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SIMULATION OF SPRAY DRYER ABSORBER FOR REMOVAL OF SO_2 FROM FLUE GASES

A Thesis

Presented for the

Master of Science

Degree

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Mehdi Maibodi

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ABSTRACT

The focus of the present activity is the development of a mechanistically based mathematical model of sulfur dioxide removal in a pilot plant scale spray dryer.

In the spray dryer, flue gas from a coal burning boiler is contacted with an atomized lime slurry. During this contact sulfur dioxide absorbs and reacts with calcium hydroxide. The developed mathematical model superimposes the sulfur dioxide absorption and reaction phenomena on existing mathematical descriptions of spray dryer operation. Using established spray dryer terminology, the sulfur dioxide removal processes occur in the constant and falling rate periods.

Efficiency predictions using the model presented here were compared with data from the pilot plant taken at different inlet flue gas temperatures, stoichiometric ratios, slurry flow rates, and droplet sizes. This comparison shows a good agreement with the individual data points and with overall trends in the data.

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LIST OF SYMBOLS

A^* = interfacial concentration of SO_2, gmol/cm^3

A_p = surface area of particles, cm^2 / cm^3 dispersion

B_s = saturation solubility of solid, gmol/cm^3

BW2 = moisture fraction by volume of flue gas leaving spray dryer

C_{Ag} = molar concentration of SO_2 in gas phase, mole/cm^3

C_{CaCO_3} = solubility of limestone in the liquid phase, gmole/cm

C_{H^+} = concentration of hydronium ion in liquid phase, gmol/cm^3

d = droplet diameter, cm

d_{vs} = Sauter mean diameter, cm

D = liquid phase diffusivity, cm^2/sec

DELTAT = difference between dry bulb and wet bulb temperature, units ^oF

DT_o = difference between inlet flue gas and feed temperature, units ^oF

DT_1 = difference between critical temperature of flue gas and droplet, ^oF

DT_2 = difference between outlet flue gas and dry product temperature, ^oF

E = enhancement factor

EFFSD = SO_2 removal efficiency of the spray dryer (%)

G = mass velocity, g/sec

GPM = slurry feed rate (gal/min)

GY = mole of sulfur dioxide reacted per second

LIST OF SYMBOLS (continued)

H = Henry's constant, gmol/cm^{3}atm

I = ionic strength, g ion/l

K_1 = defined by equation (2-11)

K_2 = defined by equation (2-12)

K_{ga} = gas side mass transfer coefficient, gmol/cm^3 sec atm

K_L = liquid side mass transfer coefficient, cm/sec

K_d = thermal conductivity of the drops, cal/cm hr k

K_s = mass transfer coefficient for solid dissolution, cm/sec

L = reaction plane, cm

L_w = wetted periphery of centrifugal-disk atomizer, cm

m = molecular weight

M = droplet mass

N = rate of rotation of centrifugal-disk atomizer, rev/sec

N_A = rate of absorption of SO_2 in lime slurry solution, gmol/sec cm^2

N_{nu} = Nusselt number

N_{pr} = Prandtl number

N_{re} = Reynolds number

N_{sc} = Schmidt number

N_{sh} = Sherwood number

P = partial pressure of SO_2, atm

P_T = total pressure, atm

PBAR = atmospheric or barometric pressure, inches Hg

r = specific rate of reaction, gmol/cm^2 sec

LIST OF SYMBOLS (continued)

R = radius, cm

R_d = radius of centrifugal disk atomizer, cm

SCFM1C = inlet flue gas flow rate at standard temperature and pressure, ft^3/min

SLCONC = slurry concentration, lb $Ca(OH)_2$/gal

SO2ONC = inlet SO_2 concentration, ppm

SP1 = static pressure below atmospheric pressure for inlet flue gas, inches H_2O

SP2 = static pressure below atmospheric pressure for outlet flue gas, inches H_2O

SR = stoichiometric ratio

t = time, sec

T = temperature, ^oF

T1 = inlet temperature of the flue gas, ^oF

TEMP1C = inlet flue gas temperature, ^oF

TEMP2 = outlet flue gas temperature, ^oF

TSLURR = inlet slurry temperature, ^oF

TW2 = wet bulb temperature, ^oF

U = droplet velocity, cm/sec

V_p = volume of dispersion ratio to surface area of dispersion, cm^3/cm^2

W = moisture content, g H_2O/g solid

W_s = amount of solid, g solid/cm^3 slurry

W_2 = final moisture content, g H_2O/g solid

LIST OF SYMBOLS (continued)

X = droplet position, cm

Z = number of moles of SO_2

Greek Symbols

Δt = time step along the trajectory

ΔT = log mean temperature difference

ρ = density, g/cm^3

δ = film thickness, cm

λ = latent heat of vaporization, cal/g

μ = viscosity of liquid, poses

ϕ = surface tension of liquid, dynes/cm

ε = voidage in unreacted calcium hydroxide particles

Subscripts

A = SO_2

B = $Ca(OH)_2$

c = liquid core

cp = constant period

cr = critical point

d = dry

e = effective

fp = falling period

g = bulk gas

l = liquid

o = initial

Subscripts (continued)

p = particle

s = solid

w = wet

CHAPTER 1

INTRODUCTION

Early in the 1980's, The United States Environmental Protection Agency (EPA) restricted the emission of sulfur dioxide into the atmosphere. Even scrubbing of emissions from the burning of low sulfur coal is now being required (1). Sulfur dioxide is soluble in water and produces H_2SO_3 which is a strong, reactive acid, and a contributor to acid rain. Sulfur dioxide causes respiratory diseases, injures vegetation, and contributes to many other environmental problems (2,3). The most important source of SO_2 emission in many parts of the country is coal burning power plants. A typical coal fired power plant emits two million SCFM of flue gas containing 2000 PPM of SO_2 by volume. Even though wet scrubbing gives good removal efficiency, waste handling has always been a major problem (1). Spray drying is becoming one of the most attractive alternatives in the 80's. Even though spray dryers have been used by the food industry for a long time, only recently did their use in Flue Gas Disulfurization (FGD) receive attention. Spray drying for FGD can meet national standards concerning particulate emissions as well. By mid 1981 a total of 12 utilities and 11 industrial spray dryer systems had been sold in the United States for control of sulfur dioxide and particulate emissions.

Lime slurrys may be used for the removal of sulfur dioxide from gas streams. In a spray dryer the lime slurry is atomized with a

rotary atomizer into finely dispersed droplets having a high surface to mass ratio. The liquid flow is co-current with the flue gas. Because of the extensive surface area of the droplets, and thermal energy in the flue gas, droplet diameter decreases by evaporation of the water in the droplet. At the same time, sulfur dioxide is absorbed into the droplet where it reacts with calcium hydroxide. The drying process, which takes place near the wet-bulb temperature of the flue gas, primarily occurs in two periods, which are defined in terms of spray dryer operation (4):

1. the constant rate period and
2. the falling rate period.

Reaction between sulfur dioxide and calcium hydroxide is instantaneous and exothermic (18). The reaction can be shown as (5):

$$Ca(OH)_2 + 2\ SO_2 \longrightarrow Ca(HSO_3)_2 \qquad (1\text{-}1)$$

$$Ca(HSO_3)_2 + Ca(OH)_2 \longrightarrow 2\ CaSO_3 + 2\ H_2O \qquad (1\text{-}2)$$

The dry product that is generated in the spray dryer contains sulfur dioxide which has reacted with calcium hydroxide. This dry product exits at the bottom of the spray dryer.

In the following study, the physical behavior of the droplets as they are converted to dry products is considered. The mechanistically based model uses the Ramachandran and Sharma (6) equation to predict the rate of the absorption of sulfur dioxide

into the calcium hydroxide solution for the first period or constant rate period and for the second period or falling rate period.

To find the sulfur dioxide removal efficiency of the system, the following quantities are considered: contact times for both periods; diameter of the dry product; heat and mass transfer; and chemical reaction.

CHAPTER 2

LITERATURE REVIEW

Even though extensive work has been done to improve the understanding of the fundamental physical phenomena which takes place in spray dryers, literature describing FGD by spray dryers is limited.

Midkiff (1) described the advantages of spray drying and the problems that one will face if wet scrubbing is used. He explained that the liquid to gas ratio is lower because of the nature of the spray drying operation, and the needed water and pumping losses are reduced. The dry product from the spray dryer FGD eliminates sludge-handling problems. In his paper, the multi atomizer concept, which is being tested by Rockwell International, is mentioned. This concept is reported to be more reliable than a single atomizer according to the manufacturer.

Topar (7) predicted that the spray drying process can better be described by knowing the real size distribution of the droplets rather than using the Sauter mean diameter. He mentioned that the droplet size has an effect on the droplet motion and transfer coefficients. Also flue gas near the atomizer might become saturated due to the fast evaporation of small droplets, so larger droplets might even absorb more moisture at first. By using the droplet size distribution, drying of the droplet takes place over a much longer time than using the Sauter mean diameter.

In his book, Mujumdar (8) described drying technology based on the papers presented at the first international symposium on drying held at McGill University in August 1978. Crowe, et al. in this book described mass, momentum, and energy calculation for dispersed phase flows. This approach, called Particle Source In cell (PSI-cell) model, is a complete analysis of gas-droplet flow; this method is also very complicated. He mentioned that local conditions of the drying gases, as well as the properties of the droplet, affect the mass, momentum and energy transfer between the drying gas and the droplet. So unlike most of the others, he took into consideration the effect of the drying medium on the evaporating droplets, and he called his model axisymmetric two-way coupling. Most of the other modelings involve one-way coupling, where properties such as density, velocity, and temperature are assumed uniform across each section (8). The mass transfer rate from the droplet to the bulk gas phase is given as:

$$\frac{dM}{dt} = N_{sh}\ 3.14\ m\ D\ d\ \frac{(P-P_s)}{RT} \qquad (2\text{-}1)$$

where:

M = droplet mass.

Droplet size history at any given time is calculated from:

$$d = d_o \frac{d(d)}{d(t)} \Delta t \qquad (2\text{-}2)$$

and a droplet position at time Δt is given as:

$$X = X_o + (U+U_o) \frac{\Delta t}{2} \qquad (2-3)$$

the droplet properties are obtained using the Lagrangian approach.

Frazier and Hellier (9) also determined the vaporization rate of water droplets in high temperature air streams. They also considered vaporization of Freon 113 droplets in a 669°C temperature air stream. They cautioned that the obtained value of the mass transfer coefficient (K_g) is about four times greater than the one obtained by Ranz and Marshall. They concluded that the high temperature of the flue gas as well as the droplet oscillation rather than the low temperature that was used by Ranz and Marshall caused this deviation.

Lijn (10) also described the heat and mass transfer in spray dryers assuming a plug flow through the dryer for a perfectly co-current operation. He used a system called cellular model to find the concentration in the vapour and evaporation rate. Heat and mass transfer coefficients may almost be doubled because of the internal circulation. Oscillation inside droplets can increase the outside transfer coefficient, but it only occurs at high Reynolds numbers. He mentioned that because of the variable diffusion coefficient, and decrease of the droplet diameter, none of the models available give an accurate result. He mostly emphasized the use of this model for agricultural product operation.

Guavin, et al. (11) published two papers: one describing the spray drying process and the other describing the design of a spray dryer. They gave the following equation for Sauter mean diameter calculation for droplets coming out of the centrifugal disk atomizer:

$$\frac{d_{vs}}{R_d} = 0.4 \left(\frac{G}{\rho N R_d^2}\right)^{0.6} \left(\frac{\mu}{G}\right)^{0.2} \left(\frac{\phi \rho L_w}{G^2}\right) \tag{2-4}$$

the largest droplet size is:

$$d_{max} = 3d_{vs} \tag{2-5}$$

Heat and mass transfer rates are similar to those of Crowe, et al. The spray drying region is divided into the nozzle zone and the free-entrainment zone. Heat, mass, and momentum transfer rates were calculated for both zones. Their method is quasi-one dimensional and involves two-way coupling, as described by Crowe. They assumed the droplets did not effect the velocity field, and momentum coupling was neglected.

Uchida and McMichael (12) described the dissolution rate for limestone into acid solutions. They showed that the solution PH or hydronium ion concentration has an effect on the rate of dissolution, and reaction products do not greatly affect the dissolution reaction. Also particle size does not affect the dissolution rate. For reaction of:

$$2CaCo_3 + 2H^+ \longleftrightarrow Ca(HCo_3)_2 + Ca^{++} \tag{2-6}$$

dissolution rate is given as:

$$R = E\ K_s\ C_{CaCo_3} \tag{2-7}$$

$$E = 1 + \frac{C_{H^+}}{C_{CaCo_3}} \tag{2-8}$$

In this study, gas was absorbed into a slurry containing solid calcium hydroxide and this absorbed gas enhanced the dissolution rate.

Change, et al. (13) described a changing grain size model for gas-solid reaction, and measured the absorption of SO_2 from flue gas by finely powdered limestone. They mentioned that the reaction product $CaSO_3$ has a much larger molar volume than the reactant CaO (almost three times). Georgakis, et al. (14) and Bhatia (15) also concluded the same thing concerning the effect of the pore structure on fluid-solid reaction and its application to a sulfur dioxide-lime reaction. Their conclusion was that reactivity increases with surface area, but rapidly plugging smaller pores at the particle surface reduces the ultimate conversion.

Davis and Reed (16,17) presented two reports concerning the experimental tests which have been done on a 1000 ACFM spray dryer/fabric filter FGD system. Sulfur dioxide from a coal burning boiler flue gas was removed by calcium hydroxide droplets injected into the spray dryer by a centrifugal atomizer. This atomizer generated droplets in the sizes ranging from 70 to 80 μm (with the atomizer disk speed of 17000 RPM). Removal efficiency was measured while changing different parameters such as stoichiometric ratio

(SR, mole of available calcium hydroxide with respect to sulfur dioxide), temperature of the flue gas, temperature approach to saturation (difference between dry bulb and wet bulb temperatures), and droplet size. The main conclusion about the performance of the system was that by increasing the stoichiometric ratio, the efficiency of the system in terms of sulfur dioxide removal will improve. Also, an increase in the approach to saturation temperature of the flue gas can increase efficiency considerably. Recycling generated dry products back to the lime slurry also increases efficiency. There also seems to be an improved performance at lower sulfur dioxide concentration in the flue gas.

Gelter and Shelton (18) qualitatively described the changes that occur to the lime slurry droplet during the absorption of sulfur dioxide from laboratory dry scrubbing experiments. They contacted the flue gas containing 1000 ppm SO_2 with lime slurry droplets (50-80 μm) using a rotary atomizer, a stoichiometric ratio of 1.3 (or 11% total solid), and inlet flue gas temperatures varied from 325 to 375^{o}F. Evaporation of water and reaction between SO_2 and $Ca(OH)_2$ occur in two periods. During first period the droplet velocity decreases to one tenth of the original velocity in less than 0.1 second, and 75% of the droplet moisture evaporates because of the high temperature flue gas. Lime slurry droplets contain insoluble particles that are in constant motion and initially separated from each other by several particle diameters. The reaction between sulfur dioxide and calcium hydroxide occurs in the

liquid phase. In the second period, Gelter and Shelton point out that the moisture left in the droplet, is more difficult to remove, and diffusion is the limiting factor. As the drying proceeds, the droplet diameter decreases due to the evaporation of the moisture and undissolved particle surfaces touch one another. They also concluded that more reaction occurs at the surface of the particle; a gas-solid surface reaction was suggested. To verify it, calcium and sulfur analysis across the diameter of a dried particle was performed that showed sulfur concentration is at a maximum at the surface and the core is almost unreacted at the center. They also noted if proper lime slaking for a high surface area is done, quicklime is formed; there will then be more active surface areas available for reaction with sulfur dioxide.

Downs, et al. (19) however, concluded that the predominate reaction is aqueous ionic reaction. Tests had been performed on a pilot plant and scanning electron microscopy of the dry product has shown many free-standing ionic crystals of $CaSO_3.1/2H_2O$ and $CaSO_4.2H_2O$. They rejected the gas-solid reactions as Gelter, et al. concluded.

Uchida and Tsuchlya (20) described the removal of HCl in flue gas by spray drying. They presented a mathematical model for mass and heat transfer between the droplet and the flue gas. The liquid droplet in this case consists of three phases; two solid phases, one made of unreacted $Ca(OH)_2$, and the other $CaCl_2$, and one liquid phase containing the soluble $CaCl_2$, the reaction product. Here

again, two reaction periods (constant rate and falling rate periods) are considered. In the first period the rate of absorption is given by:

$$N_A = \frac{P_A}{\frac{1}{K_{ga}} + \frac{1}{HK_L}} \qquad (2\text{-}9)$$

and in period two:

$$N_A = \frac{R_c D_e C_{Ag}}{(R-R_c) R} \qquad (2\text{-}10)$$

The gas-liquid reaction mostly takes place during first period, and the gas-solid reaction in the second period. They also assumed that axial dispersion was not important in their co-current operation. They mentioned it is caused by higher flue gas density at the lower part of the chamber and density difference along the tower in co-current operation. Velocity of the flue gas is not limited in co-current flow, co-current flow was preferred over counter-current flow. The critical moisture content (moisture content of the droplet at the end of the constant rate period, where the moisture content is insufficient to maintain saturated condition) is given as:

$$W_{cr} = \frac{\rho_l \varepsilon}{\rho_s (1-\varepsilon)} \qquad (2\text{-}11)$$

where:

W_{cr} = critical moisture content.

ε = Voidage in unreacted calcium hydroxide particles (0.48).

Ranz and Marshall (21), studied the rate of evaporation of pure liquid drops and water drops containing dissolved or suspended solids (600 to 1100 μm in diameter). For the constant rate period the evaporation rate for both pure drops and drops containing insoluble materials were the same. Heat was transferred by conduction and convection from hot flue gas to the droplet for evaporation of the moisture; evaporated moisture was transferred by diffusion and convection into the flue gas. Temperature, humidity, and transport properties of the gas, as well as diameter, temperature, and relative velocity of the drops were important in the rate of the transfer. For mass transfer coefficients from a spherical droplet an empirical equation was used in dimensionless form which had been used previously by Froessling (26):

$$N_{sh} = 2.0 + K_1 (N_{sc})^{1/3} (N_{re})^{1/2} \qquad (2\text{-}12)$$

and for heat transfer:

$$N_{nu} = 2.0 + K_2 (N_{pr})^{1/2} (N_{re})^{1/2} \qquad (2\text{-}13)$$

They also proposed two equations to estimate the time of constant and falling rate period, even though the falling rate period calculation might not be reliable (4).

Marshall (22), and Master (4) have done extensive work on atomization, heat, and mass transfer of pure liquid droplets in spray dryers. Master has done a superb job in describing all the

processes that the droplets go through in spray drying, and presents lots of information which can be used to predict the outcome of these processes. Master explained that the residence time of most of the dried product in the spray dryer is higher than that of the flue gas, because of the recirculating air flow regions in the dryer, and air in some part of the dryer has lower velocity than the average velocity. The initial velocity of the droplet is much higher than the flow gas, but it decreases very rapidly because of the drag forces. Master also mentioned that heat and mass transfer rates are dependent upon the temperature, humidity and transport properties of the flue gas surrounding droplet, and droplet diameter and relative velocity with respect to flue gas. The drying driving force is between the vapour pressure of water at the surface of the droplet and the partial pressure of water vapour in the flue gas. If the droplet contains dissolved solids it evaporates at a lower rate than pure liquid droplet of equal size, because dissolved solids lower the vapour pressure of the liquid. If the relative velocity between the droplet and flue gas is zero, the evaporation is the same as in a still-air condition. In his book different equations are given to predict the droplet diameter from different kind of atomizers, including rotary atomizers. Also many equations for prediction of droplet velocity are given.

The Tennessee Valley Authority (TVA) had sponsored pilot plant testing for scrubbing sulfur dioxide from a coal burning boiler (17); experimental data from these tests have been used in this

work. Pearson (23) used a semi-theoretical approach and developed and tested a mathematical model of a spray dryer removal efficiency for FGD. He expanded the two film models described by Danckwerts (24) to include ash and dissolution resistances for both constant rate and falling rate period. To calculate the ash film resistance he used a tortuosity factor, and found the effective diffusivity of the absorbing gas. He determined the tortuosity factor by comparing the theoretical with experimental efficiency data. The calculated results sometimes are hard to accept. To describe sulfur dioxide absorption in the constant rate period he used case one of Ramachandran and Sharma, where solid dissolution in the liquid film is not important. He assumed this case is valid because one of the conditions given by them is being satisfied; the equation is given as:

$$r = \frac{HP_g + \frac{D_B}{D_A} B_s}{\frac{H}{K_{ga}} + \frac{1}{K_L} + \frac{D_B}{D_A} \frac{1}{K_s A_p}} \qquad (2\text{-}14)$$

and the condition is:

$$\frac{K_s A_p D_A^2}{4 K_L^2 D_3} \ll 1 \qquad (2\text{-}15)$$

where

K_s = mass transfer coefficient for solid dissolution, cm/sec

A_p = surface area of solid particles, cm^2/cm^3 dispersion

K_L = true liquid side mass transfer coefficient in the absence of chemical reaction, cm/sec

D_A, D_B = diffusivities of species A and B in liquid phase respectively, cm^2/sec

For this condition to be valid, however, the average diameter of the lime particles must be greater than liquid film thickness by factor of five. The last condition is not satisfied. Because if the average diameter of the lime particles is considerably less than the thickness of the liquid film, case two where the solid dissolution in the liquid film is important should have been used. At the beginning of the falling rate period he assumed the partially dried droplet breaks up into smaller drops and an ash layer begins to form which provides the major resistance to the absorption of sulfur dioxide during this period. The reason for assuming the breakup of the droplets was the experimentally measured mass mean diameters for the dry products (by Coulter Counter) averaging 7.8 μm (17), and the conclusion that evaporation alone could not reduce the droplet size at 70-80 μm to the observed mean diameter dry product.

CHAPTER 3

DESCRIPTION OF SPRAY DRYER OPERATION

Spray drying process for flue gas disulfurization by lime slurry consists of five steps:

1. preparation of lime slurry by slaking lime with water;
2. atomization of lime slurry by centrifugal atomizer;
3. drying of the lime slurry droplets;
4. absorption and reaction of SO_2 with $Ca(OH)_2$;
5. separation and collection of dry product from the flue gas.

Preparation of Lime Slurry

In the studies by Davis and Reed (16,17), the lime slurry is prepared as a concentrated solution in a slaking tank. The reaction between lime and water is extremely exothermic and explosive. By adding lime to stirred hot water (140°F), the temperature of the solution reaches about 212°F (20 lb. lime to 50 gal. water), in approximately thirty seconds. Lime reacts with water as the following equation:

$$CaO + H_2O \longrightarrow Ca(OH)_2 \qquad (3\text{-}1)$$

Then the needed lime slurry concentration is prepared by adding water to the solution; the solution is then stirred before it is fed to the atomizer.

Atomization

Droplet generation by means of atomization is very important in spray drying. There are four important types of atomizers that are being used today, pressure nozzles, pneumatic nozzles, sonic nozzles, and centrifugal disk atomizers. For experimental data used in this work, the lime slurry was atomized with a high speed centrifugal atomizer and discharged co-currently into a hot gas inside a seven foot diameter spray drying chamber with total volume of 224 cubic foot (CF) as shown in Figure 1. The atomizer contains six nozzles which rotate at about 17000 RPM producing droplets ranging from about 70 to 80 μm depending upon the concentration of the lime slurry. A good reason for using the centrifugal atomizer is that droplet diameters do not change considerably due to the solution flow rate; as long as the atomizer speed is constant the droplet diameters are constant. Droplet diameters can be changed by changing the rotary atomizer speed.

The lime slurry is finely dispersed as droplets with high surface area to mass ratio to facilitate heat and mass transfer. Rapid evaporation occurs due to the extensive surface area of the droplet and high temperature of the inlet flue gas; simultaneously, sulfur dioxide is absorbed into the drop and reacts with calcium hydroxide. Larger dry products settle at the bottom of the chamber; flue gas with low sulfur dioxide concentration and smaller products exit from the chamber. The next stage of separation and collection

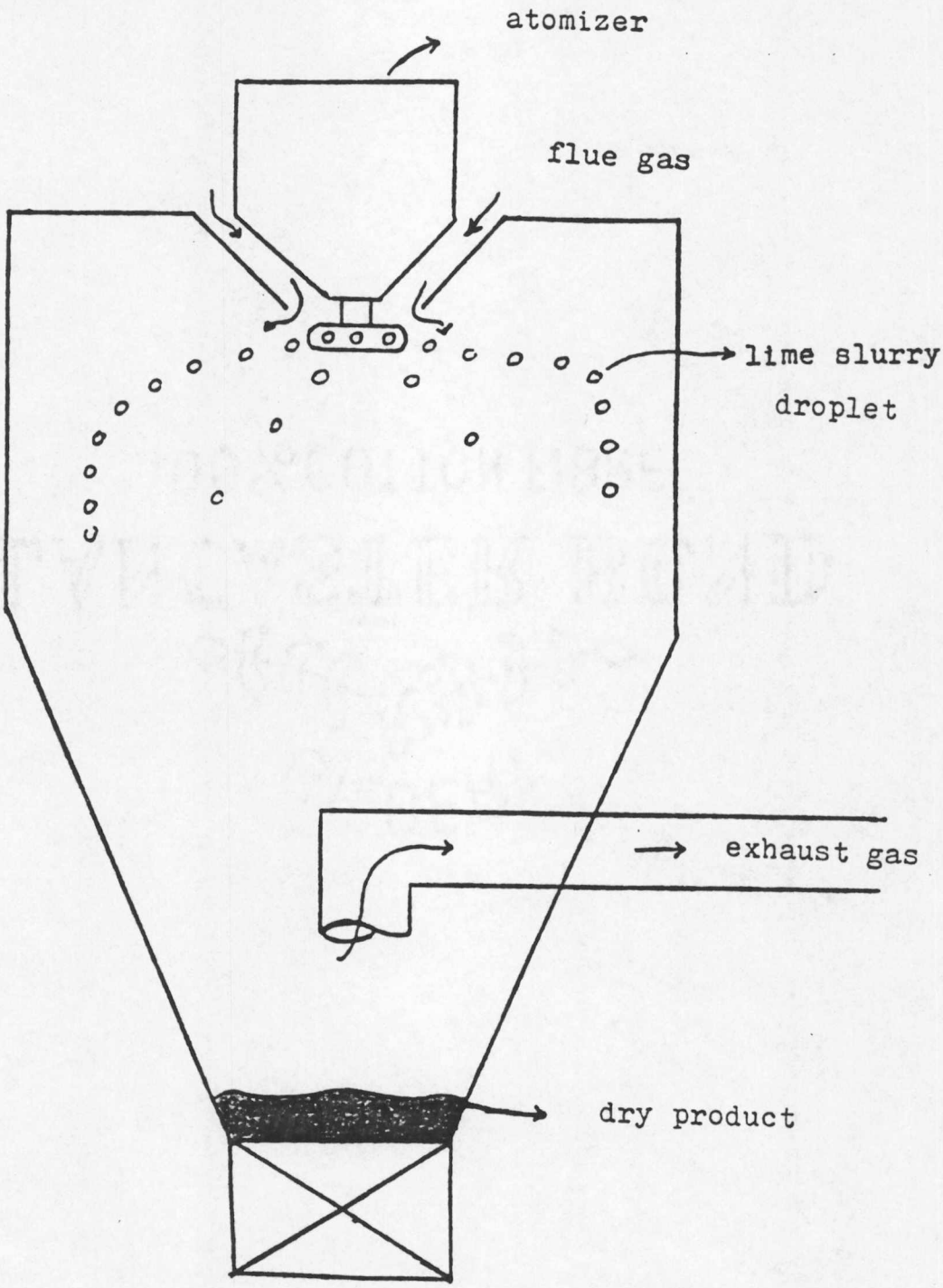


Figure 1. Spray Dryer Schematic.

is a bag house filter which removes the remainder of the dry product.

Sulfur dioxide concentration before entering and after leaving the spray dryer were monitored by two Lear Siegler SM800 analyzers. Different parameters such as inlet-outlet temperature of the flue gas, slurry feed rate, concentration of the lime slurry, pressure drop across the spray dryer, wet bulb temperature of the flue gas, and drop diameters as determined by mean of atomizer speed and slurry concentration, etc. were measured.

Drying of Droplets

Heat is transferred from the flue gas to the droplets by convection, and largely converted to latent heat during evaporation of the moisture from the slurry droplets into the gas. Temperature decreases in the flue gas, and increases in the evaporating drop as shown in Figure 2.

The diameter of the dispersed droplets from atomizer is assumed to decrease by evaporation in two important stages. In the first period there is sufficient moisture within the droplet, so that the droplet maintains a saturated surface condition. Most of the moisture is removed from the slurry droplet during this initial or constant rate period; this period is so named because the evaporation rate is assumed constant. Solubility of calcium hydroxide in water is very low (11), so there are insoluble solid particles in the solution. Drops evaporate in the initial period as though they are pure water (25); there appears to be negligible

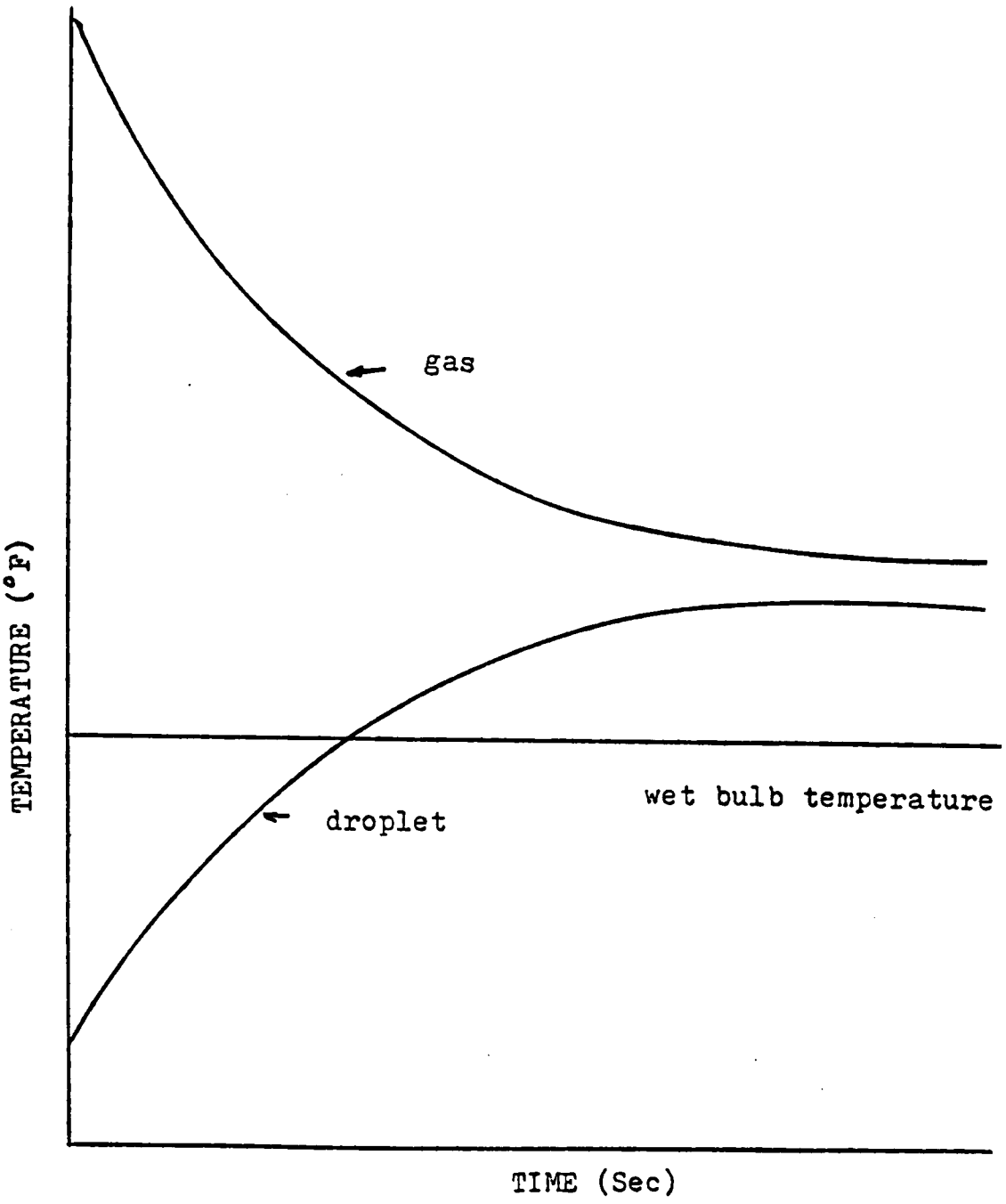


Figure 2. Temperature of a Droplet and Its Surrounding Gas.

vapour pressure lowering effect in the drop due to the presence of these solids.

As the water concentration in the droplet continues to fall, the so-called critical moisture content is reached; at this point the evaporation rate starts to decrease. This stage marked by a decreasing evaporation rate is called the falling rate period; the moisture content is insufficient to maintain saturated condition at the droplet surface. During this period solid structure begins to form, and the diameter of the drop stays approximately constant. A check of the product size of dry product samples produced in the same apparatus and similar conditions as used by Davis, et al. and was performed using electron microscopic photography, the dry product particles were determined to be much larger than 7.8 μm; no breakup seems to occur during the falling rate period as concluded by Pearson. The drying process is assumed to be nearly complete at the end of the falling rate period with the gas and droplet near equilibrium. The next pseudo equilibrium period is called the diffusional period. This period is not very important in terms of drying and absorption of sulfur dioxide. The evaporation rate of water during a droplet residence time in a spray dryer is shown in Figure 3.

Absorption and Reaction

As the slurry droplets are dispersed into the hot flue gas, drying of the droplets starts, sulfur dioxide in the flue gas dissolves into the water phase and reacts with calcium hydroxide.

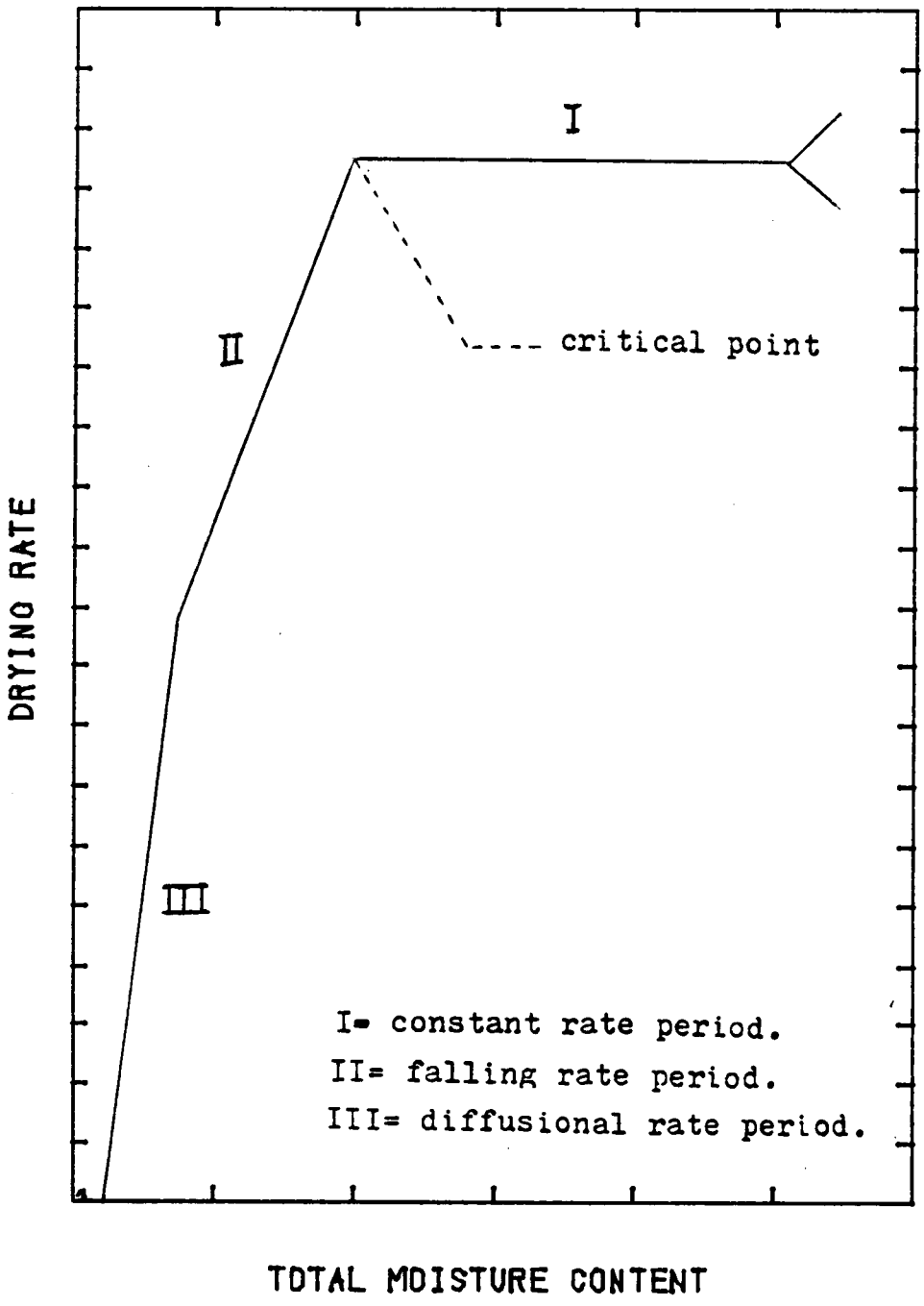


Figure 3. Drying Rate vs. Total Moisture Content of a Drop.

There are many ways to represent this reaction. One is given by Babu, et al. (5):

$$2\ SO_2 + Ca(OH)_2 \longleftrightarrow Ca(HSO_3)_2 \qquad (3\text{-}2)$$

$$Ca(HSO_3)_2 + Ca(OH)_2 \longleftrightarrow 2\ CaSO_3 + 2\ H_2O \qquad (3\text{-}3)$$

Or the one which is given by Wark (32).

$$CaO + H_2O \longleftrightarrow Ca(OH)_2 \qquad (3\text{-}4)$$

$$Ca(OH)_2 + CO_2 \longleftrightarrow CaCO_3 + H_2O \qquad (3\text{-}5)$$

$$CaCO_3 + SO_2 + H_2O \longleftrightarrow CaSO_3 \cdot 2H_2O + 2\ CO_2 \qquad (3\text{-}6)$$

$$CaSO_3 \cdot 2H_2O + 1/2\ O_2 \longleftrightarrow CaSO_4 \cdot 2H_2O \qquad (3\text{-}7)$$

Even though a study has not been conducted on the reaction of CO_2 with lime slurry, it seems from the above reactions the so-called competitive reaction between SO_2 and CO_2 with calcium hydroxide result in favor of the SO_2; the product from this reaction is $CaSO_4.2H_2O$ which is a crystal. It should be mentioned that an aqueous solution of SO_2 is stronger Lewis acid than an aqueous solution of CO_2. Also the solubility of SO_2 is much larger than that of CO_2 in water and aqueous solution.

The drying and reaction sequence of a slurry droplet is shown schematically in Figure 4. Electron Microscopic pictures of the products (Figures 5, 6, 7) show that the diameter of the droplets are 30-40 μm.

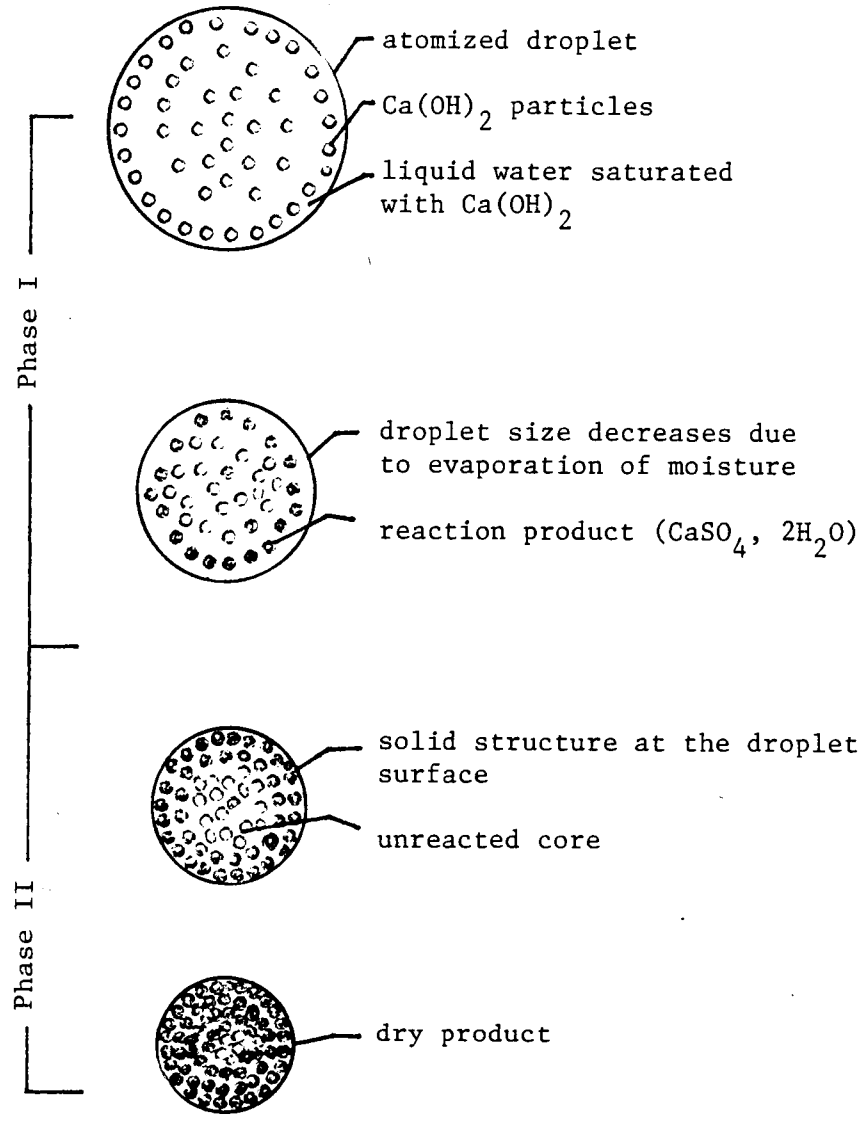


Figure 4. Dry Scrubbing by Atomized Droplet Model.

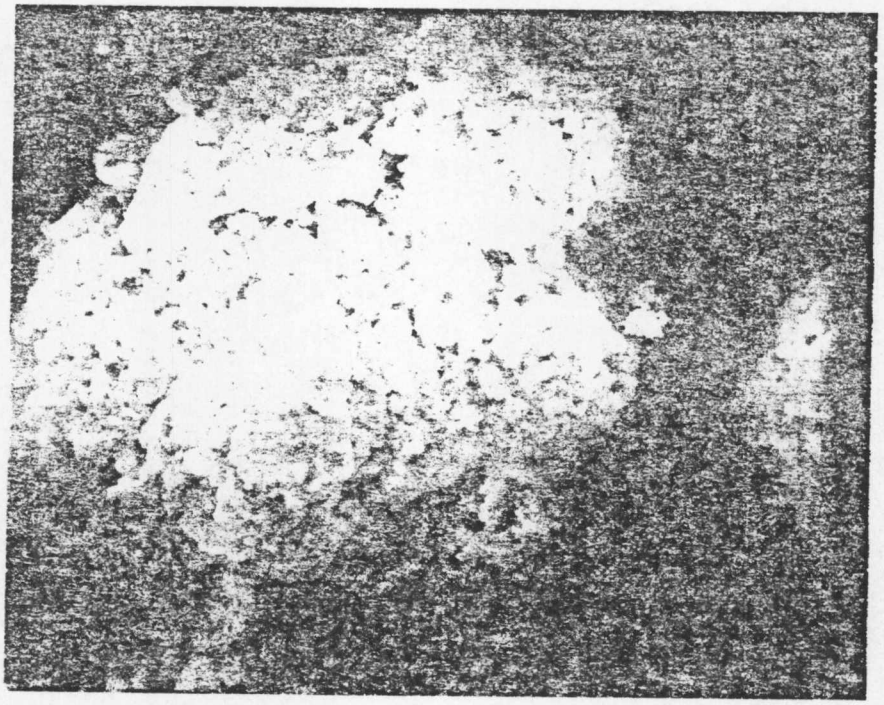


Figure 5. Electron Microscopic Picture of a Porous Dry Product (——— = 10μ).

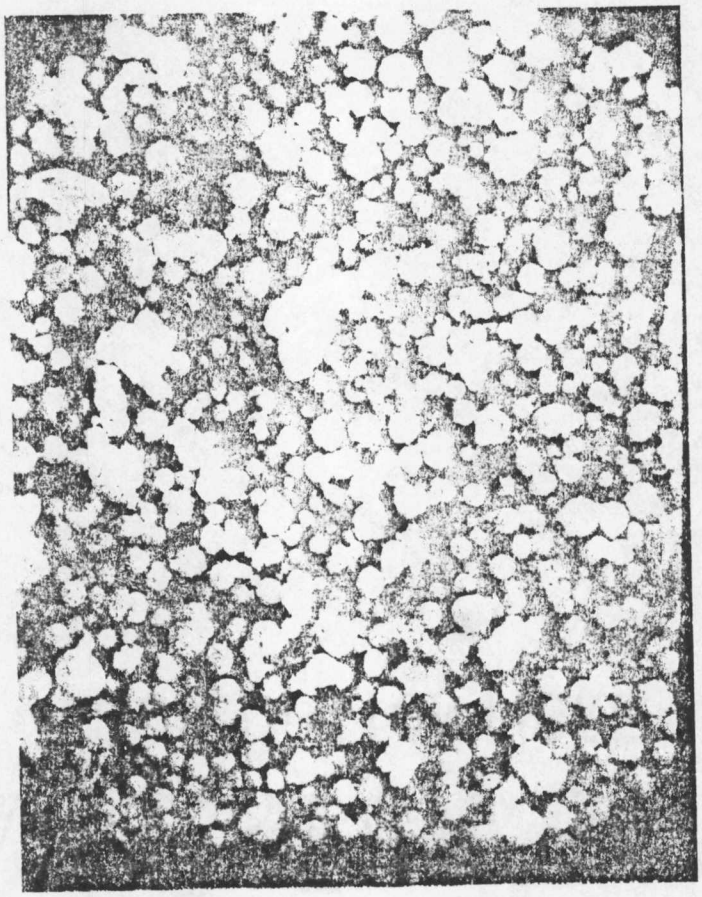


Figure 6. Electron Microscopic Picture of Dry Products (- = 14.7μ).

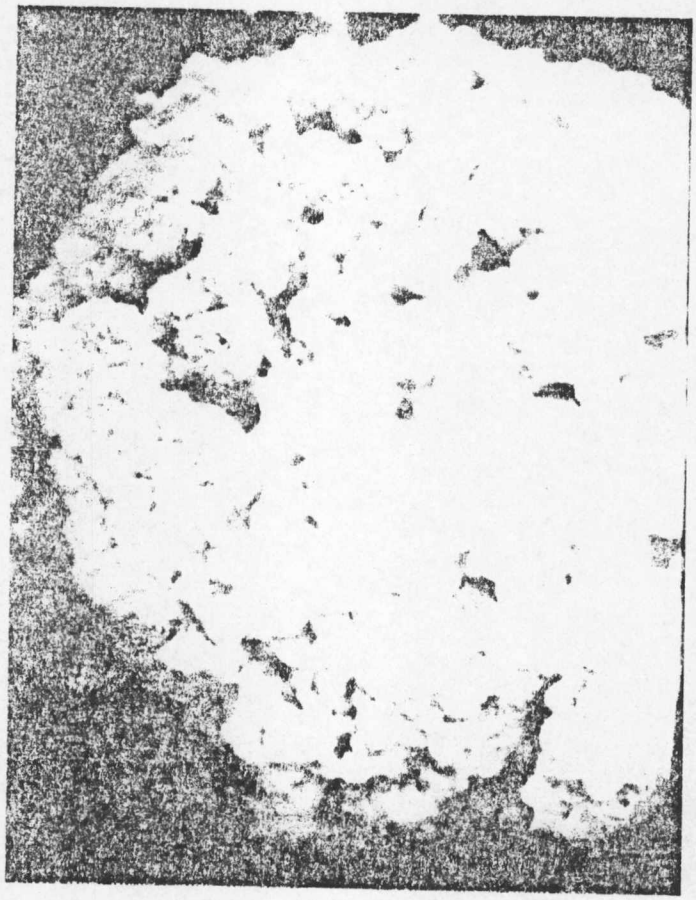


Figure 7. Electron Microscopic Picture of a Dry Product (——— = 3.1μ).

As mentioned before Uchida, et al. (20) concluded that there is no back-mixing in co-current flow, but as Pinilla, et al. (27) mentioned even though plug flow is assumed in spray columns (including spray dryer) axial dispersion should be taken into consideration for commercial equipment.

CHAPTER 4

MATHEMATICAL MODEL DEVELOPMENT

In the Sulfur dioxide removal model, constant and falling rate periods are assumed to describe the evaporation of water from a drop. Constant rate and falling rate periods both were found from the following equations; even though the falling rate period which is given by Ranz and Marshall cannot be very reliable (4).

$$t_{cp} = \frac{\lambda \rho_d (D_o^2 - D_{cr}^2)}{8\ K_d\ \Delta T_{cr}} \tag{4-1}$$

$$t_{fp} = \frac{\lambda D_{cr}^2 \rho (W_{cr} - W_2)}{12\ K_d\ \Delta T_{fp}} \tag{4-2}$$

To calculate the critical droplet diameter where the constant rate period ends and falling rate period starts, the following equations can be used (4):

$$\frac{D_d}{D_w} = \left[\frac{\rho_w}{\rho_d} \frac{1+W_{cp}}{1+W_{fp}} \right]^{1/3} \tag{4-3}$$

$$D_{cr} = \frac{D_d}{D_w} D_w \tag{4-4}$$

As in the case with drying, the primary absorption and reaction of SO_2 occurs in two periods, constant and falling rate. A model of the reaction of sulfur dioxide into the lime slurry is given by Ramachandran and Sharma (6), and is modified by Uchida, et al.

(26). The reaction occurs between sparingly soluble lime which produces OH^- ions and dissolved sulfur dioxide. Equations of the reaction in a general case are given as:

$$A(q) \longleftrightarrow A\ (aq)$$

$$B(s) \longleftrightarrow B\ (aq)$$

$$A(aq) + zB(aq) \longrightarrow \text{Product}$$

Case two of Ramachandran and Sharma has been considered, where solid dissolution in the liquid film is important. It is because of the diameter of the particle is much less than the thickness of the liquid film. The liquid film thickness can be found from the following equation (6):

$$\delta = \frac{D_A}{K_L} \tag{4-5}$$

where liquid side mass transfer coefficient (K_L) was estimated by Pearson (23). It should be mentioned that the reaction between sulfur dioxide and calcium hydroxide is instantaneous, and there is no gas side resistance to mass transfer (5,6,26, also Appendix A). Ramachandran and Sharma rate of absorption can be used for SO_2, absorption into the lime slurry for constant rate period. The equations are:

$$r = \frac{D_A A^*}{L} + \frac{K_s A_p B_s L}{2} \tag{4-6}$$

and

$$r = B_s \sqrt{D_B K_s A_p} \quad \coth \sqrt{\frac{K_s A_p}{D_B}} (\delta - L) + K_s A_p B_s L \tag{4-7}$$

$$A_p = \frac{6W_s}{\rho D_p} \tag{4-8}$$

The method of trial and error should be used for calculation of the rate of absorption. Rate of absorption is dependent upon the particle size, and surface area of the particles, as can be seen from the equations 4-6 and 4-7. Uchida, et al. modified the above equations as:

$$r = mD_A A^* \coth mL + \frac{mD_B B_s}{Z} \left(\coth mL - \frac{1}{\sinh mL}\right) \tag{4-9}$$

and

$$r = \frac{mD_B B_s}{Z} \coth m(\delta - L) + m\left(D_A A^* + \frac{2D_B B_s}{Z}\right) \left(\coth mL - \frac{1}{\sinh mL}\right) \tag{4-10}$$

where:

$$m = \sqrt{\frac{K_s A_p}{D_B}} \tag{4-11}$$

The reaction plane (L) calculation is also by trial and error, and can be found from:

$$\frac{D_B B_s}{Z} \left(\coth mL + \coth m(\delta - L) - \frac{1}{\sinh mL}\right) - \frac{D_A A^*}{\sinh mL} = 0 \tag{4-12}$$

The solubility of sulfur dioxide in slurry droplet is calculated using Henry's law constant for sulfur dioxide in pure water and then correcting it for the calcium hydroxide solution (24 and Appendix A).

The constant rate period extends until most of the water inside the droplet is evaporated (about 80%), at this point the so-called

critical point is reached and the particles are fixed in place. In the falling rate period the diffusion resistance through the pores increases as the reaction proceeds. Here a series of resistances exist, such as gas, liquid and ash, etc. If the dryed product or ash film resistance is the controlling steps for absorption of SO_2, the rate expression using the unreacted-core shrinking model is given as:

$$r_A = \frac{R_c D_e C_{Ag}}{R_p(R_p - R_c)RT} \tag{4-13}$$

and it can be used if the following condition is met:

$$\frac{P_A}{\frac{R_p(R_p - R_c)RT}{R_c D_e}} < \frac{D_A A^*}{L} + \frac{K_s A_p B_s L}{2} \tag{4-14}$$

and gas-phase resistance is negligible the Ramachandran and Sharma model is the same as for constant rate period is used; the SO_2, absorption flux is calculated at average condition of each period. Mole of sulfur dioxide absorbed per second is calculated as:

$$GY_{cp,fp} = r_A \cdot t \cdot \text{Area of a drop} \cdot \text{drop/sec} \tag{4-15}$$

CHAPTER 5

FORTRAN PROGRAM DESCRIPTION

Most of the variables used in the program are defined at the beginning of the main program. After inputing the required data which were given by Davis and Reed (16,17, also Table 1) into the model, the predicted efficiencies of the spray dryer are calculated by using the described program.

Operating pressure and stoichiometric ratios between SO_2 and $Ca(OH)_2$ are calculated. To find the operating pressure, static pressures before and after the spray drying chamber were measured. Molar inputs of calcium hydroxide and sulfur dioxide were used in stoichiometric ratios calculation. An enthalpy balance over a spray dryer is performed to estimate the critical temperature of the flue gas. The general equation is:

Heat input - Heat outlet - Heat lost +/- Reaction

Heat = 0 (5-1)

where:

Heat input = Enthalpy of liquid droplets and air entering chamber.

Heat outlet = Enthalpy of dried product and exhaust flue gas.

Heat lost = Heat lost from the spray dryer wall.

Reaction Heat = Heat generated due to the exothermic reaction between SO_2 and $Ca(OH)_2$.

Table 1. Experimental Input Data.

RUN	CAG	SO2ONC	TEMP1C	SLCONC	SCFM1C	GPM	PBAR	SP1	SP2	TSLURR	TEMP2	TW2	d	EFFSD	GW2
1	0.0019	1949	271	1.100	721	0.300	29.36	4.0	6.0	70	144	119.0	8.65E-05	65.6	0.110
2	0.0017	1723	270	0.755	744	0.140	30.00	4.0	8.5	70	150	114.0	7.16E-05	44.9	0.087
3	0.0018	1831	284	0.755	731	0.240	30.00	4.0	8.5	70	135	114.0	8.15E-05	73.5	0.092
4	0.0019	1923	273	0.750	711	0.260	29.35	6.0	7.8	70	144	119.0	8.46E-05	62.3	0.110
5	0.0020	1958	277	1.120	740	0.294	29.78	4.0	6.0	70	137	115.0	8.62E-05	74.2	0.095
6	0.0022	2184	275	1.126	735	0.250	29.78	4.0	6.0	70	147	115.0	8.27E-05	53.9	0.092
7	0.0019	1948	271	0.364	739	0.312	29.30	4.2	6.8	70	135	114.5	8.62E-05	54.2	0.094
8	0.0020	2012	272	0.377	739	0.274	29.30	4.0	6.2	70	140	115.0	8.35E-05	21.7	0.096
9	0.0018	1864	273	0.377	735	0.225	29.30	4.0	6.2	70	150	115.0	7.97E-05	29.4	0.092
10	0.0020	2014	253	1.330	732	0.300	29.80	6.0	7.9	70	133	113.0	8.67E-05	73.1	0.091
11	0.0019	1903	255	1.340	729	0.290	29.80	6.0	7.9	70	140	113.0	8.78E-05	67.2	0.088
12	0.0020	2040	255	0.868	745	0.237	29.30	4.0	6.0	70	135	115.0	8.14E-05	63.2	0.097
13	0.0019	1943	254	0.420	757	0.228	29.30	4.0	6.1	70	138	113.0	7.95E-05	39.5	0.090
14	0.0021	2058	257	0.416	745	0.222	29.30	4.0	6.0	70	134	114.0	7.95E-05	37.9	0.095
15	0.0020	1967	256	0.862	745	0.220	29.30	4.0	6.1	70	140	113.0	8.00E-05	68.3	0.089
16	0.0020	2041	255	0.405	744	0.138	29.29	3.8	6.0	70	149	114.0	7.63E-05	17.5	0.095
17	0.0019	1916	261	1.340	744	0.173	29.29	4.0	6.8	70	151	116.0	7.61E-05	57.0	0.095
18	0.0018	1843	260	0.853	744	0.150	29.29	3.9	6.8	70	151	116.0	7.30E-05	32.2	0.095
19	0.0020	1961	296	1.110	727	0.338	29.33	4.8	7.2	70	140	115.0	8.91E-05	69.6	0.096
20	0.0021	2118	296	0.318	729	0.233	29.29	4.8	7.4	70	135	116.0	8.03E-05	29.3	0.100
21	0.0020	2001	293	0.585	732	0.224	29.29	4.2	6.2	70	140	115.0	7.99E-05	54.6	0.096
22	0.0020	1967	287	0.585	735	0.292	29.29	4.2	6.1	70	135	115.0	8.52E-05	54.8	0.097
23	0.0021	2087	299	0.585	726	0.213	29.29	4.9	7.2	70	150	115.0	8.00E-05	42.8	0.092
24	0.0020	2012	293	0.318	736	0.207	29.29	4.9	7.2	70	140	116.0	7.80E-05	32.7	0.099
25	0.0021	2052	297	0.318	733	0.198	29.33	4.8	7.2	70	150	115.0	7.72E-05	28.7	0.093

Since at the start of the program, the amount of $Ca(OH)_2$ reacted with SO_2 is not known, it is assumed that one third of the SO_2 reacted with $Ca(OH)_2$, then the computer calculates the SO_2 removal efficiency. Further iterations are necessary to recalculate the amount of reacted SO_2. But since heat of reaction does not have much effect on the whole process this iteration is not necessary. The times for constant and falling rate periods are calculated using equations 4-1 and 4-2 (page 29) as given by Master (4) for the case of evaporation of droplets containing insoluble solids. It should be mentioned that the average gas temperature after leaving the spray dryer chamber and the wet bulb temperature (liquid droplet surface temperature) were used in the calculation of the thermal conductivity of the drops. To calculate the log mean temperature for constant and falling rate periods, the following equations are used:

$$\Delta T_{cp} = \frac{DT_o - DT_1}{LN(\frac{DT_o}{DT_1})} \qquad (5\text{-}2)$$

$$\Delta T_{fp} = \frac{DT_1 - DT_2}{LN(\frac{DT_1}{DT_2})} \qquad (5\text{-}3)$$

where:

ΔT_{cp} = Log mean temperature difference for constant rate period.

ΔT_{fp} = Log mean temperature difference for falling rate period.

DT_o = Difference between inlet flue gas and feed temperature.

DT_1 = Difference between critical temperature of flue gas and droplet.

DT_2 = Difference between outlet flue gas and dry product temperature.

The sulfur dioxide diffusion coefficient in water is found from Stokes-Einstein equation, modified by Wilke-Change (4) as:

$$D_{SO_2} = 5.171 \times 10^{-12} \frac{(T+273)}{\mu_{H_2O}} \qquad (5-4)$$

Solubility of sulfur dioxide into the calcium hydroxide solution is calculated by estimating the Henry's constant for sulfur dioxide into the pure water and correcting it for the calcium hydroxide ion in the aqueous solution (24). Sulfur dioxide removal efficiency for constant rate period is calculated using case two of Ramachandran and Sharma equation as given in equation (4-6). Newton's method was used to estimate the reaction plane in equations 4-6 and 4-7 (page 30). Falling rate efficiency is calculated using equation 4-13 if the condition specified by equation 4-14 is met, otherwise equation 4-6 (page 30) is used. Equation 4-15 is used to estimate the mole of reacted sulfur dioxide. Flow sheet for the dry scrubbing computer model is shown in Figure 8.

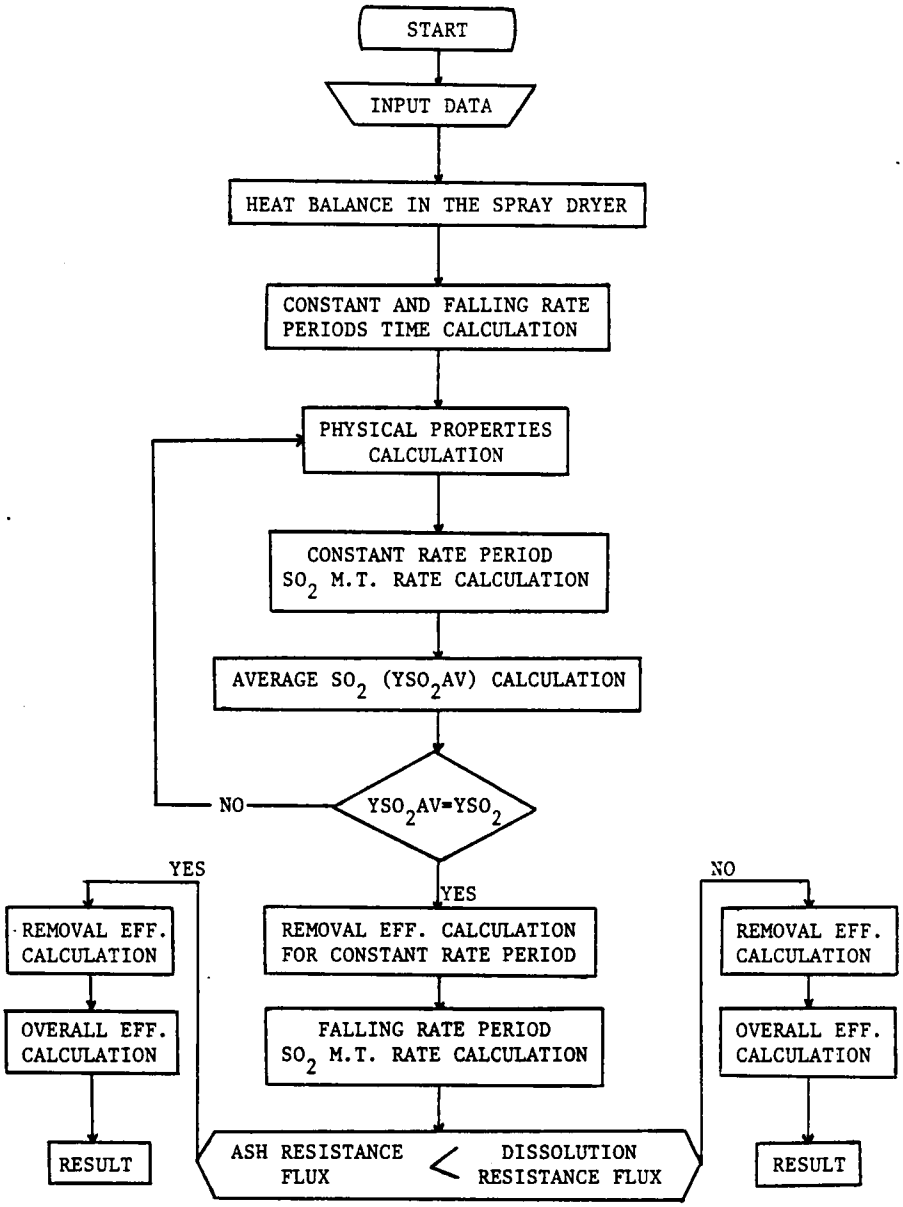


Figure 8. Flow Sheet for the Dry Scrubbing Computer Model.

CHAPTER 6

RESULTS OF STUDY

To calculate the extent of sulfur dioxide absorption in the constant and falling rate periods, case 2 of Ramachandran and Sharma is used; in this case the solid dissolution in the liquid film is important. Solid dissolution mass transfer coefficients were determined by varying these parameters so that the theoretical efficiency agreed with experimental efficiency; correlation of the resulting K_s values yields the following equation:

$$\begin{aligned} K_s = {} & 0.021 + 0.16 \times 10^{-5}\ \text{DELTAT} - 0.1 \\ & \times 10^{-10}\ \text{DELTAT}^4 - 11 \times 10^{-5} \sin(\text{SR}) \\ & + 24 \times 10^{-6} \sin(\text{SR}^2) + 49 \times 10^{-6} \cos(\text{SR}^2) \\ & -25 \times 10^{-3}\ \text{SLCONC} - 0.019 \cos(\text{SLCONC}) \\ & + 89 \times 10^{-7} \cos(\text{SLCONC}^2) + 0.02 \sin(\text{SLCONC}) \\ & -24 \times 10^{-4} \sin(\text{SLCONC}^2) \end{aligned} \qquad (6\text{-}1)$$

The K_s values should be between $2\text{x}10^{-5}$ to $8\text{x}10^{-5}$ m/sec according to Ramachandran and Sharma (6). Predicted mass transfer coefficients for solid dissolution (K_s) are plotted vs. experimental values (Figure 9); straight line represents a perfect fit. Behaviors of K_s vs. stoichiometric ratio and slurry concentration were studied and plotted on Figure 10 and 11.

It is shown as in Figures 12 and 13 (as well as in Table 2) that theoretically calculated efficiencies of flue gas

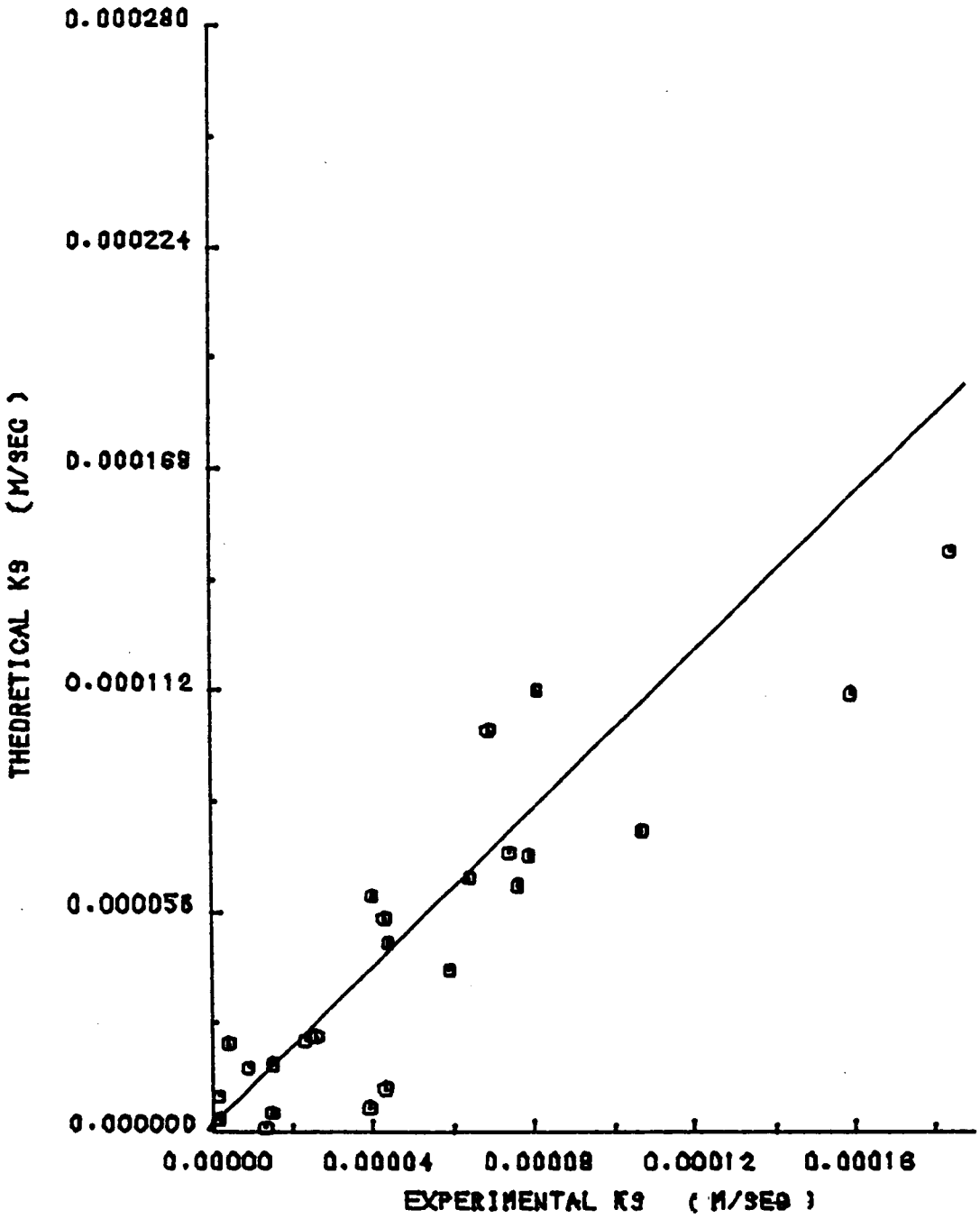


Figure 9. Predicted Mass Transfer Coefficient for Solid Dissolution vs. Experimental.

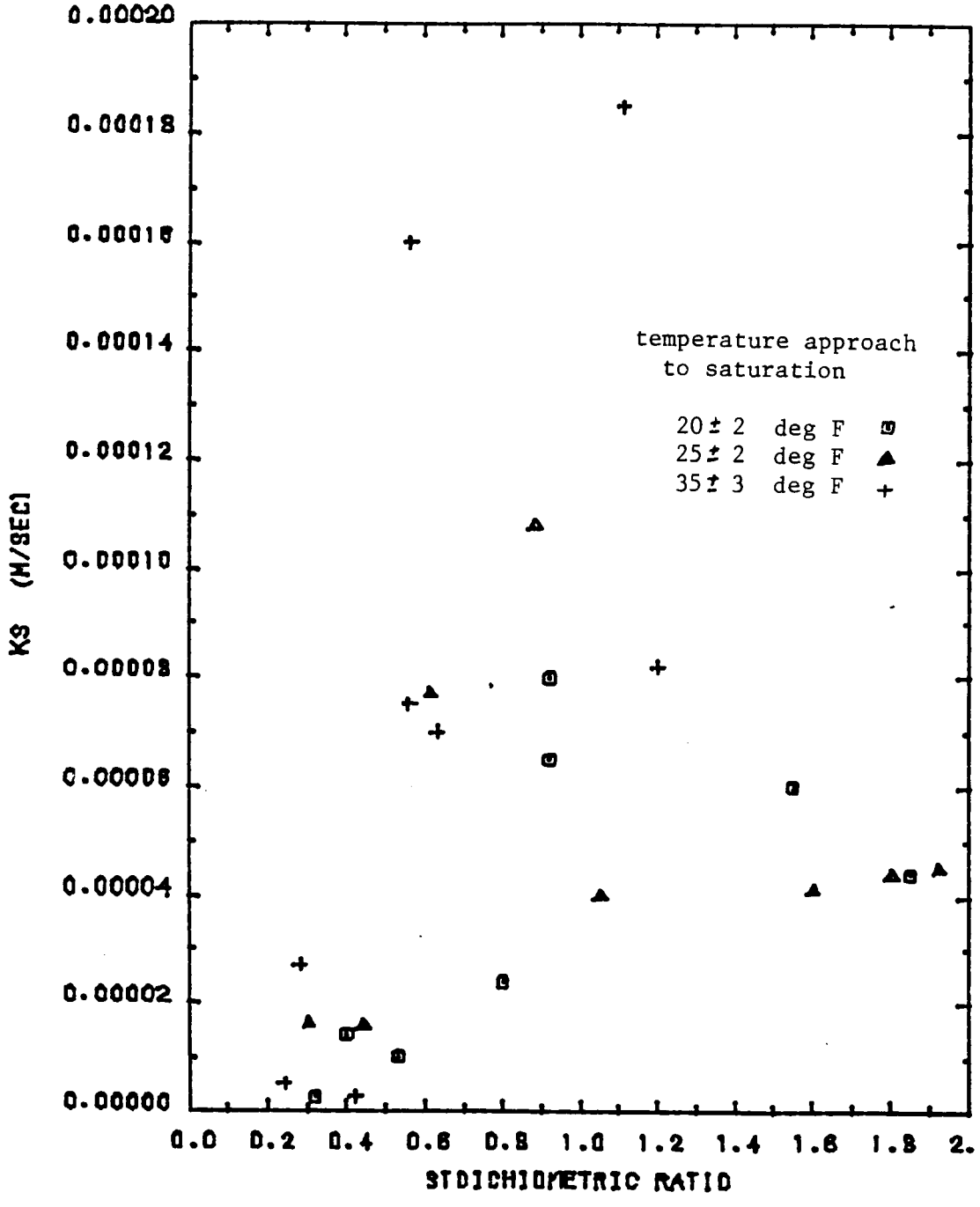


Figure 10. Experimental Mass Transfer Coefficient for Solid Dissolution vs. Stoichiometric Ratio.

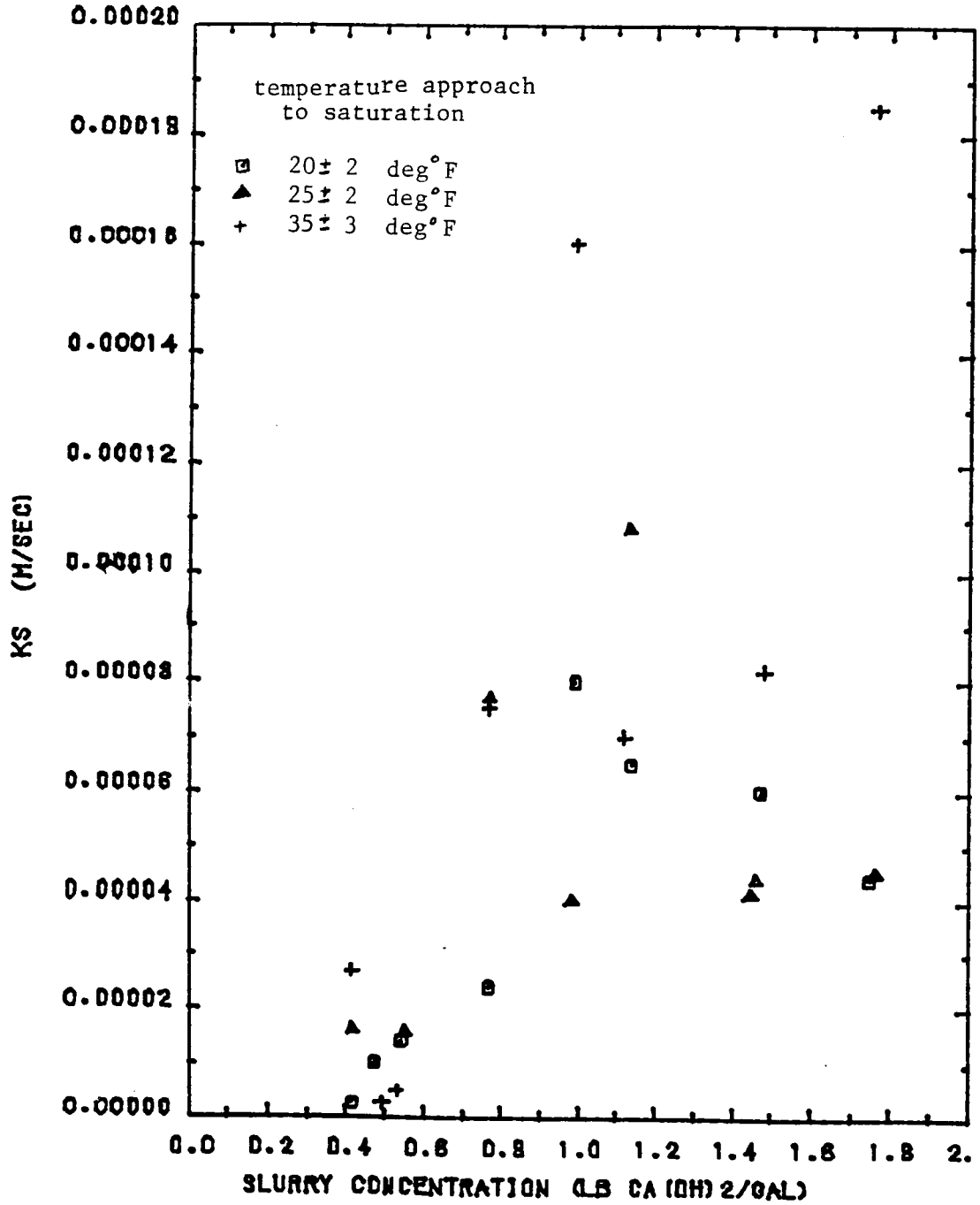


Figure 11. Experimental Mass Transfer Coefficient for Solid Dissolution vs. Slurry Concentration.

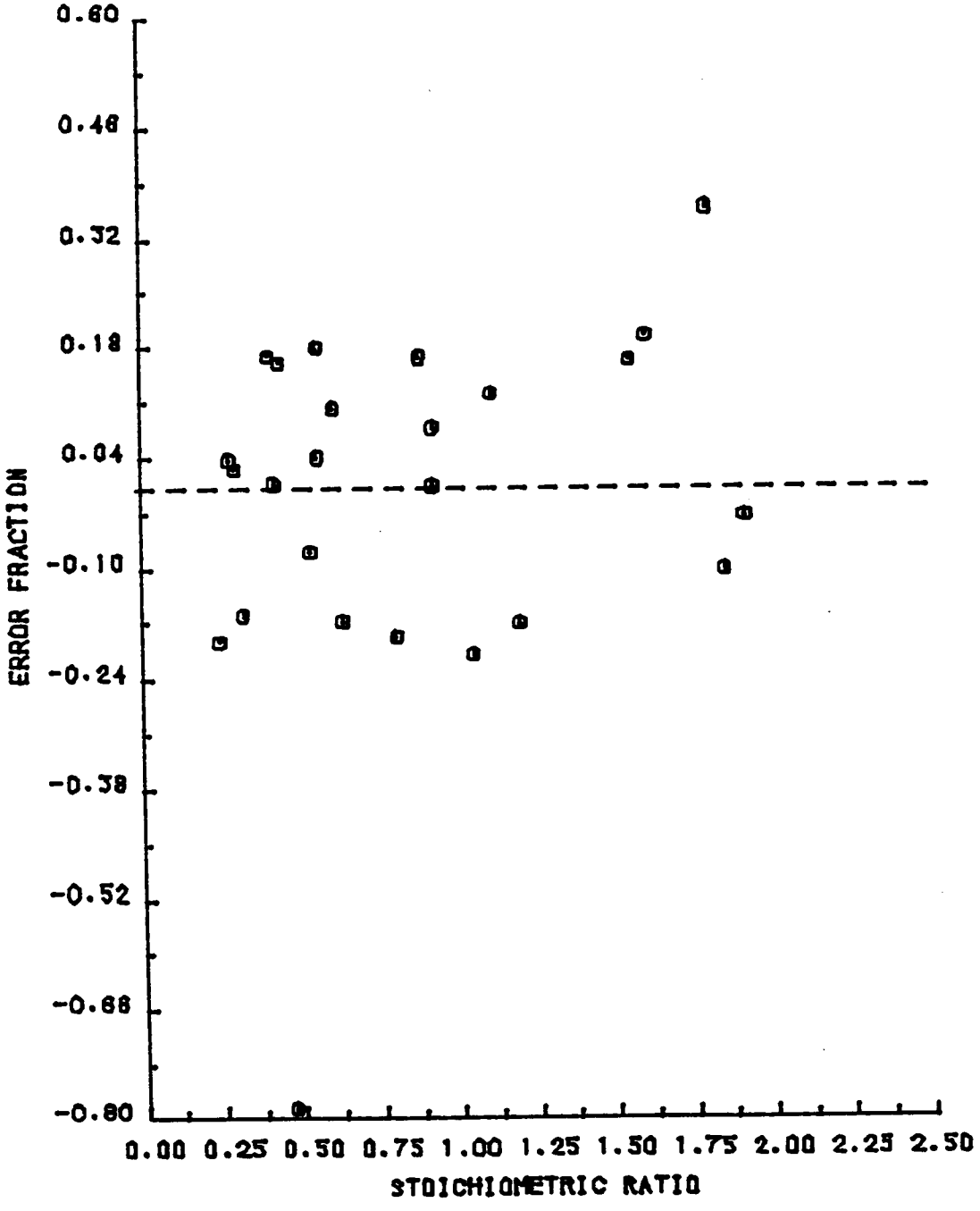


Figure 12. Fractional Difference Between Experimental and Theoretical Efficiencies vs. Stoichiometric Ratio.

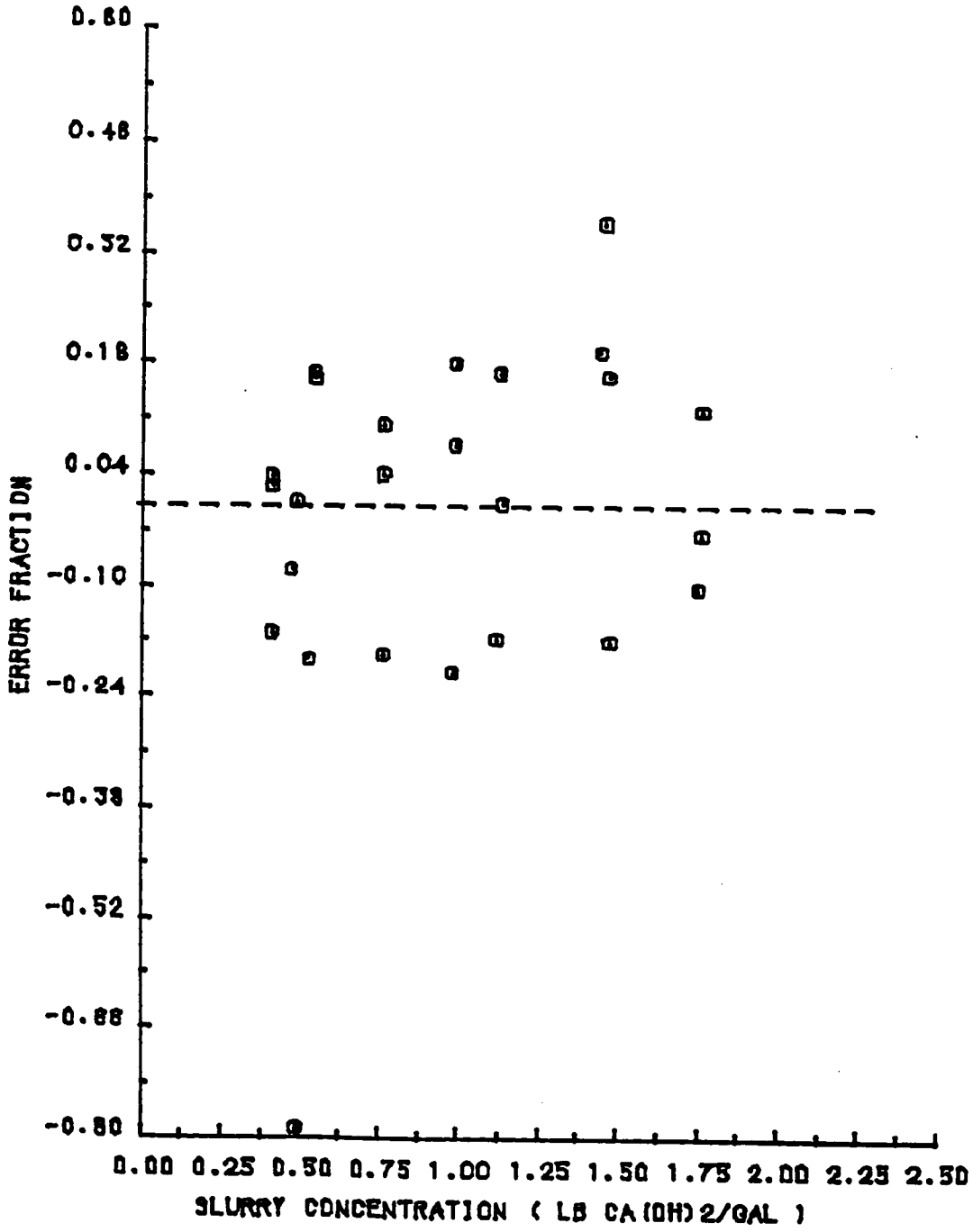


Figure 13. Fractional Difference Between Experimental and Theoretical Efficiencies vs. Slurry Concentration.

Table 2. Results of Computer Model for Dry Scrubbing.

SR	DELTAT (deg.F)	THEORETICAL EFFICIENCY	EXPERIMENTAL EFFICIENCY	SLCONC (lb/gal)	GPM (gal/min)	Ks (M/sec)
1.61	25.0	50.36	65.6	1.452	0.300	2.308E-05
0.57	36.0	36.09	44.9	0.997	0.140	1.107E-04
0.93	21.0	65.33	73.5	0.997	0.240	6.973E-05
1.06	25.0	72.58	62.3	0.990	0.280	5.964E-05
1.56	22.0	58.55	74.2	1.478	0.294	4.127E-05
1.21	32.0	60.00	53.9	1.486	0.250	1.115E-04
0.54	20.5	57.91	54.2	0.480	0.312	1.639E-05
0.48	25.0	38.45	21.7	0.498	0.274	5.776E-06
0.43	35.0	29.03	29.4	0.498	0.225	2.563E-06
1.86	20.0	75.05	73.1	1.756	0.300	5.401E-05
1.93	27.0	64.88	67.2	1.769	0.290	4.777E-05
0.93	20.0	60.51	63.2	1.146	0.237	6.414E-05
0.45	25.0	32.86	39.5	0.554	0.228	4.415E-06
0.41	20.0	31.18	37.9	0.549	0.222	5.688E-07
0.89	27.0	54.99	68.3	1.138	0.220	7.604E-05
0.25	35.0	20.70	17.5	0.535	0.138	2.227E-05
1.12	35.0	47.58	57.0	1.177	0.173	1.467E-04
0.64	35.0	36.64	32.2	1.126	0.150	1.014E-04
1.81	25.0	42.72	69.6	1.465	0.338	1.094E-05
0.33	19.0	33.72	29.3	0.420	0.233	9.032E-06
0.62	25.0	48.00	54.6	0.772	0.224	6.216E-05
0.81	20.0	63.45	54.8	0.772	0.292	3.954E-05
0.57	35.0	40.41	42.8	0.772	0.213	7.056E-05
0.31	24.0	31.63	32.7	0.420	0.207	1.715E-05
0.29	35.0	27.47	28.7	0.420	0.198	2.406E-05

desulfurization by the spray drying program are in good agreement with experimental data. The fractional differences between experimental and theoretical efficiencies calculated using the following equation:

$$\frac{\text{(experimental efficiency - theoretical efficiency)}}{\text{experimental efficiency}} \qquad (6\text{-}2)$$

are plotted vs. stoichiometric ratios and slurry concentrations on Figure 12 and 13. It is shown on these figures that the error fraction is less than $\pm$ 0.2 (or $\pm$ 20%), except one data point; this data point should have been probably discarded. Experimental efficiencies vs. theoretical efficiencies are plotted on Figure 14 with the straight line representing perfect agreement between the two efficiencies. In general, theoretical efficiencies are in good agreement with experimental efficiencies. The efficiency of the system increases as stoichiometric ratio increases. If the temperature approach to saturation (difference between dry and wet bulb temperature) decreases, the efficiency of the system increases; this is probably due to the longer drying residence time during the constant and falling rate periods. As shown in Figure 15, as the sulfur dioxide concentration in the inlet flue gas increases while everything else are relatively kept constant, the predicted efficiency of the system decreases. Electron Microscopic pictures of the dry products (Figures 5,6,7, pages 25-27) show that the diameter of the droplets are 30-40 μm, and not 7.8 μ m as measured by Davis and Reed (17). Evaporation alone decreases the diameter of

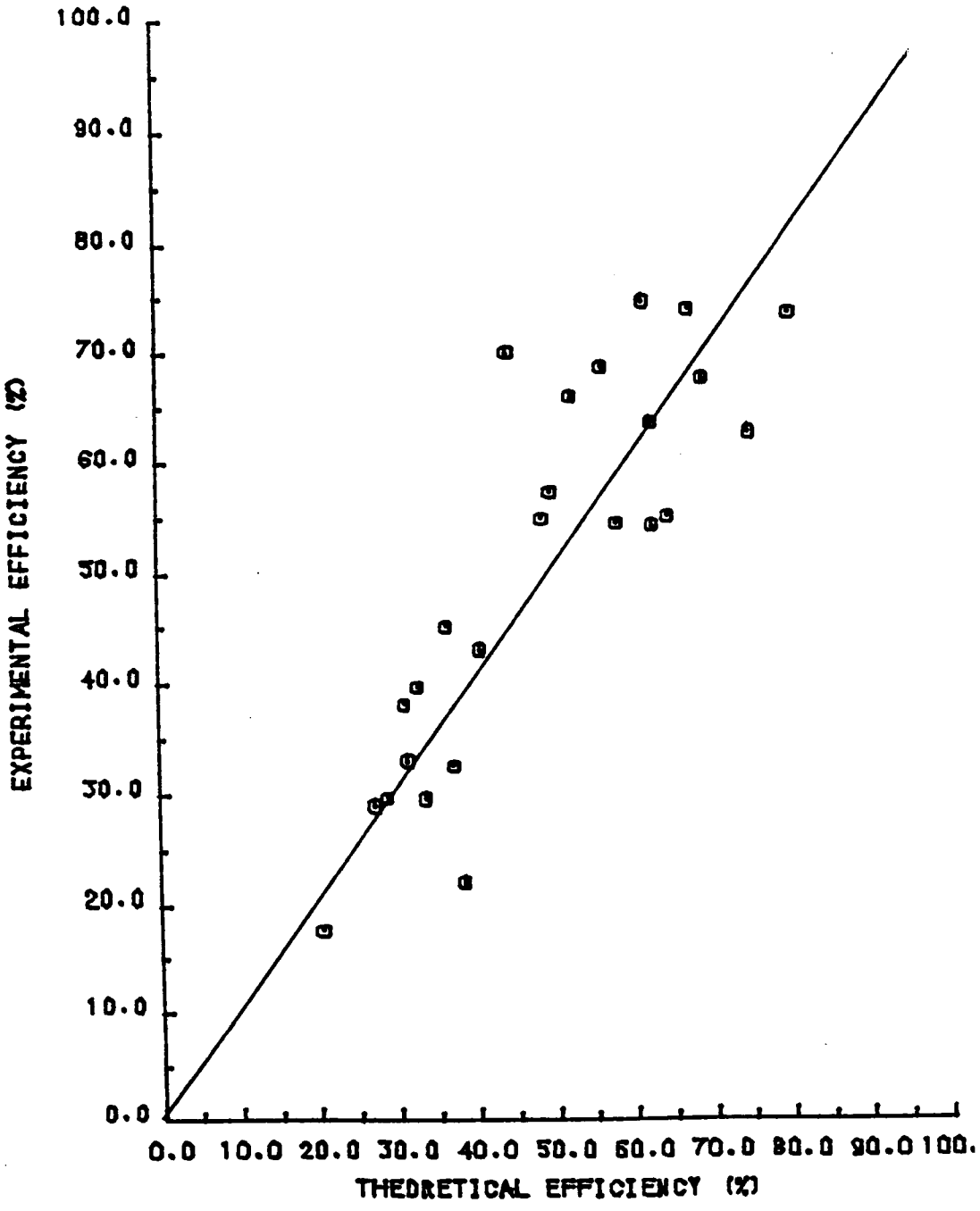


Figure 14. Experimental vs. Predicted Efficiencies.

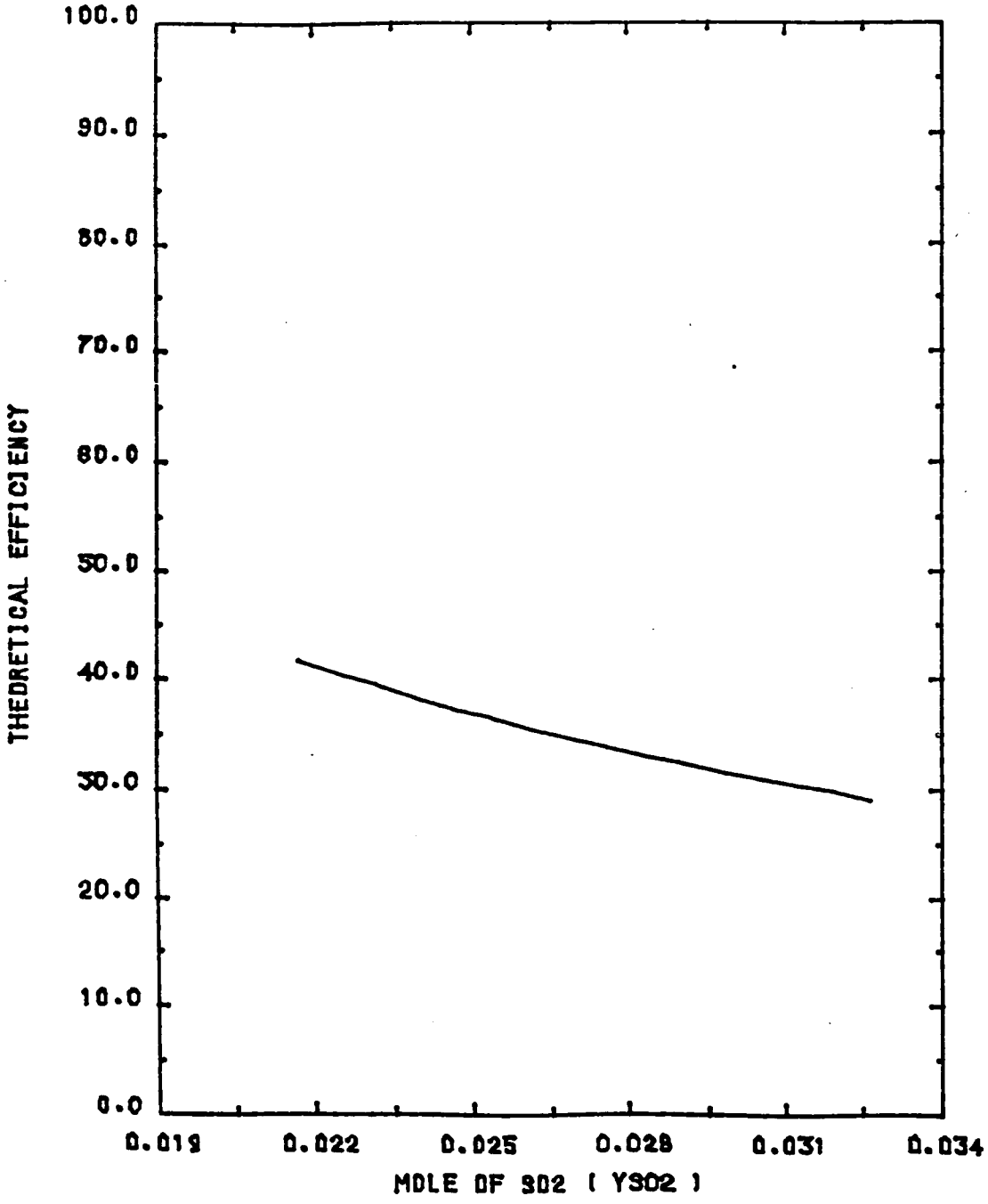


Figure 15. Efficiency Prediction vs. Inlet Sulfur Dioxide Concentration.

the droplets to the dry product size observed in this study (which can be estimated using equations 4-3 and 4-4, page 29). There appeared to be no basis for the assumption of "breakup of the liquid droplets" as concluded by Pearson (23).

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

A computer program has been developed in which an attempt was made to predict the efficiency of a spray dryer for absorption of sulfur dioxide from flue gas by lime slurry droplets. The following conclusions and recommendations were drawn from this study:

1. The model can reasonably predict the sulfur dioxide removal efficiency of the system and trends in this efficiency with changing input variables such as stoichiometric ratio, temperature approach to saturation, etc.
2. Better quality lime can be used for better sulfur dioxide removal efficiency, because better quality lime produces finer solid particles that increases the efficiency. The dissolution rates can change as much as thirty times due to the lime quality as specified by Uchida, et al. (12).
3. Product recycling causes better efficiency. More study is needed on product recycling. This model can be expanded to take into consideration the product recycling effect on the efficiency calculation.
4. The effect of CO_2 and competitive reaction between SO_2 and CO_2 with $Ca(OH)_2$ should be studied.
5. Even though slurry effects such as concentration of the calcium hydroxide and the particle size on efficiency of

the system had been considered to some extent in the model, the effect of the drop diameter may not easily be studied experimentally from constant volume spray dryer system for the following reasons:

a. If the generated drops are too large the evaporation will not be completed in the first period, causing deposition of partially-dried particles on the spray dryer wall.

b. On the other hand, if the generated drops are too small, they will not cover the cross section area of the spray dryer, and by-passing of the flue gas will occur.

6. The effect of the addition of alkaline fly ash to slurries for sulfur dioxide absorption should also be studied.

7. Axial dispersion should be taken into consideration in future modeling efforts.

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BIBLIOGRAPHY

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APPENDIXES

APPENDIX A

CONFIRMATION OF MAJOR RESISTANCES

The rate of absorption of sulfur dioxide into the atomized lime slurry droplets can be estimated based on three different models. One is using Ramachandran and Sharma (6) methods based on solid dissolution alone controls the specific rate of absorption of sulfur dioxide in calcium hydroxide slurry solution. The other cases are the ash resistance alone, and the gas film resistance alone controlling the specific rate of absorption.

The rate of absorption given by Ramachandran and Sharma (6) may be used to estimate the specific rate of absorption of sulfur dioxide in lime slurry droplets based on solid dissolution rate for very small particles as (6):

$$r_s = \frac{D_A A^*}{L} + K_s A_p B_s \frac{L}{2} \qquad \text{(A-1)}$$

Interfacial concentration of sulfur dioxide (A^*) into the water can be estimated using the following equation (6):

$$A^* = \frac{Z}{(1-Z)18.02} \qquad \text{(A-2)}$$

where (23):

$$Z = P_T Y_{SO2}/(H/101323.2) \qquad \text{(A-3)}$$

$$H = 10^{(-1285.85/(T+273) + 8.805)} \cdot 133.32 \qquad \text{(A-4)}$$

and for experiment number one where the wet bulb temperature is 48.3°C (17):

$$H = 8.384 \cdot 10^{6} \quad \text{atm m}^3/\text{gmole}$$

and it has been corrected to take into consideration the effect of ions concentration in the solution. The Henry's law coefficient for the solution is related to the value in water by empirical equation:

$$\text{LOG} \frac{H}{H_o} = -h\ I \tag{A-5}$$

$$\text{ION} = \frac{1}{2} Z_i^2 C_i \tag{A-6}$$

$$H = H_o(10^{0.106\ I}) \tag{A-7}$$

$$H = 2.632 \cdot 10^{7} \quad \text{atm m}^3/\text{grmol}$$

so:

$$A^* = \frac{3.3327 \cdot 10^{-6}}{(1-3.3327 \cdot 10^{-6}) \cdot 18.02} = 1.8494 \cdot 10^{-4} \quad \text{grmole/m}^3$$

Reaction plane (L) is estimated by the computer model using equation (A-1) by Newton's method.

The solid dissolution mass-transfer coefficient (K_s) is found from the experimental value (equation 6-1, page 38).

The surface area of the particle is given as (6):

$$A_p = 6W/\rho\, d_d \qquad \text{(A-8)}$$

The amount of calcium hydroxide (W) in the slurry solution for case one is 797.7 mole/m^3

$$A_p = \frac{6 \cdot 797.67}{2500(3e\text{-}4\text{-}3e\text{-}4 \cdot 0.504)} \cdot 100 = 128656.1\ m^2/m^3$$

The saturation solubility of solid is given as:

$$B_s = C_{ca}/74.1 \qquad \text{(A-9)}$$

Solubility of calcium hydroxide is given as (23):

$$C_{ca} = 10 \cdot (-0.0011T+0.185) \qquad \text{(A-10)}$$

$$C_{ca} = 10 \cdot (-0.0011 \cdot 48.33+0.185) = 1.32\ Kg/m^3$$

$$B_s = 1.32/74.1e\text{-}3 = 1.779e\text{-}5\ gmol/m^3$$

Using equation (A-1):

$$r_s = \frac{7.708e\text{-}5 \cdot 1.8494e\text{-}4}{8.8e\text{-}6} + \frac{2.3e\text{-}3 \cdot 12856 \cdot 1.77e\text{-}5 \cdot 8.88e\text{-}6}{2}$$

$$= \frac{\frac{m^2}{sec}\,\frac{gmol}{m^3}}{m} + \frac{m}{sec}\,\frac{m^2}{m^3}\,\frac{gmol}{m^3}\,m$$

$$r_s = 5.694e\text{-}3\ grmol/m\ sec$$

The rate of diffusion assuming that diffusional resistance through the ash film controls is given as:

$$r_e = \frac{P_t \cdot Y_{SO2}}{\frac{R_p (R_p - R_c) RT}{R_c D_e}} \qquad \text{(A-11)}$$

Volume of the liquid core is estimated to be half of the volume of the particles.

The effective diffusivity for the sulfur dioxide into the calcium hydroxide solution can be found from the experimental values given by Marsh and Ulrichson, using equation (A-11).

$$r_e = \frac{0.9689 \cdot 8.935e\text{-}4}{3086.852} = 2.8045e\text{-}7 \ \text{gmol/m}^2\text{sec}$$

The rate of absorption of sulfur dioxide into lime slurry droplet based on gas film resistance is given as:

$$r_g = K_g P_t Y_{SO2} \qquad \text{(A-12)}$$

$$r_g = 3.275e\text{-}2 \ \ \text{grmol/m}^2\text{sec}$$

Since r_e is much smaller than r_s or r_g, the ash film resistance, and gas film resistance were neglected; therefore diffusional resistance through the ash film controls the rate of absorption of sulfur dioxide into the lime slurry droplet.

APPENDIX B

COMPUTER PROGRAM WITH RESULTS

```
C
C*************************************************************************
C*                                                                       *
C*    SUBJECT    ----> ABSORBTION OF SO2 IN FLUE GAS WITH LIME SLURRY    *
C*                          BY SPRAY DRYING.                             *
C*                                                                       *
C*************************************************************************
C
C
C*************************************************************************
C***  AP     =SURFACE AREA OF SOLID PARTICLES,M**2/M**3 DISPERSION       *
C***  ASTAR =INTERFACIAL CONCENTRATION OF SO2,KGMOLE/M**3                *
C***  BW2    =MOISTURE FRACTION BY VOLUME IN THE SPRAY DRYER             *
C***  BS     =SATURATION SOLUBILITY OF SOLID KGMOLE/M**3                 *
C***  CAPD   =GRMOLE OF CA(OH)2 PER DROP                                 *
C***  CCA    =SOLUBILITY OF CA(OH)2 IN WATER,KG/M**3                     *
C***  CP     = SPECIFIC HEAT OF FLUE GAS CAL/(GRMOLE,DEG C)              *
C***  DELTAT=TEMPERATURE APPROACH TO SATURATION,DEG F                    *
C***  DPS    =NUMBER OF DROPLETS ENTERING THE SPRAY DRYER PER SECOND     *
C***  DROPDI=MEAN DROP DIAMETER,M                                        *
C***  EFF    =PREDICTED SPRAY DRYER EFFICIENCY,%                         *
C***  EFFSD =EXPERIMENTAL SPRAY DRYER EFFICIENCY,%                       *
C***  GGASPS=GRMOLE OF GAS PER SECOND                                    *
C***  GPM    =SLURRY FEED RATE,GAL/MIN                                   *
C***  HENRY =HENRY LAW CONSTANT FOR SO2 ABSORBTION IN H2O,ATM/MOLE FR.   *
C***  KD     =THERMAL CONDUCTIVITY OF THE DROPS,KCAL/(M,HR,DEG K)        *
C***  KG     =GAS SIDE MASS TRANSFER COEFFICIENT,KGMOLE/(M**3,SEC,ATM)   *
C***  KL     =LIQUID SIDE MASS TRANSFER COEFFICIENT,M/SEC                *
C***  KS     =MASS TRANSFER COEFFICIENT FOR SOLID DISSOLUTION,M/SEC      *
C***  LMTDC =LOG MEAN TEMPERATURE DIFFERENCE FOR CONSTANT RATE PERIOD    *
C***  LMTDF =LOG MEAN TEMPERATURE DIFFERENCE FOR FALLING RATE PERIOD     *
C***  MWAVG =AVERAGE MOLECULARE WEIGHT OF FLUE GAS                       *
C***  NSO2RX=MASS TRANSFER RATE AT CONSTANT RATE PERID,MOLE/(M**2,SEC)   *
C***  PAGE   =PAGE NUMBER CORRESPONDING TO DR.DAVIS FINAL REPORT         *
C***  PBAR   =ATMOSPHERIC PRESSURE,INCHES HG                            *
C***  PRODDN=PRODUCT DENSITY,KG/M**3                                     *
C***  PT     =TOTAL PRESSURE INSIDE SPRAY DRYER,ATM                      *
C***  SCFM1C=FLUE GAS FLOW RATE,FT**3/MIN                                *
C***  SLCONC=SLURRY CONCENTRATION,LB CA(OH)2/GAL                         *
C***  SLDEN =DENSITY OF LIME SLUURY,KG/M**3                              *
C***  SO2ONC=CONCENTRATION OF SO2 IN THE INLET FLUE GAS,PPM              *
C***  SO2PSI=MOLE OF SO2 PER SECOND INTO THE SPRAY DRYER                 *
C***  SP1    =STATIC PRESSURE BELOW ATMOSHERIC PRESSURE BEFORE S.D."HG   *
C***  SP2    =STATIC PRESSURE BELOW ATMOSPHERIC PRESSURE AFTER S.D."HG   *
C***  SR     =STIOCHIOMETRIC RATIO OF SO2 TO CA(OH)2                     *
C***  TEMP1C=ENTERING FLUE GAS TEMPERATURE,DEG F                         *
C***  TEMP2 =FLUE GAS TEMPERATURE AFTER LEAVING SPRAY DRYER              *
C***  TEMPC =CRITIICAL TEMPERATURE,DEG C                                 *
C***  TSLURR=SLURRY TEMPERATURE,DEG F                                    *
C***  TW2    =WET BULB TEMPERATURE,DEG F                                 *
C***  W1     =INITIAL MOISTURE CONTENT OF THE DROPS,KG H2O/KG CA(OH)2    *
C***  W2     =FINAL MOISTURE CONTENT OF THE DROPS,KG H2O/KG CA(OH)2      *
C***  YCO2   =MOLE FRACTION OF CO2 IN FLUE GAS                          *
C***  YH2O   =MOLE FRACTION OF H2O IN FLUE GAS                          *
C***  YN2    =MOLE FRACTION OF N2  IN FLUE GAS                          *
C***  YO2    =MOLE FRACTION OF O2  IN FLUE GAS                          *
C***  YSO2   =MOLE FRACTION OF SO2 IN FLUE GAS                          *
C*************************************************************************
C
C
```

```
        DIMENSION EFF(29),EFFSD(29),PERDIF(29),WLANDA(99),TEMC(51)
        REAL LMTDC,KD,LMTDF,MWAVG,NH2O,KG,NSO2,MSO2,NSO2RX,MCCA,N2PS
     $,KL,KGW,KS,M,MIDTEP,MS,LGASPH,KDT,LMTDFB,KS1,KS2,KS3,KS4,KS5,MOLAR
     $,ION,KS6
C****** UP HERE USE IMPLICIT REAL FOR K  ***************
C       IMPLICIT REAL K
       INTEGER RUN,PAGE
        COMMON YN2,YCO2,YO2,YH2O,YSO2,PT,T,FGDEN,UMIX,DSO2N2,DSO2CO
     $,DSO2O2,DSO2H2,VINFIN,RET,SLDEN,DROPDI,KGW,NH2O,DSO2MX,CCA,XA
     $,AP,DOSO2,DOCA,KS,ASR,DOSO2R,RKS,BR,RKL,MN,ASTAR,APM,BS
c       WRITE(50,777)
        WRITE(50,876)
876     FORMAT(19X,'THEORETICAL',3X,' EXPERIMENTAL')
        write(50,877)
877     format('  SR',4X,' DELTAT  ',2X,' EFFICIENCY',4X,' EFFICIENCY',
     $4x,' SLCONC',4X,' GPM','       KS')
777     FORMAT(' DI',9X,'SR',4X,' DELTAT  ',4X,'EC',4X,'ET',5X,'EX',4X,
     $'SLCONC',3X,'GPM',5X,'KS')
        WRITE(50,*)' ------------------------------------------------
     $----------------'
  101 READ(22,*)RUN,PAGE
CCCCC
        KKK=KKK+1
        WRITE(49,*)'KKK=',KKK
        WRITE(51,*)'                    KKK=',KKK
        II=0
        III=0
        EFMTRC=0.0
      IF(RUN.EQ.999)GO TO 100
        WRITE(43,214)
 214    FORMAT('1')
      WRITE(43,35)RUN,PAGE
   35 FORMAT(/,10X,'RUN = ',I3,5X,'PAGE NO. = ',I3)
      READ(22,*)YN2,YCO2,YO2,YH2O,YSO2
      READ(22,*)SO2ONC,TEMP1C,SLCONC,SCFM1C
      READ(22,*)GPM,PBAR,SP1,SP2,TSLURR
      READ(22,*)TEMP2,TW2,DROPDI,PRODDN
        TEM=TEMP2
        T1=TEMP1C
        PRODDN=2500.
        WRITE(44,638)DROPDI
 638    FORMAT(1X,'DROPDI= ',E11.5)
        DINITI=DROPDI
        DI=DROPDI
      READ(22,*)EFFSD(RUN),BW2
C
C   TO GET SLURRY CONCENTRATION OF CA(OH)2.
C
        SLCONC=1.32*SLCONC
C
C      ADJUSTING THE INLET FLUE GAS CONCENTRATION
C
      YFIX=YH2O+YSO2
      YADJST=1.-YFIX
      YN2=(YADJST/.95)*YN2
      YCO2=(YADJST/.95)*YCO2
      YO2=(YADJST/.95)*YO2
        SLDEN=1000.5+65.325*SLCONC
        W1=8.35/SLCONC-0.4548
```

```
      DELTAT=TEMP2-TW2
C
C       NUMBER OF DROPS ENTERING THE SYSTEM
C
      DPS=(GPM/(DROPDI)**3.)*1.204E-04
C
C     SPRAY DRYER OPERATING PRESSURE
C
      PT=(PBAR/29.921)-((SP1+SP2)/810.62)
      WRITE(43,8)PT
    8 FORMAT(/,5X,'OPERATING PRESSURE = ',F5.3,4X,'ATM')
         WRITE(43,11)YSO2
   11    FORMAT(5X,'INLET SO2 CONCENTRATION=',E11.5)
C
C     MOLES OF GAS ENTERING THE SYSTEM
C
         GGASPS=SCFM1C*1.9545E-02
         WRITE(44,283)GGASPS
283      FORMAT(1X,' GGASPS=',F15.9)
      YSO2I=YSO2
      SO2PS=GGASPS*YSO2
         SO2RXC=SO2PS/3.
         SO2PSI=SO2PS
      SO2AVG=SO2PSI/2.
      N2PS=GGASPS*YN2
      CO2PS=GGASPS*YCO2
      O2PS=GGASPS*YO2
      H2OPS=GGASPS*YH2O
      WRITE(43,9)SO2PS
    9 FORMAT(5X,'MOLES OF SO2 PER SECOND = ',F6.4)
C
C     MOLES OF CA(OH)2 PER DROP
C
         CAPD=SLCONC*(8.456E+02)*(DROPDI**3)
C
C     STIOCHIOMETRIC RATIO CALCULATION
C
         CAPS=CAPD*DPS
      SR=CAPS/SO2PS
         WRITE(43,44)CAPS
 44      FORMAT(5X,'MOLES OF CA(OH)2 PER SECOND =',F6.4)
      WRITE(43,107)SR
  107 FORMAT(5X,'STOICHIOMETRIC RATIO = ',F6.4)
         CP1=(YN2*7.31)+(YCO2*11.088)+(YO2*8.96)+(YH2O*8.55)+(YSO2*11.5)
         AVGMW=(YN2*28.)+(YCO2*44.)+(YO2*32.)+(YH2O*18.)+(YSO2*64.)
         CP1=CP1/AVGMW
       HVAPB=-0.3290*TW2+608.2879
C*************   I ASSUMED TEMP OF 100 DEG C AS MASTER   *************
         HVAP=-0.565*(100.)+597.12
         AVGDEB=(SLDEN+500.)/2.
      W3=4.4732E+04/(DELTAT**4.3463)
      W2=W3/(1.-W3)
         WC=0.0018*SLDEN*500./PRODDN
       DC=DROPDI*((SLDEN/PRODDN)*((1.+W2)/(1.+W1)))**(1./3.)
CCCCC
         WRITE(51,*)' W1=',W1,'  WC=',WC,'  W2=',W2,'  DI=',DI,' DC=',DC
       WRITE(51,*)' SLDEN=',SLDEN,'  PRODDN=',PRODDN,'   DROPDI=',DROPDI
         WRITE(51,*)'   SLCONC=',SLCONC,'   DELTAT=',DELTAT
      WRITE(43,190)DELTAT
```

```
  190 FORMAT(5X,'TEMPERATURE APPROACH TO SATURATION = ',F5.1,'DEG F')
C
       AVGDEN=(SLDEN+PRODDN)/2.
       KDT=8.64E-05*(((TW2-32.)/1.8)+273.)-1.196E-02
         KD=(((TW2+TEMP2)/2.)/4.3353E04)+1.3207E-02
         H1PT=YH2O*(18./AVGMW)
         LGASPH=GGASPS*AVGMW*7.947
         GA=LGASPH*(1.-H1PT)
         H1=H1PT/(1.-H1PT)
         QA1=CP1*(TEMP1C-32.)+1075.5*H1
         QS1=(21.4/74.1)*(TSLURR-32.)+W1*(TSLURR-32.)
         QS2=(21.4/74.1)*((TEMP2+TW2)/2.-32.)+W2*((TEMP2+TW2)/2.-32.)
         QSC=(21.4/74.1)*(TW2-32.)+WC*(TW2-32.)
         MS=GPM*SLCONC*60.
         EVAMOC=MS*(W1-WC)
         EVAMO2=MS*(W1-W2)
         HC=(EVAMOC+GA*H1)/GA
         H2=(EVAMO2+GA*H1)/GA
         QA2=CP1*(TEMP2-32.)+1075.5*H2
         HCPT=HC/(1.+HC)
         A=GA*QA1+MS*QS1
         BC=GA*1075.5*HC+MS*QSC
168      HVAP=HVAP*1.8
         AVGDEN=AVGDEN*0.062428
         DROPDI=DROPDI*3.281
         DC=DC*3.281
         AA=-98269.*SO2RXC*3600./251.6
         WRITE(44,158)AA,A,B2
158     FORMAT(1X,'AA=',E11.5,'  A=',E11.5,'  B2=',E11.5)
         QLT=(GA*(QA1-QA2)+MS*(QS1-QS2)-AA)
         QLC=QLT*(W1-WC)/(W1-W2)
         TEMPC=(A-BC+GA*CP1*32.-QLC-AA)/(GA*CP1)
        TEMPC=(TEMPC-32.)/1.8
      TSLURR=(TSLURR-32.)/1.8
      TEMP1C=(TEMP1C-32.)/1.8
      TEMP2=(TEMP2-32.)/1.8
      TW2=(TW2-32.)/1.8
      T=TW2
         HVAP=HVAP/1.8
C
C    BACK TO METRIC SYSTEM
C
         AVGDEN=AVGDEN/0.062428
         DROPDI=DROPDI/3.281
         DC=DC/3.281
      WCAVG=(W1+WC)/2.
      WFAVG=(WC+W2)/2.
CCCCC
         WRITE(51,*)'WCAVG=',WCAVG,'   WFAVG=',WFAVG
         TEPC=TEMPC*1.8+32.
      WRITE(43,63)TEPC
   63 FORMAT(5X,'CRITICAL TEMPERATURE =',F6.2,2X,'DEG F')
C
C     CONSTANT RATE PERIOD CALCULATION
C
         DT0=TEMP1C-TSLURR
         DT1=TEMPC-TW2
         DT2=TEMP2-1.1*TW2
         LMTDC=(DT0-DT1)/(ALOG(DT0/DT1))
```

```
      TC=HVAP*AVGDEN*((DROPDI)**2.-(DC)**2.)*3600./(8.*KD*LMTDC)
C
C     FALLING RATE PERIOD CALCULATION
C
         LMTDF=(DT1-DT2)/(ALOG(DT1/DT2))
       TF=HVAP*PRODDN*DC**2.*(WC-W2)*3600./(12.*KD*LMTDF)
C
C     RESULTS FROM TIME PERIOD CALCULATIONS
C
      WRITE(43,5)
    5 FORMAT(/,5X,'CONSTANT RATE PERIOD',5X,'FALLING RATE PERIOD')
      WRITE(43,6)TC,TF
    6 FORMAT(9X,F6.3,4X,'SEC',13X,F6.3,4X,'SEC')
C
C     CA++ DIFFUSION IN WATER - WILKE/CHANG EQN.
C
      DOCA=4.781E-12*(T+273.)/(1.002*10.**((1.3272*(20.-T)-
     $0.001053*(T-20.)**2.)/(T+105.)))
      WRITE(43,25)DOCA
   25 FORMAT(/,5X,'CA++ DIFFUSION IN WATER = ',E12.5,4X,'M2/SEC')
C
C     SO2 DIFFUSION IN WATER - STOKES-EINSTEIN,MODIFIED BY WILKE/CHANGE
C
         VISH2O=73./(T*1.8+32)
         DOSO2=(5.171E-12)*(T+273)/VISH2O
      WRITE(43,26)DOSO2
   26 FORMAT(5X,'SO2 DIFFUSION IN WATER = ',E12.5,4X,'M2/SEC')
C
C     GAS PHASE PHYSICAL PROPERTY ESTIMATIONS
C
C     DENSITY OF FLUE GAS
C
C      WRITE(43,45)
C    45 FORMAT(27X,'CONSTANT RATE PERIOD VALUES')
      AVGDIA=(((DROPDI**3.)+(DC**3.))/2.)**(1./3.)
         DINEW=DROPDI
      DROPDI=AVGDIA
C
C     RATE EQUATION FOR INSTANTANEOUS REACTION
C
      IF(T.LE.30.)HENRY=(10.**((-1285.85/(T+273.))+8.805))*133.32
      IF(T.LE.30.)GO TO 62
      IF(T.GE.52.)HENRY=((29.597*T)-657.2676)*10000.
      IF(T.GE.52.)GO TO 62
         WRITE(52,*)' KKK=',KKK
      HENRY=((19.265*T)-92.6574)*10000.
   62 CONTINUE
         WRITE(52,*)'HENRY CONSTANT=',HENRY,'   T=',T
C
C HERE HENRY'S CONSTANT IS CORRECTED FOR THE LIME SLURRY SOLUTION.
C
         MOLAR=CAPS/(3.785*GPM/60)
         ION=0.5*(MOLAR*4+MOLR*4)
         HENRY=HENRY*(10**(0.106*ION))
         WRITE(52,*)'CORECTED HENRY ',HENRY,'     MOLAR=',MOLAR
         WRITE(52,*)' ION=',ION,'    CAPS=',CAPS,'    GPM=',GPM
   84 FORMAT(5X,'HENRYS LAW CONSTANT = ',E12.5,' ATM/MOLE FRAC')
      CCA=10.0*((-0.0011*T)+0.185)
      MCCA=CCA*13.495
```

```
         RKL=2.*SQRT(2.25*DOSO2*10000./(3.1416*TC))
         RKL=(5.*DOSO2/DROPDI)*100.
C*****************************************************************
C*****************************************************************
         WRITE(52,*)'KL=',RKL/100,'       DROPDI=',DROPDI
         WRITE(52,*)' DOSO2=',DOSO2
         WRITE(52,*)'TC=',TC,'     DT/R-2=',SQRT(DOSO2*TC/((DROPDI/2)**2))
C
C     RATE OF SO2 ABSORBTION AT CONSTANT RATE PERIOD, MODIFIED EQ. OF
C     RAMACHANDRAN & SHARMAS
C
C        KS1=0.9923998E-2
C        KS2=-224.1*DI+0.1355E11*(DI**3)-0.1749E-2*(2.34**DI)
C        KS3=0.279E-3*(SR**2)-0.3003E-4*(SR**3)-0.3414E-3*(2.34**SR)
C        KS4=0.2535E-3*SLCONC-0.1678E-4*(SLCONC**2)
C        KS5=0.3337E-1*GPM-0.1407*(GPM**2)+0.1748*(GPM**3)
C        KS6=.6773E-4*DELTAT-.1388E-5*(DELTAT**2)+.1694E-16*(2.34**DELTAT)
C        KS=KS1+KS2+KS3+KS4+KS5+KS6
         KS=18.5E-5
         KS1=0.02068211
         KS2=0.1615E-05*DELTAT-0.1068E-10*(DELTAT**4.)
         KS3=-0.1076E-03*(SIN(SR))+0.2392E-04*(SIN(SR**2))
         KS4=0.4893E-04*(COS(SR**2))-0.02518*(SLCONC)
         KS5=0.02056*(SIN(SLCONC))-0.2393E-02*(SIN(SLCONC**2))
         KS6=-0.01984*(COS(SLCONC))+0.8989E-05*(COS(SLCONC**2))
         KS=KS1+KS2+KS3+KS4+KS5+KS6
         ks=abs(ks)
         W5=1./(1.+WCAVG)
         W6=1./(1.+WFAVG)
CCCCC
         WRITE(51,*)'W5=',W5,'   W6=',W6
804         XA=PT*YSO2/(HENRY/101323.2)
      HC=HENRY*(1.-XA)/5.624E+09
C
C     DISSOLUTION IS TAKEN INTO THE CONSIDERATION FOR PARTICLE SIZE.
C
         AP=6*W5/((SLDEN/1000.)*(3.E-04-(3.E-04*EFMTRC/100.)))
C  200 MEANS 100% TIME EFF./2 FOR AN AVERAGE
*****************************************************************
         AP=6*(AVGDEB)/(PRODDN*(3.E-04-(3.E-04*EFMTRC/200.)))
CCCCC
C        WRITE(5,*)' SLDEN=',SLDEN,'  PRODDN=',PRODDN
         II=II+1
         CALL DIS(WLANDA)
927      R1C=DOSO2R*ASR/WLANDA(MN)+RKS*AP*BR*WLANDA(MN)/2.
         C1=DOSO2R*ASR/WLANDA(MN)
         C2=RKS*AP*BR*WLANDA(MN)/2.
         NSO2RX=R1C*10000.
      GO TO 20
   18 CONTINUE
   20 CONTINUE
   36 FORMAT(5X,'GAS PHASE DIFFUSIVITY OF SO2 = ',E12.5,2X,'M2/SEC')
   23 FORMAT(5X,'GAS PHASE MASS TRANSFER COEFFICIENT = ',E12.5,X,
     $'GM-MOLES/SEC.M2.ATM')
   68 FORMAT(5X,'SO2 MASS TRANSFER',
     $' = ',E12.4,2X,'GM-MOLES/SEC.M2')
      SO2RXC=NSO2RX*TC*3.1416*(DROPDI**2.)*DPS
893      SO2PS=SO2PSI-SO2RXC
      IF(SO2PS.LT.0.0)SO2PS=0.0
```

```
      SO2AVC=(SO2PSI+SO2PS)/2.
      GAS=N2PS+CO2PS+O2PS+H2OPS+SO2AVC
      YAVG=SO2AVC/GAS
      EFMTRC=(SO2RXC/SO2PSI)*100.
      ERROR=ABS((YSO2-YAVG)/YSO2)
      IF(ERROR.LE.0.02)GO TO 200
      YN2=N2PS/GAS
      YCO2=CO2PS/GAS
      YO2=O2PS/GAS
      YH2O=H2OPS/GAS
      YSO2=YAVG
         IF(II.GE.2) GO TO 200
      GO TO 804
  200 CONTINUE
         WRITE(43,122)APM
  122   FORMAT(5X,'SURFACE AREA OF SOLID PARTICLES=',E11.5,' M**2/M**3')
         WRITE(43,123)ASTAR
  123    FORMAT(5X,'INTERFACIAL CONCENTRATION OF SO2=',E11.5,'KGMOLE/M
     $**3')
         WRITE(43,124)BS
  124    FORMAT(5X,'SATURATION SOLUBILITY OF SOLID=',E11.5,'KGMOLE/M**3')
      WRITE(43,84)HENRY
      WRITE(43,52)KS
48    FORMAT(5X,'LIQUID PHASE MASS TRANSFER COEFFICIENT=',E11.5,'M/SEC')
      WRITE(43,68)NSO2RX
  202 FORMAT(5X,'SOLUTION DOES NOT CONVERGE;',
     $' ERROR = ',F8.6)
  203 FORMAT(5X,'SOLUTION CONVERGES AFTER',I3,' ITERATIONS;',
     $' ERROR = ',F8.6)
      WRITE(43,32)EFMTRC
   32 FORMAT(5X,'SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD',
     $' = ',F8.4,2X,'%')
C
C     FALLING RATE PERIOD MODEL
C
         B=0.50
      X=SO2RXC
      SO2PS=SO2PSI-X
      DRYTOT=N2PS+CO2PS+O2PS+SO2PS
      WETTOT=DRYTOT/(1.-BW2)
      H2OPS=WETTOT-DRYTOT
      YH2O=BW2
      YN2=N2PS/WETTOT
      YCO2=CO2PS/WETTOT
      YO2=O2PS/WETTOT
      YSO2=SO2PS/WETTOT
C        YSO2I=YSO2
      ACFS=WETTOT*0.7913*((TEMP2+273.)/273.)*(1./PT)
C      WRITE(43,40)
C   40 FORMAT(27X,'FALLING RATE PERIOD VALUES')
         PPS=DPS
         DX=DC
      DROPDI=DC
      SLDEN=PRODDN
      R=DC/2.
      VPART=4.18879*(R**3.)
      VAVG=VPART/2.
      RC=(VAVG/4.18879)**(1./3.)
204      CALL TERVEL
```

```
      XA=PT*YSO2/(HENRY/101323.2)
         KL=2.*SQRT(2.25*DOSO2*10000./(3.1416*TF))/100.
         KL=5.*DOSO2/(2.*RC)
      HC=HENRY*(1.-XA)/5.624E+09
      VP=RC/6.
         WRITE(51,*)'AP=',AP
         AP=6.*W6/((PRODDN/1000.)*(3.E-04-3.E-04*(EFMTRC/100)))*100.
*********************************************************************
         AP=6*(AVGDEB)/(PRODDN*(3.E-04-3.E-04*(EFMTRC/100)))*100
CCCCC
         APD=AP*W5/W6
         WRITE(51,*)'AP2=',AP/100.,'    APD=',APD/100.
CCCCC
         WRITE(51,*)'W6=',W6,' PRODDN=',PRODDN,' EFMTRC=',EFMTRC
      DO 85 I=1,200
      KG=(DSO2MX/(DROPDI*(1.-YSO2)))*(2.0+0.6*(UMIX/(FGDEN*DSO2MX))**(1.
     $/3.)*((DROPDI*VINFIN*FGDEN)/UMIX)**(1./2.))/(82.057E-06*(T+273.))
       DE=B*DSO2MX
C   ***** I ASUUMED EFFECTIVE DIFFUSIVITY AS IN MARCH & ULRICHSON PAPER
         DE=4E-11
      G=(RC**2.)/(HC*KG*(R**2.))
      D=RC*(R-RC)*(82.057E-06*(T+273.))/(HC*DE*R)
      E=DOCA/(DOSO2*KS*AP*VP)
      F=1./KL
      NSO2=((DOCA*MCCA/DOSO2)+(PT*YSO2/HC))/(G+D+E+F)
      AA1=1./KG
      AA2=((82.057E-06*(T+273.))*(R-RC)*R)/(DE*RC)
      AAB=PT*YSO2/(AA1+AA2)
         WRITE(49,*)' AFTER THE SUBROUTINE'
         WRITE(49,*)'DSO2MX=',DSO2MX,'   DROPDI=',DROPDI,'   YSO2=',YSO2
         WRITE(49,*)'UMIX=',UMIX,'   FGDEN=',FGDEN,'   VINFIN=',VINFIN
         WRITE(49,*)'KG=',KG,'   AA1=',AA1,'   R=',R,'   RC=',RC
         WRITE(49,*)'B=',B
         WRITE(49,*)'DE=',DE,'    T=',T,'    AA2=',AA2
         WRITE(49,*)'PT=',PT,'   YSO2=',YSO2,'   AAB=',AAB
      BBA=KL*DOCA*MCCA/DOSO2
         WRITE(44,989)KG,DE,G,D,F,NSO2,AA1,AA2,AAB,BBA
989      FORMAT(1X,'KG=',E11.5,' DE=',E11.5,' G=',E11.5,' D=',E11.5,
     $' F=',E11.5,' NSO2=',E11.5,' AA1=',E11.5,' AA2=',E11.5,
     $' AAB=',E11.5,' BBA=',E11.5)
      IF(AAB.LT.BBA)NSO2=AAB
         NSO2=AAB
      DSO2C=(NSO2-YSO2*(NSO2-NH2O))/((YN2*NSO2/DSO2N2)+(YCO2*NSO2/
     $DSO2CO)+(YO2*NSO2/DSO2O2)+(((YH2O*NSO2)+(YSO2*NH2O))/DSO2H2))
      COMPAR=ABS((DSO2MX-DSO2C)/DSO2MX)
      IF(COMPAR.LT.0.05)GO TO 89
      DSO2MX=DSO2C
   85 CONTINUE
      GO TO 90
   89 CONTINUE
   90 CONTINUE
   92 FORMAT(5X,'SO2 MASS TRANSFER = ',
     $E12.5,' GM-MOLES/SEC.M2')
C*********************************************************************
         AP=AP/100
         CALL DIS(WLANDA)
         R1F=DOSO2R*ASR/WLANDA(MN)+RKS*AP*BR*WLANDA(MN)/2.
         R1F=R1F*10000.
         WRITE(49,*)'DOSO2R=',DOSO2R,'    CCA=',CCA,'   BS=',BS
```

```
          WRITE(49,*)'XA=',XA
          WRITE(49,*)'AVGDEB=',AVGDEB,'    PRODDN=',PRODDN
          WRITE(49,*)'EFMTRC=',EFMTRC,'    AP=',AP
          WRITE(49,*)'RKS=',RKS,'   ASTAR=',ASTAR,'    ASR=',ASR
          WRITE(49,*)'BR=',BR,'    WLANDA=',WLANDA(MN)
CCCCC
C         WRITE(51,*)'AP2=',AP
         WRITE(39,*)'KG=',KG,'  AA1=',AA1,'  T=',T,'  R=',R,'  RC=',RC
         WRITE(39,*)'DE=',DE,'  AA2=',AA2,'  YSO2=',YSO2,'  AAB=',AAB
         WRITE(39,*)'WLANDA(',MN,')=',WLANDA(MN),'  RKS=',RKS,' AP=',AP
         WRITE(39,*)'BR=',BR
          WRITE(39,*)'R1F=',R1F,'  DOSO2R=',DOSO2R,'  ASR=',ASR
          IF(R1F.LT.AAB) NSO2=R1F
          WRITE(49,*)'            R1F=',R1F,'              AAB=',AAB
       SO2FR=NSO2*TF*12.56637*(RC**2.)*PPS
       SO2PS=SO2PSI-SO2RXC-SO2FR
       IF(SO2PS.LT.0.0)SO2PS=0.0
       SO2AVG=(SO2PSI-SO2RXC+SO2PS)/2.
       GAS=N2PS+CO2PS+O2PS+H2OPS+SO2AVG
       YAVG=SO2AVG/GAS
       ERROR=ABS((YSO2-YAVG)/YSO2)
       IF(ERROR.LE.0.02)GO TO 205
       IF(III.EQ.200)GO TO 205
       YN2=N2PS/GAS
       YCO2=CO2PS/GAS
       YO2=O2PS/GAS
       YSO2=YAVG
       YH2O=H2OPS/GAS
          III=III+1
          GO TO 204
  205 CONTINUE
C       WRITE(43,36)DSO2MX
C       WRITE(43,23)KG
C       WRITE(43,53)DE
C    53 FORMAT(5X,'EFFECTIVE DIFFUSIVITY =',E12.5,2X,'M2/SEC')
C       WRITE(51,*)'KL=',KL/100,KL
C       WRITE(43,52)KS
    52 FORMAT(5X,'DISSOLUTION MASS TRANSFER COEFFICIENT =',
     $E12.5,' M/SEC')
C       WRITE(43,92)NSO2
C       IF(III.EQ.200)WRITE(43,202)ERROR
C       IF(III.LT.200)WRITE(43,203)III,ERROR
       EFF(RUN)=((SO2FR+X)/SO2PSI)*100.
  208 CONTINUE
       WRITE(43,890)
  890 FORMAT(/,37X,'RESULTS')
       WRITE(44,59)EFF(RUN)
          WRITE(43,59)EFF(RUN)
   59 FORMAT(/,13X,'PREDICTED SPRAY DRYER EFFICIENCY   =',F12.4,2X,'%')
       WRITE(44,91)EFFSD(RUN)
          WRITE(43,91)EFFSD(RUN)
c         WRITE(50,74)DINITI,SR,DELTAT,EFMTRC,EFF(RUN),EFFSD(RUN),SLCONC,
C      $GPM,KS
74       FORMAT(E10.5,2X,F4.2,4X,F5.2,5X,F5.2,2X,F5.2,2X,F5.2,
     $2X,F5.3,2X,F5.3,3X,E11.5)
          WRITE(50,888)SR,DELTAT,EFF(RUN),EFFSD(RUN),SLCONC,GPM,KS
888    FORMAT(1X,F4.2,4X,F5.2,10X,F5.2,10X,F5.2,7X,F5.3,4X,F5.3,2X,E11.5)
          WRITE(55,1)SR,EFFSD(RUN)
1        FORMAT(4G15.7)
```

```
          IF ((DELTAT.GE.18).AND.(DELTAT.LE.22)) IZ=30
         IF ((DELTAT.GE.23).AND.(DELTAT.LE.27)) IZ=31
          IF ((DELTAT.GE.32).AND.(DELTAT.LE.38)) IZ=32
C         WRITE(IZ,*)DELTAT,EFF(RUN)
         WRITE(IZ,1)SR,EFF(RUN)
          WRITE(IZ+6,1)SR,KS
          WRITE(IZ+10,1)SLCONC,KS
          WRITE(46,*)SO2PSI,EFF(RUN)
C         WRITE(32,*)DELTAT,EFFSD(RUN)
          PERCEN=(EFFSD(RUN)-EFF(RUN))/EFFSD(RUN)
          WRITE(35,*) EFF(RUN),EFFSD(RUN)
          WRITE(33,*)SR,PERCEN
          WRITE(45,*)SLCONC,PERCEN
   91 FORMAT(12X,'EXPERIMENTAL SPRAY DRYER EFFICIENCY =',F12.4,2X,'%')
      GO TO 101
  100 CONTINUE
      STOP
      END
C
C
C
C
C
          SUBROUTINE TERVEL
C
C
        DIMENSION EFF(29),EFFSD(29),PERDIF(29),WLANDA(99),TEMC(51)
       REAL LMTDC,KD,LMTDF,MWAVG,NH2O,KG,NSO2,MSO2,NSO2RX,
     $MCCA,N2PS,KL,KGW,KS,M,MIDTEP,LMTDFB,KS1,KS2,KS3,KS4,KS5
       INTEGER RUN,PAGE
          COMMON YN2,YCO2,YO2,YH2O,YSO2,PT,T,FGDEN,
     $UMIX,DSO2N2,DSO2CO,
     $DSO2O2,DSO2H2,VINFIN,RET,SLDEN,DROPDI,KGW,NH2O,DSO2MX
   43  MWAVG=YN2*28.02+YCO2*44.01+YO2*32.+YH2O*18.016+YSO2*64.06
       FGDEN=(PT*MWAVG/(82.057*(T+273.)))*1000.
C
C      VISCOSITY OF FLUE GAS
C
       UN2=0.0208*((T+273.)/373.)**(3./2.)*(486.484/(T+386.484))
       UCO2=0.0178*((T+273.)/373.)**(3./2.)*(658.915/(T+558.915))
       UO2=0.0239*((T+273.)/373.)**(3./2.)*(505.3/(T+405.3))
       UH2O=0.0124*((T+273.)/373.)**(3./2.)*(921.31/(T+821.31))
       USO2=0.0163*((T+273.)/373.)**(3./2.)*(759.61/(T+659.61))
       UMIX=(((YN2*5.2934*UN2)+(YCO2*6.6340*UCO2)+(YO2*5.6569*UO2)+
     $(YH2O*4.2445*UH2O)+(YSO2*8.0037*USO2))/((YN2*5.2934)+
     $(YCO2*6.6340)+(YO2*5.6569)+(YSO2*8.0037)+(YH2O*4.2445)))/1000.
C
C      GAS PHASE COMPONENT DIFFUSIVITIES
C
       DH2ON2=3.535E-05*((T+273.)/373.)**(7./4.)/PT
       DH2OCO=2.505E-05*((T+273.)/373.)**(7./4.)/PT
       DH2OO2=3.525E-05*((T+273.)/373.)**(7./4.)/PT
       DH2OSO=1.979E-05*((T+273.)/373.)**(7./4.)/PT
       DSO2N2=2.090E-05*((T+273.)/373.)**(7./4.)/PT
       DSO2CO=1.466E-05*((T+273.)/373.)**(7./4.)/PT
       DSO2O2=2.044E-05*((T+273.)/373.)**(7./4.)/PT
       DSO2H2=1.979E-05*((T+273.)/373.)**(7./4.)/PT
C
C      TERMINAL VELOCITY CALCULATION
```

```
C
      FORCE=5.1348*SLDEN*(DROPDI)**3.
      VINFIN=((2.*UMIX)/(FGDEN*DROPDI))*((9.+(FGDEN*FORCE)/
     $(3.1416*(UMIX)**2.))**(1./2.)-3.0)
      RET=(FGDEN*DROPDI*VINFIN)/UMIX
      IF(RET.LE.10.)GO TO 13
      VINFIN=((4.8*UMIX)/(FGDEN*DROPDI))*((447.+(FGDEN*FORCE)/
     $(3.1416*(UMIX)**2.))**(1./2.)-20.4)
      RET=(FGDEN*DROPDI*VINFIN)/UMIX
      IF(RET.LE.700.)GO TO 14
      GO TO 15
   14 IF(RET.GT.10.)GO TO 13
   15 VINFIN=(2.4/DROPDI)*(FORCE/FGDEN)**(1./2.)
      RET=(FGDEN*DROPDI*VINFIN)/UMIX
   13 CONTINUE
C
C     GAS PHASE MASS TRANSFER CALCULATION
C
      DH2OMX=(1.0-YH2O)/((YN2/DH2ON2)+(YCO2/DH2OCO)+(YO2/DH2OO2)+
     $(YSO2/DH2OSO))
      PSAT=EXP(-7.2465822E+03/(T+273.)+77.641232+(5.74471242
     $E-03*(T+273.))+(-8.2470402*ALOG(T+273.)))/101325.
      YSAT=PSAT/PT
      YH2OLM=(YSAT-YH2O)/ALOG(YSAT/YH2O)
      KGW=(DH2OMX/(DROPDI*(1.-YH2OLM)))*(2.0+0.6*(UMIX/(FGDEN*DH2OMX))**
     $(1./3.)*((DROPDI*VINFIN*FGDEN)/UMIX)**(1./2.))/(82.057E-06*(T+273.
     $))
      NH2O=KGW*(PSAT-PT*YH2O)
      DSO2MX=(1.0-YSO2)/((YN2/DSO2N2)+(YCO2/DSO2CO)+(YO2/DSO2O2)+
     $(YH2O/DSO2H2))
          WRITE(49,*)'SLDEN=',SLDEN,'   DROPDI=',DROPDI,'  FORCE=',FORCE
          WRITE(49,*)'UMIX=',UMIX,'   FGDEN=',FGDEN,'   VINFIN=',VINFIN
          WRITE(49,*)'DH2OMX=',DH2OMX,'   PSAT=',PSAT,'   YH2OLM=',YH2OLM
          WRITE(49,*)'KGW=',KGW,'   NH2O=',NH2O,'   DSO2MX=',DSO2MX
          END
C
C
C
C
C
          SUBROUTINE DIS(WLANDA)
C
C
          DIMENSION WLANDA(99)
          REAL KS
          COMMON YN2,YCO2,YO2,YH2O,YSO2,PT,T,FGDEN,UMIX,DSO2N2,DSO2CO
     $,DSO2O2,DSO2H2,VINFIN,RET,SLDEN,DROPDI,KGW,NH2O,DSO2MX,CCA,XA
     $,AP,DOSO2,DOCA,KS,ASR,DOSO2R,RKS,BR,RKL,MN,ASTAR,APM,BS
          BS=CCA/74.1
          ASTAR=((XA/(1-XA))/18.02)*1000.
          APM=AP*100.
C   EVERYTHING IS CHANGED BACK TO CGS
          DOSO2R=DOSO2*10000.
          DOCR=DOCA*10000.
          RKS=KS*100.
          BR=BS/1000.
          ASR=ASTAR/1000.
          SIGMA=DOSO2R/RKL
C*********************************************************************
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```
      WRITE(52,*)'SIGMA/100=',SIGMA/100.
      WLANDA(1)=1.E-6
      ABA=BR*SQRT(DOCR*RKS*AP)
      SM=SQRT(RKS*AP/DOCR)
      MN=0
      DO 901 I=1,50
      XX=SM*(SIGMA-WLANDA(I))
      CSCH=2./(EXP(XX)-EXP(-XX))
      COTH=(EXP(XX)+EXP(-XX))/(EXP(XX)-EXP(-XX))
      F=-DOSO2R*ASR/WLANDA(I)+RKS*AP*BR*WLANDA(I)/2.+ABA*COTH
      DF=(DOSO2R*ASR)/(WLANDA(I)**2.)+RKS*AP*BR/2.+ABA*CSCH**2.
      WLANDA(I+1)=WLANDA(I)-F/DF
      DIFLAN=(WLANDA(I+1)-WLANDA(I))/WLANDA(I)
      MN=I+1
      IF(DIFLAN.LT.0.0) GO TO 901
      IF(WLANDA(I+1).LT.0.0)WLANDA(I+1)=-WLANDA(I+1)
      IF(DIFLAN.LT.1.E-5) GO TO 927
901   CONTINUE
CCCCC
      WRITE(51,*)'I IN THE DIS LOOP IS=',I
C 927 WRITE(51,*)'LANDA IN THE SUB=',WLANDA(MN)
C     WRITE(51,*)SIGMA,RKL,DOSO2R,ASR,BR,RKS,DOCR,SM,BS,ABA,AP
 927  END
```

RUN = 1 PAGE NO. = 53

OPERATING PRESSURE = .969 ATM
INLET SO2 CONCENTRATION= .19490E-02
MOLES OF SO2 PER SECOND = .0275
MOLES OF CA(OH)2 PER SECOND = .0443
STOICHIOMETRIC RATIO = 1.6147
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =153.15 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.184	SEC	0.859	SEC

CA++ DIFFUSION IN WATER = 0.27313E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.27087E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .83563E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .30822E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .17791E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.26320E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.23081E-04 M/SEC
SO2 MASS TRANSFER = 0.5017E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 50.3628 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY = 50.3630 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY = 65.6000 %

RUN = 2 PAGE NO. = 53

OPERATING PRESSURE = .987 ATM
INLET SO2 CONCENTRATION= .17230E-02
MOLES OF SO2 PER SECOND = .0251
MOLES OF CA(OH)2 PER SECOND = .0142
STOICHIOMETRIC RATIO = .5670
TEMPERATURE APPROACH TO SATURATION = 36.0DEG F
CRITICAL TEMPERATURE =156.21 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.107	SEC	0.332	SEC

CA++ DIFFUSION IN WATER = 0.25804E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25724E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .75244E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .46261E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18204E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.17212E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.11068E-03 M/SEC
SO2 MASS TRANSFER = 0.8928E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 36.0873 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY = 36.0874 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY = 44.9000 %

RUN = 3 PAGE NO. = 55

OPERATING PRESSURE = .987 ATM
INLET SO2 CONCENTRATION= .18310E-02
MOLES OF SO2 PER SECOND = .0262
MOLES OF CA(OH)2 PER SECOND = .0244
STOICHIOMETRIC RATIO = .9309
TEMPERATURE APPROACH TO SATURATION = 21.0DEG F
CRITICAL TEMPERATURE =141.00 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.073	SEC	0.654	SEC

CA++ DIFFUSION IN WATER = 0.25804E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25724E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .87822E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .42130E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18204E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.17212E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.69729E-04 M/SEC
SO2 MASS TRANSFER = 0.7663E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 65.3330 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	65.3330 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	73.5000 %

RUN = 4 PAGE NO. = 56

OPERATING PRESSURE = .964 ATM
INLET SO2 CONCENTRATION= .19230E-02
MOLES OF SO2 PER SECOND = .0267
MOLES OF CA(OH)2 PER SECOND = .0282
STOICHIOMETRIC RATIO = 1.0561
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =149.97 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.254	SEC	0.652	SEC

CA++ DIFFUSION IN WATER = 0.27313E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.27087E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .91462E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .39029E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .17791E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.18290E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.59639E-04 M/SEC
SO2 MASS TRANSFER = 0.7318E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 72.5755 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	72.5755 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	62.3000 %

RUN = 5 PAGE NO. = 57

OPERATING PRESSURE = .983 ATM
INLET SO2 CONCENTRATION= .19580E-02
MOLES OF SO2 PER SECOND = .0283
MOLES OF CA(OH)2 PER SECOND = .0443
STOICHIOMETRIC RATIO = 1.5626
TEMPERATURE APPROACH TO SATURATION = 22.0DEG F
CRITICAL TEMPERATURE =146.48 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.199	SEC	0.917	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .86818E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .31242E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.25501E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.41270E-04 M/SEC
SO2 MASS TRANSFER = 0.6074E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 58.5511 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	58.5512 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	74.2000 %

RUN = 6 PAGE NO. = 59

OPERATING PRESSURE = .983 ATM
INLET SO2 CONCENTRATION= .21840E-02
MOLES OF SO2 PER SECOND = .0314
MOLES OF CA(OH)2 PER SECOND = .0378
STOICHIOMETRIC RATIO = 1.2058
TEMPERATURE APPROACH TO SATURATION = 32.0DEG F
CRITICAL TEMPERATURE =157.39 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.660	SEC	0.634	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .86651E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .34711E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.25661E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.11154E-03 M/SEC
SO2 MASS TRANSFER = 0.9380E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 60.0038 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	60.0039 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	53.9000 %

RUN = 7 PAGE NO. = 60

OPERATING PRESSURE = .966 ATM
INLET SO2 CONCENTRATION= .19480E-02
MOLES OF SO2 PER SECOND = .0281
MOLES OF CA(OH)2 PER SECOND = .0153
STOICHIOMETRIC RATIO = .5424
TEMPERATURE APPROACH TO SATURATION = 20.5DEG F
CRITICAL TEMPERATURE =137.37 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.984	SEC	0.467	SEC

CA++ DIFFUSION IN WATER = 0.25953E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25860E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .84492E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .66510E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18162E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11540E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.16390E-04 M/SEC
SO2 MASS TRANSFER = 0.4664E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 57.9083 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	57.9083 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	54.2000 %

RUN = 8 PAGE NO. = 61

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .20120E-02
MOLES OF SO2 PER SECOND = .0291
MOLES OF CA(OH)2 PER SECOND = .0139
STOICHIOMETRIC RATIO = .4777
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =142.91 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.475	SEC	0.408	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .75775E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .75180E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11776E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.57761E-05 M/SEC
SO2 MASS TRANSFER = 0.4046E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 38.4450 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	38.4451 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	21.7000 %

RUN = 9 PAGE NO. = 62

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .18460E-02
MOLES OF SO2 PER SECOND = .0265
MOLES OF CA(OH)2 PER SECOND = .0114
STOICHIOMETRIC RATIO = .4299
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =152.96 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.814	SEC	0.270	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .71747E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .72842E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11776E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.25632E-05 M/SEC
SO2 MASS TRANSFER = 0.4004E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 29.0294 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	29.0294 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	29.4000 %

RUN = 10 PAGE NO. = 68

OPERATING PRESSURE = .979 ATM
INLET SO2 CONCENTRATION= .20140E-02
MOLES OF SO2 PER SECOND = .0288
MOLES OF CA(OH)2 PER SECOND = .0536
STOICHIOMETRIC RATIO = 1.8609
TEMPERATURE APPROACH TO SATURATION = 20.0DEG F
CRITICAL TEMPERATURE =142.06 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.594	SEC	1.090	SEC

CA++ DIFFUSION IN WATER = 0.25507E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25454E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .95321E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .24351E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18286E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.30872E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.54011E-04 M/SEC
SO2 MASS TRANSFER = 0.6947E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 75.0486 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	75.0487 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	73.1000 %

RUN = 11 PAGE NO. = 69

OPERATING PRESSURE = .979 ATM
INLET SO2 CONCENTRATION= .19030E-02
MOLES OF SO2 PER SECOND = .0271
MOLES OF CA(OH)2 PER SECOND = .0522
STOICHIOMETRIC RATIO = 1.9260
TEMPERATURE APPROACH TO SATURATION = 27.0DEG F
CRITICAL TEMPERATURE =150.97 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.276	SEC	0.939	SEC

CA++ DIFFUSION IN WATER = 0.25507E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25454E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .90541E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .23984E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18286E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.31195E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.47765E-04 M/SEC
SO2 MASS TRANSFER = 0.6454E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 64.8804 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY = 64.8805 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY = 67.2000 %

RUN = 12 PAGE NO. = 70

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .20400E-02
MOLES OF SO2 PER SECOND = .0297
MOLES OF CA(OH)2 PER SECOND = .0276
STOICHIOMETRIC RATIO = .9307
TEMPERATURE APPROACH TO SATURATION = 20.0DEG F
CRITICAL TEMPERATURE =140.42 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.388	SEC	0.730	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .86230E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .41327E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.19622E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.64144E-04 M/SEC
SO2 MASS TRANSFER = 0.7351E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 60.5111 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	60.5112 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	63.2000 %

RUN = 13 PAGE NO. = 71

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .19430E-02
MOLES OF SO2 PER SECOND = .0287
MOLES OF CA(OH)2 PER SECOND = .0129
STOICHIOMETRIC RATIO = .4477
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =140.91 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.337	SEC	0.398	SEC

CA++ DIFFUSION IN WATER = 0.25507E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25454E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .73512E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .73726E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18286E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11983E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.44145E-05 M/SEC
SO2 MASS TRANSFER = 0.4068E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 32.8587 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	32.8588 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	39.5000 %

RUN = 14 PAGE NO. = 72

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .20580E-02
MOLES OF SO2 PER SECOND = .0300
MOLES OF CA(OH)2 PER SECOND = .0124
STOICHIOMETRIC RATIO = .4142
TEMPERATURE APPROACH TO SATURATION = 20.0DEG F
CRITICAL TEMPERATURE =136.43 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.553	SEC	0.433	SEC

CA++ DIFFUSION IN WATER = 0.25804E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25724E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .72889E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .78000E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18204E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.12099E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.56881E-06 M/SEC
SO2 MASS TRANSFER = 0.3877E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 31.1786 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	31.1787 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	37.9000 %

RUN = 15 PAGE NO. = 73

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .19670E-02
MOLES OF SO2 PER SECOND = .0286
MOLES OF CA(OH)2 PER SECOND = .0255
STOICHIOMETRIC RATIO = .8898
TEMPERATURE APPROACH TO SATURATION = 27.0DEG F
CRITICAL TEMPERATURE =146.67 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.975	SEC	0.596	SEC

CA++ DIFFUSION IN WATER = 0.25507E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25454E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .83576E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .42493E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18286E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.18976E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.76042E-04 M/SEC
SO2 MASS TRANSFER = 0.7790E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 54.9875 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	54.9876 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	68.3000 %

RUN = 16 PAGE NO. = 76

OPERATING PRESSURE = .967 ATM
INLET SO2 CONCENTRATION= .20410E-02
MOLES OF SO2 PER SECOND = .0297
MOLES OF CA(OH)2 PER SECOND = .0075
STOICHIOMETRIC RATIO = .2531
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =151.87 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.730	SEC	0.260	SEC

CA++ DIFFUSION IN WATER = 0.25804E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25724E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .68380E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .83336E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18204E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11961E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.22266E-04 M/SEC
SO2 MASS TRANSFER = 0.5134E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 20.7038 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	20.7038 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	17.5000 %

RUN = 17 PAGE NO. = 77

OPERATING PRESSURE = .966 ATM
INLET SO2 CONCENTRATION= .19160E-02
MOLES OF SO2 PER SECOND = .0279
MOLES OF CA(OH)2 PER SECOND = .0312
STOICHIOMETRIC RATIO = 1.1182
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =162.21 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.224	SEC	0.558	SEC

CA++ DIFFUSION IN WATER = 0.26402E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.26267E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .82189E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .25194E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18039E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.32488E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.14668E-03 M/SEC
SO2 MASS TRANSFER = 0.1042E-01 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 47.5821 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	47.5821 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	57.0000 %

RUN = 20 PAGE NO. = 83

OPERATING PRESSURE = .964 ATM
INLET SO2 CONCENTRATION= .21180E-02
MOLES OF SO2 PER SECOND = .0302
MOLES OF CA(OH)2 PER SECOND = .0100
STOICHIOMETRIC RATIO = .3300
TEMPERATURE APPROACH TO SATURATION = 19.0DEG F
CRITICAL TEMPERATURE =137.05 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.293	SEC	0.355	SEC

CA++ DIFFUSION IN WATER = 0.26402E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.26267E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .73353E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .85239E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18039E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11224E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.90317E-05 M/SEC
SO2 MASS TRANSFER = 0.4403E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 33.7201 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	33.7202 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	29.3000 %

RUN = 19 PAGE NO. = 82

OPERATING PRESSURE = .965 ATM
INLET SO2 CONCENTRATION= .19610E-02
MOLES OF SO2 PER SECOND = .0279
MOLES OF CA(OH)2 PER SECOND = .0504
STOICHIOMETRIC RATIO = 1.8095
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =151.23 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.082	SEC	0.884	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .80485E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .33475E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.25238E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.10940E-04 M/SEC
SO2 MASS TRANSFER = 0.4076E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 42.7152 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	42.7154 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	69.6000 %

RUN = 18 PAGE NO. = 78

OPERATING PRESSURE = .966 ATM
INLET SO2 CONCENTRATION= .18430E-02
MOLES OF SO2 PER SECOND = .0268
MOLES OF CA(OH)2 PER SECOND = .0172
STOICHIOMETRIC RATIO = .6416
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =157.55 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.245	SEC	0.387	SEC

CA++ DIFFUSION IN WATER = 0.26402E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.26267E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .75880E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .42426E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18039E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.19579E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.10142E-03 M/SEC
SO2 MASS TRANSFER = 0.8621E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 36.6400 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	36.6401 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	32.2000 %

RUN = 21 PAGE NO. = 84

OPERATING PRESSURE = .966 ATM
INLET SO2 CONCENTRATION= .20010E-02
MOLES OF SO2 PER SECOND = .0286
MOLES OF CA(OH)2 PER SECOND = .0176
STOICHIOMETRIC RATIO = .6151
TEMPERATURE APPROACH TO SATURATION = 25.0DEG F
CRITICAL TEMPERATURE =145.39 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.818	SEC	0.488	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .79558E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .58002E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.14620E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.62159E-04 M/SEC
SO2 MASS TRANSFER = 0.7118E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 48.0017 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	48.0018 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	54.6000 %

RUN = 22 PAGE NO. = 85

OPERATING PRESSURE = .966 ATM
INLET SO2 CONCENTRATION= .19670E-02
MOLES OF SO2 PER SECOND = .0283
MOLES OF CA(OH)2 PER SECOND = .0230
STOICHIOMETRIC RATIO = .8124
TEMPERATURE APPROACH TO SATURATION = 20.0DEG F
CRITICAL TEMPERATURE =139.24 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
3.514	SEC	0.611	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .86900E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .52212E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.14620E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.39542E-04 M/SEC
SO2 MASS TRANSFER = 0.6083E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 63.4504 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	63.4505 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	54.8000 %

RUN = 23 PAGE NO. = 86

OPERATING PRESSURE = .964 ATM
INLET SO2 CONCENTRATION= .20870E-02
MOLES OF SO2 PER SECOND = .0296
MOLES OF CA(OH)2 PER SECOND = .0167
STOICHIOMETRIC RATIO = .5655
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =155.75 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.492	SEC	0.357	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .76357E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .62891E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.14620E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.70557E-04 M/SEC
SO2 MASS TRANSFER = 0.7385E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 40.4066 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	40.4067 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	42.8000 %

RUN = 24 PAGE NO. = 87

OPERATING PRESSURE = .964 ATM
INLET SO2 CONCENTRATION= .20120E-02
MOLES OF SO2 PER SECOND = .0289
MOLES OF CA(OH)2 PER SECOND = .0088
STOICHIOMETRIC RATIO = .3056
TEMPERATURE APPROACH TO SATURATION = 24.0DEG F
CRITICAL TEMPERATURE =142.74 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.903	SEC	0.328	SEC

CA++ DIFFUSION IN WATER = 0.26402E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.26267E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .72322E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .82135E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18039E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11224E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.17149E-04 M/SEC
SO2 MASS TRANSFER = 0.4918E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 31.6349 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	31.6350 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	32.7000 %

RUN = 25 PAGE NO. = 88

OPERATING PRESSURE = .965 ATM
INLET SO2 CONCENTRATION= .20520E-02
MOLES OF SO2 PER SECOND = .0294
MOLES OF CA(OH)2 PER SECOND = .0085
STOICHIOMETRIC RATIO = .2878
TEMPERATURE APPROACH TO SATURATION = 35.0DEG F
CRITICAL TEMPERATURE =152.96 DEG F

CONSTANT RATE PERIOD		FALLING RATE PERIOD	
2.479	SEC	0.225	SEC

CA++ DIFFUSION IN WATER = 0.26102E-08 M2/SEC
SO2 DIFFUSION IN WATER = 0.25995E-08 M2/SEC
SURFACE AREA OF SOLID PARTICLES= .70586E+06 M**2/M**3
INTERFACIAL CONCENTRATION OF SO2= .87112E-03KGMOLE/M**3
SATURATION SOLUBILITY OF SOLID= .18121E-01KGMOLE/M**3
HENRYS LAW CONSTANT = 0.11075E+08 ATM/MOLE FRAC
DISSOLUTION MASS TRANSFER COEFFICIENT = 0.24057E-04 M/SEC
SO2 MASS TRANSFER = 0.5260E-02 GM-MOLES/SEC.M2
SPRAY DRYER EFFICIENCY FOR CONSTANT RATE PERIOD = 27.4717 %

RESULTS

PREDICTED SPRAY DRYER EFFICIENCY	=	27.4717 %
EXPERIMENTAL SPRAY DRYER EFFICIENCY	=	28.7000 %

VITA

Mehdi Maibodi was born in Shiraz, Iran on September 5, 1959. He attended elementary schools in that city and was graduated from Razi High School in June 1977. The following October he entered the Pahlavi University, and in Winter 1979 he transferred to the Middle Tennessee State University and then to The University of Tennessee at Knoxville, and in August 1982 he received a Bachelor of Science degree in Chemical Engineering. In the fall of 1982 he began study toward a Master's degree in Chemical Engineering. He worked for nine months as a part-time and full-time main operator of the pilot plant for Flue Gas Disulfurization by spray drying at The University of Tennessee Steam Plant. He accepted part-time and full-time teaching assistantships at The University of Tennessee in the Fall of 1984.

The author is a member of AIChE. Mr. Maibodi will continue his education toward the Doctor of Philosophy degree at The University of Tennessee at Knoxville.