRI Report GS-6307, St. Louis, MO, Oct. 1988.
2. Adler, R.J. Fan L.S., Kadambi, J.R., Keener, T.C., Khang, S.J., Prudich, M., and Raghunathan,K., "Flue Gas Desulfurization and Acid Rain Control," Report of the Consortium of Ohio Universities to OCDO, Sept. 1989.
3. Kadambi, J.R., Chinnapalaniadi, P. and T'ien, J.S. "Investigation of Transport Processes Involved in FGD", Final Report for Second Year, for Period September, 1991 to August 1992, submitted to OCDO, November 1992.
4. Dantec Electronics Inc, "Particle Dynamics Analyzer," User's Manual.
5. Kadambi, J.R., Yurteri, C., Kadaba, V. and Assar, M., "Investigation of Transport Processes in FGD - Third Year Final Report (OCRC93-2.1), submitted to OCDO. September 1993.

6. Yurteri, C., Kadaba, V. and Kadambi, J.R., "A New Approach Using Transit Time for Simultaneous Measurement of Size and Velocity of Non-Spherical Particles," FED-Vol 191, Laser Anemometry, Advances and Applications, ASME, New York, NY 1994.
7. Kadambi, J.R., Yurteri, C., Assar, M. and Kadaba, V., "Investigation of Transport Processes in FGD - Fourth Year Final Report (OCRC94-2.1), Ohio Coal Development Office, Columbus, Ohio, September, 1994.

6. NOMENCLATURE

d_o	nozzle orifice diameter
d_p	particle diameter
L	eddy length scale, 1/2 of hydraulic diameter
LDV	Laser Doppler Velocimeter
m	mass flow rate of cocurrent air
m_o	mass flow rate at nozzle exit
PDA	Particle Dynamics Analyzer
Re_p	particle Reynolds number
t_f	time scale for fluid
TTLDV	Transit Time LDV
t_p	time taken by particle to accelerate to 63.3% of the free stream velocity
U	eddy velocity scale, particle velocity
U_{edge}	particle velocity at the edge of the jet
U_c	centerline particle velocity
u	cocurrent flow velocity
u_o	centerline velocity at nozzle exit
X_p	potential core length
$Y_{0.5}$	radial distance where particle velocity is equal to $(U_c \text{ and } U_{edge})/2$

GREEK LETTERS

ρ	cocurrent flow density
ρ_o	water density
ρ_p	particle density
μ	fluid viscosity
λ	$(\rho u) / (\rho_o U_o)$