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MATHEMATICAL MODEL BASED ON FILM THEORY TO PREDICT THE ABSORPTION OF SULFUR DIOXIDE BY A CALCIUM HYDROXIDE SLURRY IN A SPRAY DRYER DURING THE FALLING RATE PERIOD

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Laura Waneta Lackey

May 1992

ACKNOWLEDGMENTS

During the course of this research and my graduate studies, I have become indebted to Dr. Robert M. Counce for his advice and constant encouragement. I also wish to thank Dr. Wayne T. Davis and Dr. J.J. Perona for their suggestions and for serving on my committee.

I especially want to express gratitude to my parents. They have continually provided encouragement and an opportunity for both their daughters to acquire a good education.

ABSTRACT

The purpose of this study was to expand on an existing mathematical model describing SO_2 absorption by a calcium hydroxide slurry in a spray dryer. The existing model provided a mechanistic approach to the mass and heat transfer occuring within the spray dryer. It also provided a rate equation based on film theory to predict SO_2 absorption during the constant rate period. Within the spray dryer, the constant rate period occurs when there is a continuous liquid phase in the atomized slurry droplet. The constant rate period continues until evaporation causes the diffusion paths to become restricted by the calcium hydroxide absorbent particles touching. At this point, the falling rate period begins and continues until evaporation causes an equilibrium moisture concentration to be reached. This study continues the modeling effort of the constant rate period by modeling the falling rate period. The model developed for the falling rate period is based on film theory and a series of resistances. The resistances are the gas film, liquid film, solid dissolution and the product ash film. The shrinking core model was used to describe the formation of dried product (ash film) during the falling rate period. An effective diffusivity parameter was regressed such that this model agreed with the experimental

data. This model fit the data very well, however, the regressed parameter was unrealistically high. The modelling activity was terminated at this point.

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NOMENCLATURE

A	=	SO_2
A_p	=	ratio of the total dispersed particle surface area to the volume of the dispersion, m^2/m^3
a_r	=	total surface area for lime particles in a droplet, cm^2
A_{s1}	=	particle specific surface area, m^2/gm
B	=	$Ca(OH)_2$
C_j	=	liquid-phase concentration of component j, $kgmol/m^3$
C_{ji}	=	liquid-phase concentration of component j at liquid-solid interface, $kgmole/m^3$
C_{js}	=	liquid-phase concentration of component j at liquid-solid interface, $kgmol/m^3$
C_s	=	saturation solubility of $Ca(OH)_2$, $gmoles/cm^3$
d_c	=	diameter of droplet core, m
d_d	=	diameter of droplet, m
d_p	=	diameter of $Ca(OH)_2$ particle, m
D_{jL}	=	liquid-phase diffusivity coefficient for component j, m^2/s
D_{jG}	=	gas-phase diffusivity coefficient for component j, m^2/s
D_e	=	gas-phase effective diffusivity coefficient SO_2, m^2/s
D_1	=	gas temperature at the critical drying point minus the droplet temperature at the critical drying point, K
D_2	=	gas temperature at spray dryer outlet minus droplet temperature at spray dryer outlet, K
D_T	=	logarithmic mean average of the difference in temperature between droplet and gas

Nomenclature, continued

E	=	model calculated efficiency assuming a continuous phase diffusivity, %
E_o	=	model calculated efficiency assuming the droplet is a slurry, %
G	=	gas molar flow rate, kgmol/s
g	=	gas
H_i	=	Henry's Law constant for component j, m^3atm/kgmol
i	=	interface
IPD	=	inter particle distance, m
k_{jG}	=	gas-phase mass-transfer coefficient, kgmol/m^2-s-atm
k_{jL}	=	liquid-phase mass-transfer coefficient, m/s
k_s	=	liquid-phase dissolution mass-transfer coefficient, m/s
K_1	=	constant utilized in Henry's Law calculation, mm Hg/mole fraction * 10^{-4}
L	=	liquid
L_t	=	latent heat of evaporation of water, cal/gm
l	=	thermal conductivity, cal/cm-sec-°C
M_s	=	molecular weight of sorbent
N_j	=	absorption flux of component j, kgmol/m^2-s
N_p	=	number of $Ca(OH)_2$ particles per drop
P	=	total pressure, atm
P_j	=	partial pressure of component j, atm
P_{ji}	=	partial pressure of component j at the gas-liquid interface, atm
P_{js}	=	partial pressure of component j at the gas-product ash interface, atm

Nomenclature, continued

P_v	=	product volume, m^3
r_i	=	absorption rate of component i, kgmol/s
R	=	universal gas constant
R_c	=	radius of droplet core, m
R_d	=	radius of droplet, m
R_p	=	radius of $Ca(OH)_2$ particle, m
Sh	=	Sherwood number, dimensionless
SGW_1	=	specific gravity of water, g/cm^3
SG_p	=	specific gravity product, g/cm^3
SG_s	=	specific gravity of $Ca(OH)_2$, g/cm^3
t	=	temperature, °C
T	=	temperature, K
V_p	=	ratio of volume of dispersion to surface area of dispersion, m^3/m^2
W	=	volume fraction of liquid
X	=	distance from the gas-liquid interface to the reaction plane, m
X_c	=	critical moisture content
X_e	=	equilibrium moisture content
X_g	=	gas-phase mass transfer film thickness, m
X_l	=	liquid-phase mass-transfer film thickness at the gas liquid interface, m
X_s	=	liquid-phase mass-transfer film thickness at the liquid-solid interface, m
Y_{gA}	=	mole fraction of SO_2 in the gas-phase
Y_{da}	=	mole fraction of SO_2 at the gas-liquid interface

Nomenclature, continued

Greek Letters

ρ_f	=	density of final dried droplet, g/cm^3
Φ	=	droplet production rate, s^{-1}
δ	=	film thickness
θ	=	volume fraction of solid in the slurry
γ	=	thermal conductivity, cal/cm-sec-°C

CHAPTER I

INTRODUCTION

Acid rain is the direct consequence of the atmosphere cleaning itself. When combustion occurs, sulfur dioxide, a fairly soluble gas, is emitted and then absorbed into the tiny, suspended droplets that make up clouds. Precipitation can then wash sulfur dioxide from the atmosphere in a form of sulfuric acid commonly known as acid rain (1). As regulations on air quality control tighten, it is becoming more important to clean combustion flue gas which contains sulfur dioxide. This cleaning process is commonly called flue gas desulfurization (FGD). For application to combustion of low-to-medium sulfur coals, a relatively new FGD process utilizes spray dryer technology combined with a fabric filter or an electrostatic precipitator. This process allows absorption of sulfur dioxide by a calcium hydroxide slurry which is subject to evaporation and, therefore, results in an essentially moisture free product. Hence, the system is commonly referred to as dry scrubbing.

Dry scrubbing combines heat and mass transfer with simultaneous chemical reaction. Damle(2), under a contract with the EPA, developed a computerized mathematical model called SPRAYMOD that simulates the spray dryer flue gas

desulfurization system. Damle considers the sulfur dioxide removal a two stage process corresponding to the wet and dry stages. During the wet stage, which consists of the constant and falling rate periods(3), SPRAYMOD neglects the liquid phase mass transfer resistance and focuses only on what he considered to be the dominant resistance. Pearson(4) developed another model based on film theory. The model uses a series of resistances and drying periods for the prediction of SO_2 removal in a spray dryer. To model the constant rate period, Partridge(5) incorporated Pearson's model based on film theory into the SPRAYMOD model. The new model, called UTSDM1, has a single relationship that includes all the individual resistances affecting the SO_2 absorption rate.

Dantuluri(6) studied the effects of lime slaking operations and its significance in spray dryer operated FGD systems using a $Ca(OH)_2$ slurry. It was found that the SO_2 absorption increased with a decrease in $Ca(OH)_2$ particle size.

The first objective of this study was to combine the work of Partridge and Dantuluri and compare efficiency predictions of the new model with pilot plant data. The model included a correction for the liquid phase diffusivity for slurries, in order to compensate for the presence of small reaction product solids in the atomized droplet. Finally, the falling rate period of Damle's wet stage was

expanded to include all individual resistances that affect the SO_2 absorption rate into a single relationship. The shrinking core model was used to describe the formation of dried product (ash film) during the falling rate period. An effective diffusivity parameter was regressed such that this model agreed with the experimental data. This model fit the data very well, however, the regressed parameter was unrealistically high. The modelling activity was terminated at this point.

CHAPTER II

LITERATURE REVIEW

A. Introduction.

During the past decade, dry scrubbing has become a common method for treating the flue gas of coal-fired utility boilers burning low-to-medium sulfur coals. This flue gas desulfurization (FGD) technology is usually utilized in a two-stage system combining the spray dryer with a fabric filter or an electrostatic precipitator. This FGD technology has been expanded beyond pilot plant test facilities and is now in successful operation in industry. As the SO_2 emission regulations are tightened, an understanding of this mass transfer phenomena and an effective means of modeling the system are becoming increasingly important.

Cannall (7) predicted a number of benefits for spray dryer FGD technology, which prompted its rapid acceptance over the more common system of wet scrubbing. Predicted benefits include lower capital and annual costs, less maintenance, less corrosion, the elimination or reduction of reheating, easily disposable waste products, and lower water consumption. While not all spray dryer FGD systems show all these advantages, the list is representative, making the spray dryer an attractive alternative to wet scrubbing.

In spray drying, flue gas is contacted with a solution, or slurry, of alkaline material. The solution, or slurry, is distributed by a rotary atomizer, a two-fluid nozzle or a rotary cup atomizer to mix the slurry intimately with the flue gas (8). Both the alkaline absorbent and flue gas typically enter the top of the cylindrical spray dryer. Both reactants then proceed cocurrently toward the conical-shaped dryer bottom. In a spray drying FGD system, the typical residence time is 7 - 20 seconds; the alkaline absorbent most commonly used is a slaked lime slurry (8). Two distinct processes occur in the spray dryer. The hot SO_2 absorbs and reacts with the $Ca(OH)_2$ present, thus forming sulfite and sulfate salt precipitates. Simultaneously, the flue gas is adiabatically humidified by the water evaporating from the finely dispersed droplets to within 10 - 20°C of the saturation temperature (8). The solid waste consisting of these salts, unreacted absorbent, and fly ash is generally dried to less than a few percent free moisture. The solid waste is collected in a fabric filter or electrostatic precipitator and is typically disposed of by landfill. Important design features include total system pressure drop and power consumption, type of atomizer, and type of slaker which affects the absorbent particle size present in the lime slurry. Important operational factors include the approach to saturation temperature in the spray dryer outlet, absorbent

stoichiometry, inlet SO_2 concentration, temperature drop across the spray dryer, and gas residence time (5).

When droplets formed by atomization contain insoluble solids, evaporation in the spray dryer is characterized by two stages; the constant and falling rate periods. The constant rate period begins as the droplets leave at high velocities from the atomizer wheel. The $Ca(OH)_2$-water droplet decelerates to velocities below 30 ft/sec in less than 0.1 seconds (9). Initially, each droplet is a $Ca(OH)_2$ slurry with interspacial distances equal to several particle diameters. During this period, evaporation rates are high. As evaporation continues in the constant rate period, particle diameter and interspacial distances shrink until approximately 75% of the water has evaporated and the solid particles touch. At this point, the droplet has reached its final diameter and the second drying period (the falling rate period) begins. During the falling rate period, drying continues by diffusion through a dried product crust which forms on the outer surface of the droplet. Evaporation continues in this phase until the equilibrium moisture content is reached. When this moisture content is reached, Downs (10) postulates a third drying period, which occurs in the baghouse or precipitator. He called this last drying phase the equilibrium period.

While evaporation occurs in the spray dryer, the absorption and reaction of SO_2 with $Ca(OH)_2$ droplets is

simultaneously taking place. This chemical reaction occurs in the liquid phase. The steps to the reaction are described by Getler (9) as:

1. Diffusion of SO_2 and CO_2 through the gas film boundary followed by absorption,

$$SO_2\ (g) \rightleftharpoons SO_2\ (l)$$

$$CO_2\ (g) \rightleftharpoons CO_2\ (l)$$

2. Dissolution of SO_2 and CO_2,

$$SO_2\ (l) + H_2O\ (l) \rightleftharpoons H_2SO_3\ (l)$$

$$CO_2\ (l) + H_2O\ (l) \rightleftharpoons H_2CO_3\ (l)$$

3. Dissociation in alkaline medium,

$$H_2SO_3H^+\ (l) + HSO_3^-(l) \rightleftharpoons 2H^+\ (l) + SO_2^=\ (l)$$

$$H_2SO_3H^+\ (l) + HCO_3^-\ (l) \rightleftharpoons 2H^+\ (l) + SO_3^=\ (l)$$

$$SO_2\ (l) + H_2O\ (l) + SO_3^=\ (L) \rightleftharpoons 2HSO_3^-\ (l)$$

$$SO_2\ (l) + HCO_3^-\ (l) \rightleftharpoons HSO_3^-\ (l) + CO_2\ (l)$$

$$2SO_2\ (l) + H_2O\ (l) + CO_3^=\ (l) \rightleftharpoons 2HSO_3^-\ (l) + CO_2(l)$$

4. Dissolution of solids,

$$Ca^{++}\ (l) + SO_3^=\ (l) + \frac{1}{2}\ H_2O\ (l) \rightleftharpoons 2HSO_3^-\ (l) + CO_2\ (l)$$

5. Formation of salts,

$$Ca^{++}\ (l) + SO_3^=\ (l) + \frac{1}{2}\ H_2O\ (l) \rightleftharpoons CaSO_3.\frac{1}{2}\ H_2O\ (s)$$

$$Ca^{++} + CO_3^=\ (l) \rightleftharpoons CaCO_3\ (s)$$

Although solid $CaCO_3$ is a product, very little is formed while operating without recycle. Only small amounts are formed because freshly precipitated $CaCO_3$ has a large surface area and a high dissolution rate. Ca^{++} ions tend to precipitate with sulfite to $CaSO_3 \cdot 1/2H_2O$ and $CaSO_4$ leaving little $CaCO_3$ as product (9).

Downs (10) has also studied the ionic reaction between SO_2 and $Ca(OH)_2$. He describes the reaction during the first two drying periods to be comparable to the reaction path in wet lime scrubbing. The reaction is visualized as follows:

Absorption:

$$SO_2\ (g) \rightarrow SO_2\ (l)$$

Dissolution:

$$Ca(OH)_2\ (s) \rightarrow Ca^{++}\ (l) + 2OH^-\ (l)$$

Primary SO_2 reaction:

$$SO_2\ (l) + H_2O\ (l) \rightarrow HSO_3^-\ (l) + H^+\ (l)$$

$$SO_2\ (aq) + OH^-\ (l) \rightarrow HSO_3^-\ (l)$$

Neutralization:

$$OH^-\ (l) + H^+\ (l) \rightarrow H_2O\ (l)$$

$$HSO_3^-\ (l) + OH^-\ (l) \rightarrow SO_3^=\ (l) + H_2O\ (l)$$

Precipitation:

$$Ca^{++}\ (l) + SO_3^=\ (l) \rightarrow CaSO_3 \cdot \frac{1}{2} H_2O\ (s)$$

It is not clear whether there is enough moisture during the third drying period for this sequence of reactions to hold.

The series of reactions shown above describing the absorption process of SO_2 into a $Ca(OH)_2$ slurry and the liquid phase reaction of the dissolved SO_2 with dissolved $Ca(OH)_2$ can be simply represented by the following:

$$SO_2\ (g) \rightarrow SO_2\ (l)$$

$$SO_2\ (l) + Ca(OH)_2\ (l) \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O\ (l) + \tfrac{1}{2}\ H_2O\ (l)$$

B. Models of SO_2 Absorption Within Spray Dryers.

The removal of SO_2 in spray dryer absorbers has been studied in pilot plants as well as commercial facilities. Cotrell Environmental Sciences, Inc., during 1980 - 1981 (11), conducted a pilot-scale testing program for low-to-moderate sulfur coals. An empirical mathematical equation was developed to predict SO_2 removal across a spray dryer. The equation contains the variables: stoichiometric ratio (moles $Ca(OH)_2$/moles SO_2 inlet gas), temperature drop across the spray dryer, and the approach to adiabatic saturation temperature. Northern States Power Company (12) has also developed an empirical correlation which predicts SO_2 removal. The correlation uses multiple linear regression to compare SO_2 removal efficiency with $Ca(OH)_2$ stoichiometric ratio, ash alkalinity content, and approach

to saturation temperature. These empirical mathematical models were recently reviewed by Partridge (5).

In contrast with the empirical mathematical models describing the SO_2 removal process using spray dryer absorption technology, work has been done to develop a theoretical model which represents the spray dryer system. Models have been developed by Pearson (4) and Damle (2). The models of Pearson and Damle were further developed by Partridge (5).

The model by Pearson (4) is based on film theory. The model uses a series of resistances and drying periods to predict SO_2 removal in a spray dryer absorber. The resistances considered are: (1) gas film, (2) liquid film, (3) solid dissolution, and (4) ash film. The drying periods are: (1) constant rate and (2) falling rate. Figure 2.1 illustrates the resistance series used to model the falling rate period.

The rate equation Pearson uses during the constant rate period was developed by Ramachandran and Sharma (13). The equation is valid provided that solid dissolution in the liquid film is unimportant. The resulting flux equation for the constant rate period is:

$$N_A = \frac{\frac{P_A}{H_A} + \frac{D_{BL}}{D_{AL}} C_s}{\frac{1}{k_{AG}} H_A + \frac{1}{k_{AL}} + \frac{D_{BL}}{D_{AL} k_s A_p V_p}} \qquad (2.1)$$

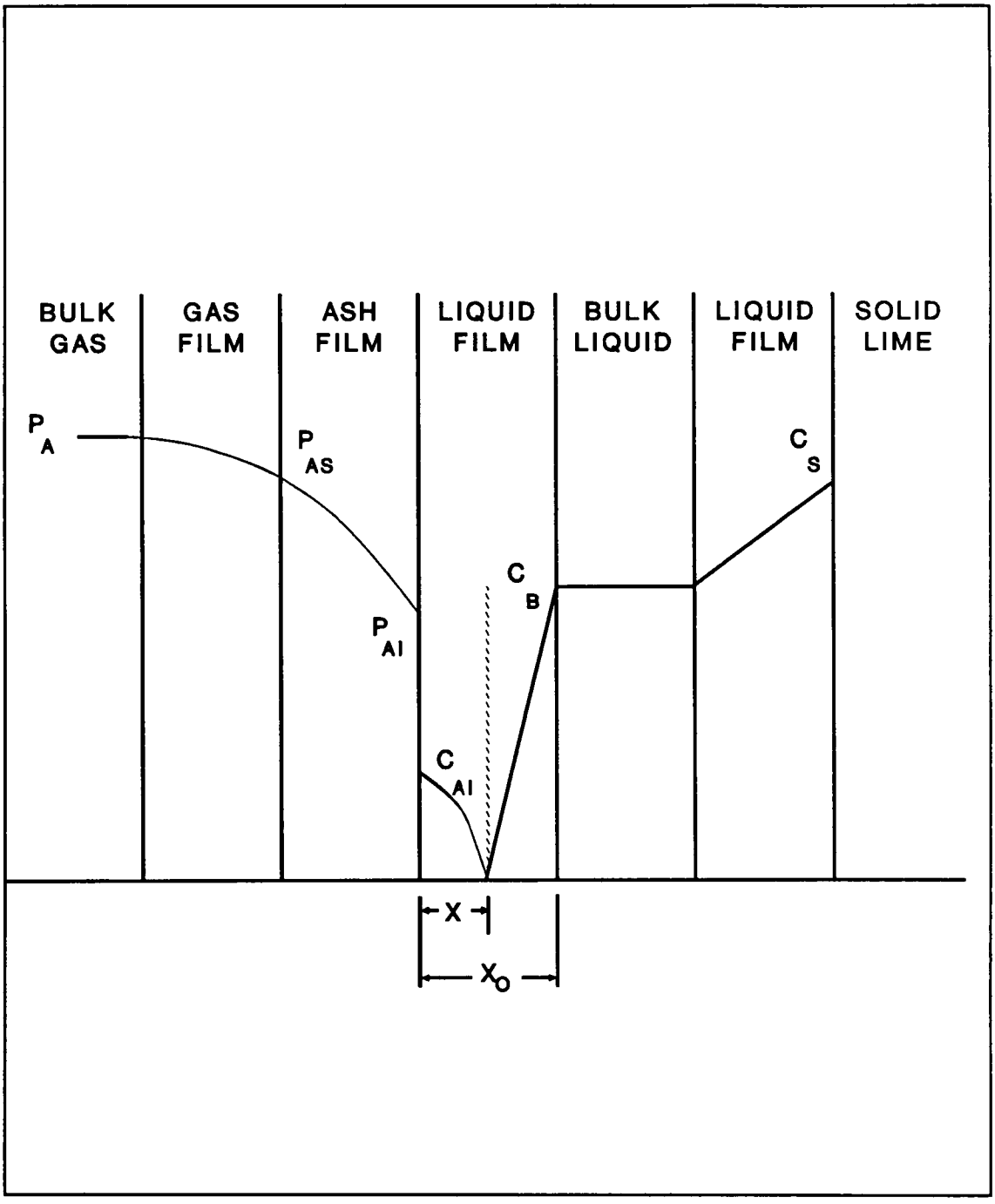

Figure 2.1 Pearson's model for the falling rate period (4)

The test condition for determining when solid dissolution in the liquid is unimportant is as follows:

$$\frac{k_s A_p D_{AL}^2}{4 k_{AL}^2 D_{BL}} \ll 1 \qquad (2.2)$$

Pearson postulates that the drop containing both unused $Ca(OH)_2$ and product $CaSO_3 \cdot 1/2H_2O$ breaks into smaller drops at the beginning of the falling rate period, and forms an ash layer and a liquid core. The ash layer adds a new resistance to SO_2 absorption. Pearson's equation for the falling rate period is as follows:

$$N_A = \frac{\frac{P_A}{H_A} + \frac{D_{BL} C_S}{D_{AL}}}{\frac{R_c^2}{H_A k_{AG} R_p^2} + \frac{1}{k_{AL}} + \frac{R_c (R_p - R_c) (RT)}{H_A D_E R_p} + \frac{D_{BL}}{D_{AL} k_s A_p V_p}} \qquad (2.3)$$

Equations (2.1) and (2.3) require the calculation of several different mass transfer coefficients. The mass transfer coefficients are calculated using the following scheme. At the relative velocity of the droplets in the spray dryer, the Sherwood number (d_d/δ_g) is approximately 2 (3). This gives

$$\delta_g = \frac{d_d}{2} \qquad (2.4)$$

$$k_{AG} = \frac{D_{AG}}{\delta_g RT} = \frac{2D_{AG}}{d_d RT} \qquad (2.5)$$

Applying film theory, the liquid phase mass transfer coefficient is calculated by using the equation

$$k_{AL} = \frac{D_{AL}}{\delta_L} \qquad (2.6)$$

In order to calculate the liquid phase mass transfer coefficient, the liquid film thickness must be determined. For this model, it is assumed that the absorbent particles within the liquid phase are uniformly spaced within the slurry droplet. This geometry of the slurry system was used to set the upper bound for the liquid film thickness. Within the slurry droplet system, the liquid phase is equally distributed around the particles. Therefore, the thickness of the liquid film can not surpass one-half of the interparticle distance. The expression for film thickness is as follows:

$$\delta_l < \frac{1}{2\,IPD} = 0.5 d_p \frac{1}{(1 - W)^{1/3}} - 1 \qquad (2.7)$$

Another boundary condition for the thickness of the liquid film is given by Al-Aswad (14). As the slurry concentration decreases, the film thickness based on 1/2 IPD increases because the volume fraction of moisture increases. As the

slurry concentration decreases and δ_L can be represented as that of a pure liquid stagnant drop, the other upper boundary for the film thickness is observed. The following equation by Al-Aswad (14) describes this situation.

$$k_{AL} = \frac{4\pi^2 D_{AL}}{3 d_d} \tag{2.8}$$

Combining equations (2.4) and (2.6) gives the boundary condition for the film thickness in the case of a pure liquid stagnant drop and is as follows:

$$\delta_L = 0.076 d_d \tag{2.9}$$

The Sherwood number is also considered to be 2 within the stagnant droplet when calculating the dissolution film thickness, thus giving:

$$\delta_s = \frac{d_p}{Sh} = \frac{d_p}{2} \tag{2.10}$$

The dissolution film thickness is also under the constraint that the film thickness cannot be greater than one-half the interparticle distance. Therefore, the dissolution mass-transfer coefficient is then calculated by:

$$k_s = \frac{D_{BL}}{\delta_s} \tag{2.11}$$

Within equations (2.1) and (2.3), two liquid phase diffusivity calculations are needed. The liquid phase diffusivities for SO_2 (D_{AL}) and $Ca(OH)_2$ (D_{BL}) are required. These diffusivities are calculated using the procedure developed by Pearson (4). Pearson used the following five step procedure to calculate the above mentioned diffusivities.

1. Values for the liquid phase diffusivities were given by Sada (15).
2. Temperatures for these values were determined by comparison with values for diffusivities given by Perry (16).
3. The Wilke-Chang estimate indicates that the diffusivity is directly proportional to the liquid absolute temperature and inversely proportional to the liquid viscosity (16).
4. An expression for water viscosity as a function of temperature is given by Weast (17).
5. The expression for water viscosity was combined with the values of diffusivities of SO_2 and $Ca(OH)_2$ in water.

The equations developed are as follows:

$$D_{AL} = \frac{5.174 \times 10^{-8} (t+273)}{1.002 \times 10^{2}} \qquad (2.12)$$

$$D_{BL} = \frac{5.472 \times 10^{-8} (t+273)}{1.002 \times 10^{Z}} \qquad (2.13)$$

$$Z = \frac{1.3272(20-t) - 0.001053(t-20)^2}{(t+5)} \qquad (2.14)$$

Several other equations are used to predict physical properties (P_A,C_s,H_A) used in equations (2.1) and (2.3). P_A, the partial pressure of SO_2 is given by the following equation:

$$P_A = CY_{g,s} \qquad (2.15)$$

where the molar density of the gas phase is given by Damle (2) as

$$C = \frac{1.2194 \times 10^{-2}}{T} \qquad (2.16)$$

Damle (2) expresses the saturation solubility of $Ca(OH)_2$ in grams/cm^3, C_s, as the following:

$$C_s = \frac{1.88 \times 10^{-3} - 1.174 \times 10^{-5} (T - 273.15)}{M_s} \qquad (2.17)$$

The value of Henry's Law Constant (H_A = (gmole/cm^3 in gas phase)/(gmole/cm^3 in liquid phase)) uses an expression appropriate for the temperature being modeled. The expressions were developed from data given by Loomis (18)

for SO_2 absorption in water and water density data by Weast (17). For the various temperature ranges, the equations used to calculate Henry's Law Constants are as follows:

$$K_1 = 0.13846(t) - 0.55 \qquad (2.18)$$

when $30 < t < 45$,

$$K_1 = 0.18376(t) - 2.6176 \qquad (2.19)$$

when $45 < t < 65$,

$$K_1 = 0.2211(t) - 5.4922 \qquad (2.20)$$

when $65 < t < 90$.

The densities of water at various temperatures in g/ml are given by the following equations:

$$\rho = 1.006615 - 0.0003616(t) \qquad (2.21)$$

when $30 < t < 45$,

$$\rho = 1.012141 - 0.000483(t) \qquad (2.22)$$

when $45 < t < 65$,

$$\rho = 1.0204777 - 0.0006102(t) \qquad (2.23)$$

when $65 < t < 90$.

The value for the Henry's Law constant can now be determined using the following equation:

$$H_A = \frac{2.88745 \times 10^{-4} (K_1 - 760)}{T} \qquad (2.24)$$

During the falling rate period, Pearson observed effective diffusivities ranging from 0.13×10^{-6} to 0.60×10^{-6} m^2/s. Others have also found the effective diffusivity of SO_2 through a nonporous layer of $CaSO_4$. A range of values has been obtained by adjusting the diffusivity in a pore or grain model until predictions fit experimental data. Table 2.1 obtained from Marsh (19) lists effective diffusivities found. The equilibrium moisture period which characterizes the dried product in the filter system is not discussed by Pearson.

Damle (2) developed the model SPRAYMOD while working with the Research Triangle Institute under contract by the EPA. SPRAYMOD combines a heat and mass transfer balance which predicts simultaneous absorption of SO_2 with $Ca(OH)_2$ in the evaporating droplet. The SO_2 removal is considered to occur during two periods corresponding to the wet and dry stages. During the wet stage, which includes both the constant and falling rate periods, moisture plays an important role providing an aqueous medium for the fast ionic reaction of SO_2. Figure 2.2 illustrates the resistances considered by Damle during the wet stage.

TABLE 2.1

Effective Diffusivity Estimates

Investigator	Source of Data	Model	Temp(C)	D_E(cm^2/s)
Bhatia and Perlmutter(20)	Borgwardt (21)	pore	650	1.3×10^{-8}
			760	6.0×10^{-8}
			870	19×10^{-8}
			980	69×10^{-8}
	Hartman and Coughlin(22)		850	0.86×10^{-8}
Hartman and Caughlin(22)	own data	grain	850	0.6×10^{-8}
Christman and Edgar(23)	own data	pore	650	3.8×10^{-8}
			800	24×10^{-8}
Georgakis et al. (24)	Hartman and Coughlin(22)	pore	850	$(300-1000) \times 10^{-8}$
		grain	850	0.8×10^{-8}
	Borgwardt(21)	grain	980	200×10^{-8}

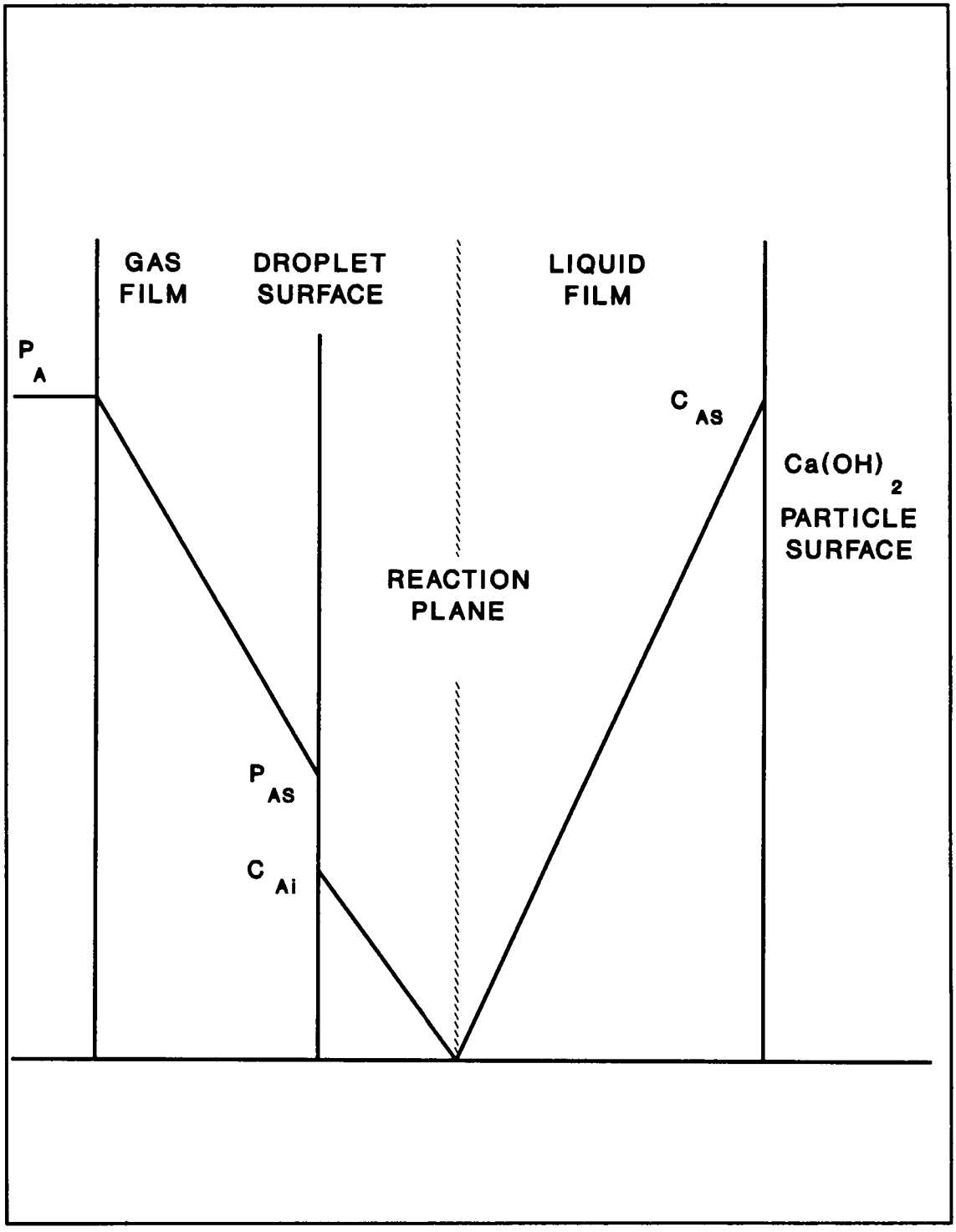

Figure 2.2 Damle's model of SO_2 absorption/reaction during the wet stage (2)

For simplicity, Damle assumes that as evaporation occurs during the wet stage and the water phase becomes discontinuous during the falling rate period, there is still enough water available within the particle for the SO_2 absorption process to occur. Damle's model assumes the controlling mechanisms of SO_2 removal will be determined by the relative values of the gas-phase mass transfer resistance and by the $Ca(OH)_2$ dissolution rate.

The maximum rate of diffusion of SO_2 in the gas phase is given by:

$$R_A = k_o \pi d_d^2 CY_{g,s} \qquad (2.25)$$

and accounting for all lime particles in a droplet, the rate of lime dissolution is:

$$R_d = R_p * \frac{\text{number of particles}}{\text{droplet}} \qquad (2.26)$$

In the model, if $R_A > R_d$ then SO_2 removal rate will be controlled by lime dissolution rate. But, if $R_d > R_A$, then gas phase mass transfer of SO_2 is the controlling resistance. Other steps are involved in this SO_2 removal process but are not considered to be rate controlling mechanisms. Such steps include the very fast ionic reaction between dissolved SO_2 and dissolved lime in the liquid phase, and liquid phase mass transfer rate. A simple

approach used for the dry particle stage uses a bulk-volume reactivity (K_r) coefficient. K_r depends on moisture content of the droplet/particle, primary lime particle size, and the diffusivity of SO_2 in the solid material. The rate of SO_2 removal by a single droplet is given by:

$$r_A = K_r \, (\pi d_d^3 / 6) C_{A,g} \, C_{\text{remaining lime}} \qquad (2.27)$$

Partridge (5) continued the work of Damle (2) and Pearson's (4) FGD model. The work done by Partridge concentrated on the constant rate period which is the first portion of Damle's wet stage. The model is based on film theory for an instantaneous liquid reaction where solid $Ca(OH)_2$ and gaseous SO_2 dissolve in the liquid phase and react. The model developed combined a series of individual resistances to form a single rate equation. The combined resistances include the resistance for gas-phase mass transfer, liquid-phase mass transfer and absorbent dissolution. These resistances are illustrated in Figure 2.3. The resulting rate equation was the same developed by Ramachandran and Sharma (13) and Pearson (4). This equation was incorporated into a system of energy and mass balances originally developed by Damle.

Included in Partridge's model are three check points. The check points determine if:

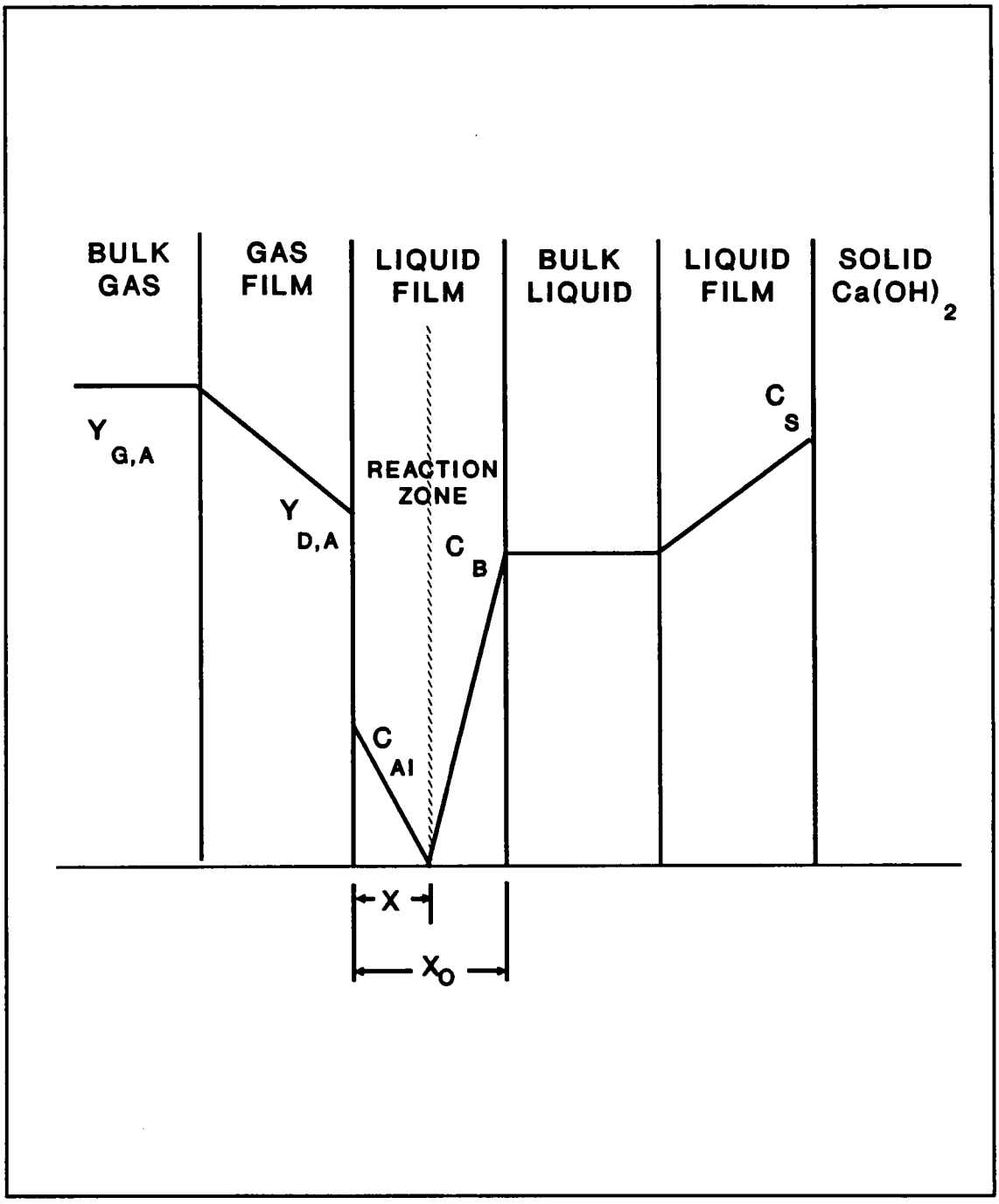

Figure 2.3 The Partridge model for the constant rate period (3)

1. solid dissolution in the liquid film is unimportant and therefore the model is valid;
2. the gas film resistance controls the SO_2 absorption flux;
3. the rate of lime dissolution controls the SO_2 absorption flux.

The equation for the first check which accounts for the condition when solid dissolution in the film is negligible is as follows:

$$\frac{3 d_d N_p D_{AL}^2}{2 \pi d_d^3 k_{AL}^2} < 1.0 \qquad (2.28)$$

The second and third check points are limiting conditions for the combined individual resistance rate equation. If the SO_2 absorption rate is less when predicted by the gas phase resistance equation alone than predicted by the combined resistance rate equation, the system is said to be gas phase controlling. In this case, SO_2 absorption rate is calculated as follows:

$$-r_{A2} = \pi d_d^2 k_G N_p C_s \qquad (2.29)$$

When C_B, the $Ca(OH)_2$ concentration in the liquid phase becomes zero, the absorption rate becomes controlled by the

$Ca(OH)_2$ dissolution rate and is given by the following equation:

$$-r_{A3} = \pi d_p^2 k_s N_p C_s \qquad (2.30)$$

Dantuluri (6) studied the effects of slaking operations and its significance in spray dryer operated FGD systems using a lime slurry. It was found that SO_2 absorption increased with a decrease in absorbent particle size. A linear relationship was seen between efficiency and inverse particle diameter. The efficiency reaches a maximum when absorbent particle size is such that the diffusion of SO_2 in the gas phase is the controlling resistance (6).

CHAPTER III

EXPERIMENTAL PROCEDURE

The source of data used in this activity is from Partridge (5). A pilot plant was constructed on a slip stream of the University of Tennessee's stoker-fired boilers. Figure 3.1 shows a schematic diagram of the pilot plant. The experimental facility consisted of an instrument operating room, a slaking system control room, and a 7 foot diameter spray dryer chamber with a variable speed Stork-Bowen AA-6 spray machine (5,000 - 21,000 rpm). The lime slurry was atomized by a 6 in. diameter centrifugal atomizer with six nozzle inserts. A 36-bag pulse jet collector with 4.5 x 12 feet fiberglass filter bags were used for particulate control. A continuous partial recycle system was available but not used which could recycle dried products from the spray dryer and baghouse.

Individual tests consisted of monitoring 18 different parameters. At ports 1 - 3, sulfur dioxide concentration, temperature, static pressure and wet bulb temperature data were all collected. Parameters also reported were the atomizer disk speed, available CaO (by HCl titration), orifice pressure drop for flow rate, lime slurry flow rate, barometric pressure, and ambient temperature.

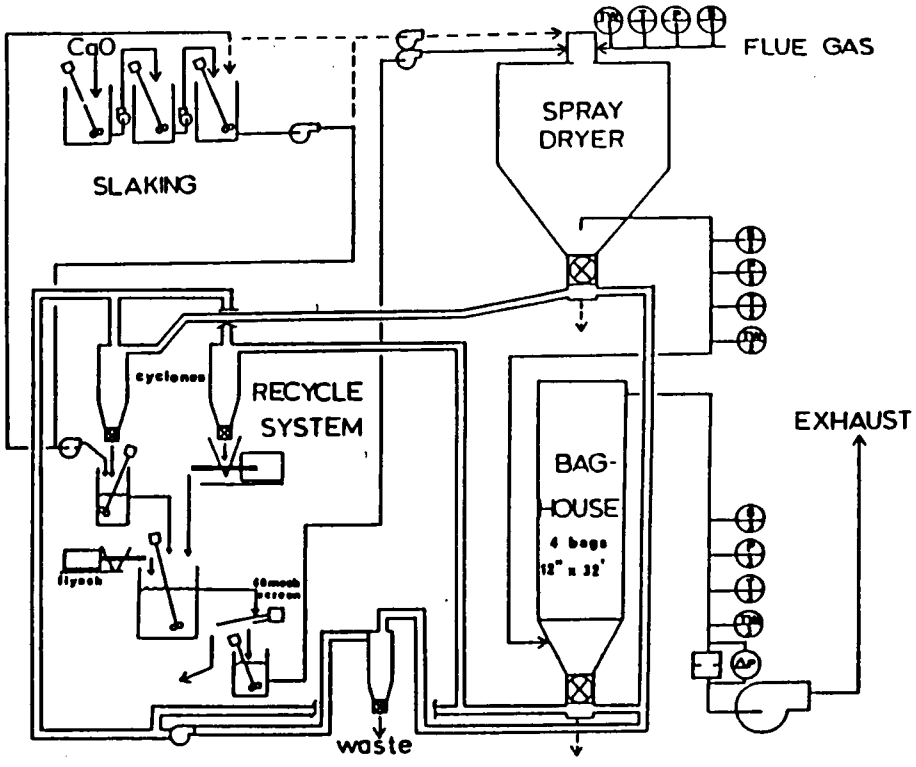

Figure 3.1 Schematic diagram of the pilot spray dryer/baghouse facility (5)

CHAPTER IV

MODEL DEVELOPMENT

A. Constant Rate Period.

Partridge (5) developed a model for the constant rate period that was based on film theory. His model combined a series of individual rate equations to form a single expression. This expression was then used in conjunction with a mechanistic approach used to model the mass and heat transfer within a spray dryer. The resulting mathematical model (UTSDM1) represented the simultaneous absorption of sulfur dioxide by a calcium hydroxide slurry and water evaporation from the droplets. The overall mass balance assumed the following:

$$\frac{d(MOLE_A)}{dt} = \frac{d(MOLE_B)}{dt} \qquad \text{(per droplet)} \qquad (4.1)$$

$$\frac{-d(MOLE_A)}{dt} = -r_A \qquad \text{(per droplet)} \qquad (4.2)$$

$$-G\,\frac{dY_A}{dt} = \frac{-d(MOLE_B)}{dt}\,\phi = -r_A\,\phi \qquad (4.3)$$

$$-G \frac{dY_A}{dt} = \phi(-r_A) \tag{4.4}$$

$$-G\, dY_A = \phi\, (-r_A\ dt) \tag{4.5}$$

$$\int_{Y_1}^{Y_2} dY_A = -\frac{\phi}{G} \int_0^{\tau} (-r_A\, dt) \tag{4.6}$$

$$\int_{Y_1}^{Y_2} \frac{dY_A}{-r_A} = \frac{\phi}{G} \int_0^{\tau} dt \tag{4.7}$$

In developing UTSDM1 for the constant rate period, Partridge recognized the following assumptions:

1. The carbon dioxide present is treated as an inert gas. Therefore, the absorption of sulfur dioxide is the reaction of concern.
2. The reaction of SO_2 and $Ca(OH)_2$ occurs in the liquid phase and is instantaneous.
3. Solid dissolution and reaction occur in series.
4. Two rates control the migration of reactant species toward the reaction plane: the dissolution of elementary $Ca(OH)_2$ particles and the diffusion of reactants.
5. Slurry droplets are spherical and symmetric.
6. The $Ca(OH)_2$ particles are spaced uniformly in the liquid phase of the slurry droplet.

Equation 2.1 represents the rate of SO_2 removal during the constant rate period. The efficiency ratios (model/data) of UTSDM1 ranged from 0.78 to 1.02. This range showed a 22% maximum underprediction versus a 2% maximum overprediction (5). The range showed that the model typically underpredicts actual experimental SO_2 removal. This underprediction is expected because only the constant rate period is being modeled. At the end of the constant rate period there was still 44.6 percent by volume moisture remaining in the droplet (5). The fact that a significant amount of moisture remained implied that additional SO_2 absorption occurred during the falling rate period.

The presence of small reaction product solids during the constant rate period was a matter of concern. Due to product formation and evaporation during the constant rate period, the continuous phase of the slurry droplet decreased as the residence time increased. The change in the droplet's continuous phase causes a reduction of the liquid phase diffusivity within the slurry droplet. Hiklta (25) developed the equation describing the diffusivity:

$$\frac{D}{D_o} = 1 - \theta \qquad (4.8)$$

Notice from equation 4.8 that as the volume fraction of solids in the slurry increased, the liquid diffusivity for the slurry decreased.

Equation (4.8) can be used to calculate the volume fraction of solid in the slurry. For this calculation, either the average diameter of the $Ca(OH)_2$ particles in the droplets is assumed to be considerably greater than the thickness of the liquid film, or the concentration of solids is assumed to be relatively small. When $d_p > \delta_L$, the $Ca(OH)_2$ reactant particles in the droplet do not significantly affect the diffusivity of SO_2 in the slurry as does the fine product $CaSO_4 \cdot 2H_2O$. Therefore, the volume fraction of solid in the slurry only depends on moisture content and product formation in the droplet.

In UTSDM1, the following equation was used to calculate the $Ca(OH)_2$ dissolution rate.

$$r_A = \frac{D_{BL}}{\delta_s} (\pi d_d^2) (C_S - C_B) \qquad (4.9)$$

In using this equation, Partridge (5) made the assumption that the primary $Ca(OH)_2$ particle is spherical. The sphere has a surface area equal to πd_p^2, which offers the smallest surface area per volume of any shape. So, if the $Ca(OH)_2$ particle is considered to be spherical, the $Ca(OH)_2$ dissolution rate is likely to be underestimated (6). As a result, when the $Ca(OH)_2$ dissolution rate is compared with rates based on other resistances or when based on the combined resistance equation, the model often incorrectly predicts $Ca(OH)_2$ dissolution to be controlling. A better

estimate of the $Ca(OH)_2$ dissolution rate is obtained by measuring the surface areas of $Ca(OH)_2$ particles because they do not possess spherical geometry.

Dantuluri (6) studied the importance of lime slaking on the spray dryer FGD system. He was able to characterized absorbent particle size and surface area as a result of using different slaking techniques. Using x-ray defraction and SEM techniques to inspect the calcium hydroxide slurry, Dantuluri developed an empirical correlation between particle diameter and specific surface area; refer to Table 4.1. Dantuluri's empirical correlation is as follows:

$$A_{s1} = -6.4825 + 103.9471 * \frac{1}{d_p} \qquad (4.10)$$

The resulting expression for the combined individual resistance rate equation is derived in much the same way as equation (2.1). The derived equation (4.11) incorporates the idea that the measured surface area of the absorbent will control $Ca(OH)_2$ dissolution rather than incorporating the assumption that the particle has a spherical geometry. The only difference in the derivation of equation 4.11 was the incorporation of the measured absorbent surface area.

TABLE 4.1

Average Particle Diameter and Corresponding Measured Surface Area Values

d_p (microns)	Surface Area (m^2/gm)
2.29	37.1
2.7	32.17
3.4	22.65
4.1	19.83

The resulting flux equation is shown by the following equation:

$$N_A = \frac{\frac{X_{g,A}}{H_A} + \frac{D_{BL}}{D_{AL}} C_s}{\frac{1}{k_{AL}} + \frac{1}{k_{Ag} H_A} + \frac{\pi d_d^2 D_{BL}}{a_r D_{AL} k_s}} \qquad (4.11)$$

A new model (MODEL A) was developed that incorporated the two new ideas: 1. corrected diffusivity (due to product formation) and 2. correction for available calcium hydroxide surface area. Within this model, the surface area decreases proportionally to a decrease in particle diameter.

B. Falling Rate Period.

The falling rate period begins when a sufficient amount of water has evaporated such that the reaction product and remaining $Ca(OH)_2$ particles touch. In order to develop a model for the falling rate period, a conceptual model must be chosen that represents the progress of reaction. The model must closely represent reality, and the mathematics involved must remain simple enough for practical modeling use (26). The model chosen was the unreacted shrinking-core model, which describes noncatalytic heterogeneous gas-solid kinetics (27). Although each system does not require all the following steps to exist, this model is best visualized by the following five steps:

1. Diffusion of the gaseous reactant through the film surrounding the droplet to the solid surface of the droplet.
2. Penetration and diffusion of gaseous reactant through the product to the surface of the unreacted core.
3. Reaction of gas at this reaction surface.
4. Diffusion of gaseous products through the solid products to the exterior surface of the solid.
5. Diffusion of gaseous products back to the main body of fluid.

This model has been widely accepted as a basis for studying many noncatalytic gas-solid reaction systems, including the absorption of SO_2 by various solid particles (28).

When attempting to use the shrinking-core model in a computer simulation, one must keep in mind the following limitations (13):

1. When chemical reaction rate is very fast compared to diffusion rate, the model describes the situation satisfactorily. In this instance, the reaction plane is assumed to be narrowly confined to the interface between the product layer and $Ca(OH)_2$ slurry. All reactant concentrations are zero at this front.
2. When geometrical instability occurs, the mathematical model describing the system becomes, at best, an approximation. If instability occurs, the reaction interface is no longer smooth. In this modeling effort, a constant spherical droplet is assumed.
3. The shrinking-core model will not be applicable if particles undergo cracking, ablation, or peeling-off during the course of reaction. These conditions may be the result of a change in density or in volume of the solids present. In this case, the particles are not expected to crack, ablate, or peel.

4. The loss of $Ca(OH)_2$, due to entrapment into the solid product matrix, is negligible.

The model's absorption process is shown in Figure 2.1. Sulfur dioxide must diffuse through the bulk gas film. For the gas film, Levenspiel (26) gives the rate of diffusion by:

$$-r_A = \pi d_d^2 \, k_{AG} \, (P_{AG} - P_{AS}) \tag{4.12}$$

The absorption of SO_2 is accompanied by its simultaneous reaction with dissolved $Ca(OH)_2$. Levenspiel (26) describes this diffusional rate by:

$$-r_A = \pi d_c^2 \, k_{AL} \, (C_{Ai} - 0) \, \frac{X_0}{X} \tag{4.13}$$

The migration of $Ca(OH)_2$ to the reaction plane is also a diffusional process. $Ca(OH)_2$ dissolves into a liquid bulk region and then diffuses through the liquid film until it reaches the reaction plane. The equations describing this process are given by Ramachandran and Sharma (13) and Levenspiel (26) and are as follows:

$$-r_A = \pi d_d^2 \, k_{BL} \, (C_B - 0) \, \frac{X_0}{(X_0 - X)} \tag{4.14}$$

$$-r_A = k_s \, (a_r) \, (C_s - C_B) \tag{4.15}$$

$$P_{Ai} = H_A C_{Ai} \tag{4.16}$$

$$\frac{k_{AL}}{k_{BL}} = \frac{\frac{D_{AL}}{X_0}}{\frac{D_{BL}}{X_0}} = \frac{D_{AL}}{D_{BL}} \tag{4.17}$$

When modeling the falling rate period, an extra resistance to the absorption of SO_2 must be considered. During this period, the droplet (which was originally a slurry) is transformed due to water evaporation into a slurry core surrounded by a dry solid film; this film, the extra resistance, is composed of $CaSO_3 \cdot 1/2H_2O(s)$ and $CaSO_4 \cdot 2H_2O(s)$. From Levenspiel (26), the rate equation describing this extra resistance can be derived and shown as follows:

$$-r_A = \frac{4\pi R_c R_d D_e (P_{AS} - P_{Ai})}{(R_d - R_c)(RT)} \tag{4.18}$$

The combination of equations 4.12 - 4.18 results in a series resistance equation for the falling rate period. The developed absorption model combined the individual resistances for gas phase mass transfer, liquid phase mass transfer, and absorbent dissolution into the following single flux relationship:

(4.19)

$$-N_A = \frac{\frac{P_{AG}}{H_A} + \frac{D_{BL}}{D_{AL}} C_s}{\frac{D_{BL}}{D_{AL}\ k_{BL}} + \frac{d_c^2}{d_d^2\ k_{AG}\ H_A} + \frac{R_c\ (R_d - R_c\ )\ (RT)}{R_d\ D_e\ H_A} + \frac{d_c^2\ D_{BL}}{D_{AL}\ k_s\ (a_r\ )}}$$

Appendix A contains the derivation of this equation.

The time required for the falling rate period is given by the following equation by Ranz and Marshall (3):

$$T_{frp} = \frac{L_t\ (X_c - X_e\ )\ (\rho_f\ )\ (d_{frp}\ )}{12\ (1)\ (T_{avg}\ )} \qquad (4.20)$$

The final droplet density is needed to calculate the falling rate period time. The following relationship describes this density:

$$\frac{1}{\rho_f} = \frac{f_w\ (1)}{SGW_1} + \frac{f_p\ (1 - f_w\ )}{SG_p} + \frac{f_s\ (1 - f_w\ )}{SG_s} \qquad (4.21)$$

Damle (2) predicts the thermal conductivity of air, cal/cm-sec-C, at temperature T (K), using the following expression:

$$\gamma = 1.82 \times 10^{-7} * T + 7.9 \times 10^{-6} \qquad (4.22)$$

The latent heat of evaporation of water, L_t, cal/gm, at temperature T, K, is given by Damle (2) as the following:

$$L_t = 597.64 - 0.55\ (t - 273.15) \qquad (4.23)$$

According to Ranz and Marshall (3), the proper time average during the falling rate period can be estimated by a logarithmic mean average of the difference in temperature between droplet and gas. Refer to Figure 4.1

$$D_T = \frac{(D_1 - D_2)}{\ln(D_1/D_2)} \qquad (4.24)$$

The calculation for the diameter of the slurry core assumes that all product present is distributed equally around the spherical droplet, and that all product is distributed to the outer shell. Therefore, there is no product in the slurry phase. The core diameter is calculated as follows:

$$d_c = (d_d^3 - P_v / 0.5236)^{1/3} \qquad (4.25)$$

Equation (4.19) and the above mentioned model parameters were incorporated into MODEL A. The new model will be referred to as MODEL B. At this point, the effective diffusivity that describes SO_2 diffusion through the dry crust surrounding the droplet was attainable.

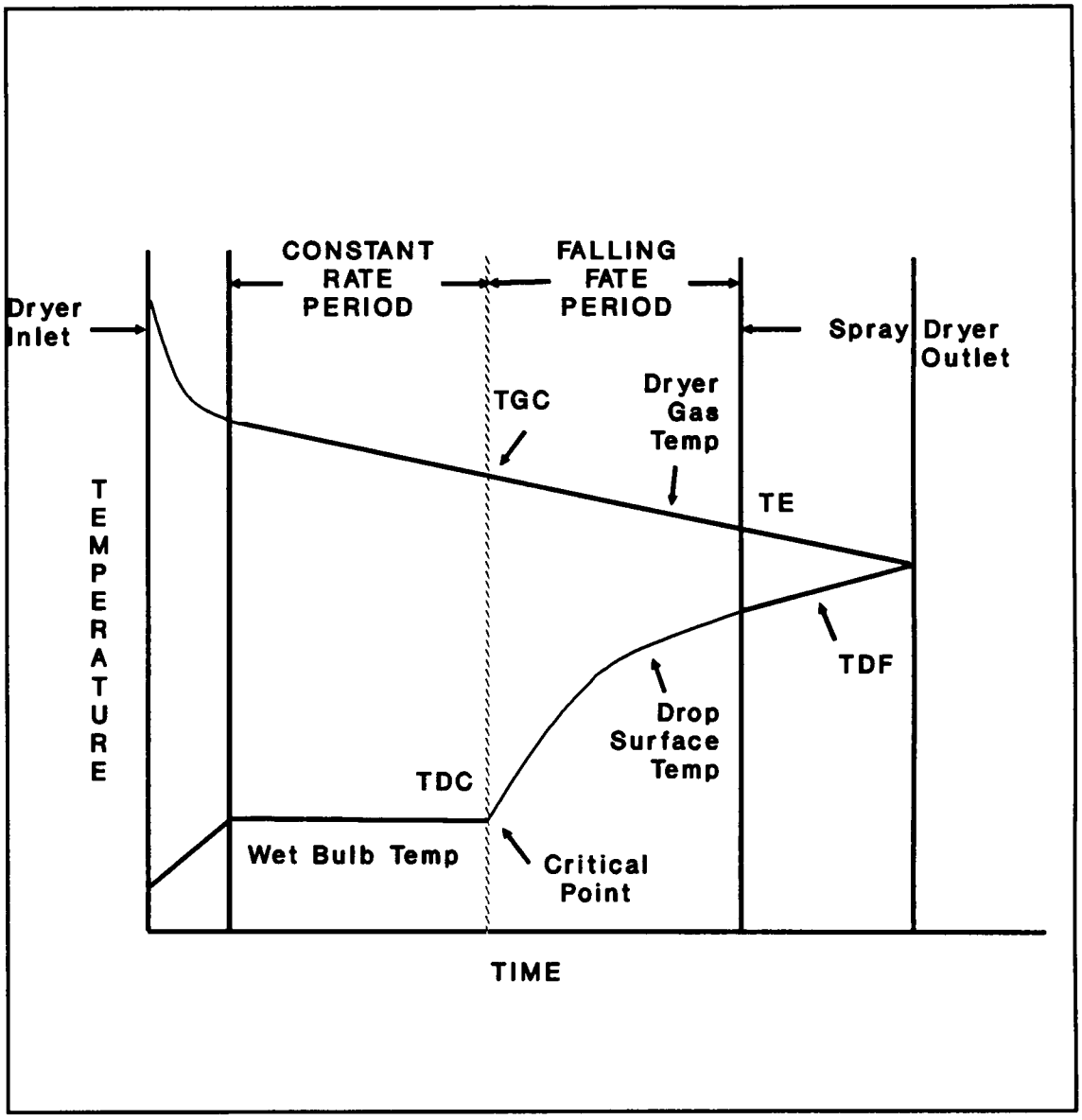

Figure 4.1 Drying History of a droplet inside a spray dryer

MODEL B was used to back calculate an effective diffusivity for each data set represented in Appendix C. Each data set contained an experimental value for the SO_2 concentration exiting the spray dryer. MODEL B, in an iterative fashion, changed the value of the effective diffusivity incorporated in the simulation. The value of the effective diffusivity was changed until the computer model calculated a value of the SO_2 exit concentration that equaled the experimental value. Once a value for the effective diffusivity was determined, it was incorporated into MODEL B. At this point, the model was rearranged to no longer include the iterative process that was used for the analysis of the effective diffusivity. The model now considers the absorption of SO_2 during both the constant and falling rate periods. This new model was called MODEL C. A model summary is provided in Table 4.2.

TABLE 4.2

Model Summary

Model Name	Description
UTSDM1	Model used by Partridge to estimate SO_2 removal during the constant rate period.
MODEL A	Updated UTSDM1 that recognizes the effects of the reaction products on the liquid phase diffusivity. This model also incorporates Dantuluri's surface area predictions.
MODEL B	MODEL A expanded to incorporate the falling rate period. This model was used to find the effective diffusivity.
MODEL C	Model used to predict SO_2 removal in a spray dryer during the constant and falling rate periods.

CHAPTER V

RESULTS AND COMPARISON OF MODELS TO PILOT PLANT DATA

A. Introduction.

The two new models, MODEL A and MODEL C, were evaluated by comparing model predicted efficiencies versus experimental pilot plant efficiencies. The 12 data sets were used in the analysis and can be seen in Appendix C. The data sets represented a range of initial SO_2 concentration of 633 - 3178 ppm. During model development, the simulation efficiency was compared to pilot plant data efficiency at two specific stages. First, the assumption that absorbent particles are spherical in geometry was abandoned and a correlation which predicted absorbent surface area was added to UTSDM1. The new model was named MODEL A. Secondly, a combined resistance equation used to predict SO_2 absorption during the falling rate period was added to UTSDM1. This new model was called MODEL C. Also, model efficiency calculations were compared before and after the addition of the correction for diffusivity due to product formation.

B. Diffusivity Correlation.

When small reaction products are formed, their presence is accounted for by correcting the diffusivity of SO_2 in the

liquid phase. Figure 5.1 shows how the diffusivity changes with respect to time during the constant rate period as described by equation 4.9. Figure 5.1 indicates that by the end of the constant rate period, the diffusivity changes by up to a factor of 10. This suggests a significant decrease in SO_2 removal in the new MODEL A versus the old UTSDM1. However, as seen in Table 5.1, the predicted decrease in SO_2 removal efficiency is not indicated by the model. This result occurs because the majority of the constant rate period is gas phase controlling. Initially, MODEL A predicts the SO_2 absorption rate by the combined resistance flux equation. As the SO_2 concentration decreases with time, the relative gas phase resistance increases. As a result, the combined resistance equation (equation 4.12) becomes less applicable and the process is controlled by the gas phase resistance. When the gas phase resistance becomes controlling, equation 4.13 is used to describe the absorption reaction. As seen in equation 4.13, the liquid phase diffusivity D_{AL} has no effect on SO_2 absorption while the gas phase resistance is controlling, thus providing an explanation for the results shown in Table 5.1. Dominance of the gas phase resistance occurs at approximately 0.5 seconds. Increasing the approach to saturation temperature or operating at higher inlet SO_2 concentrations will result in a decrease in time required for the mass transfer to become gas phase resistance controlled (5).

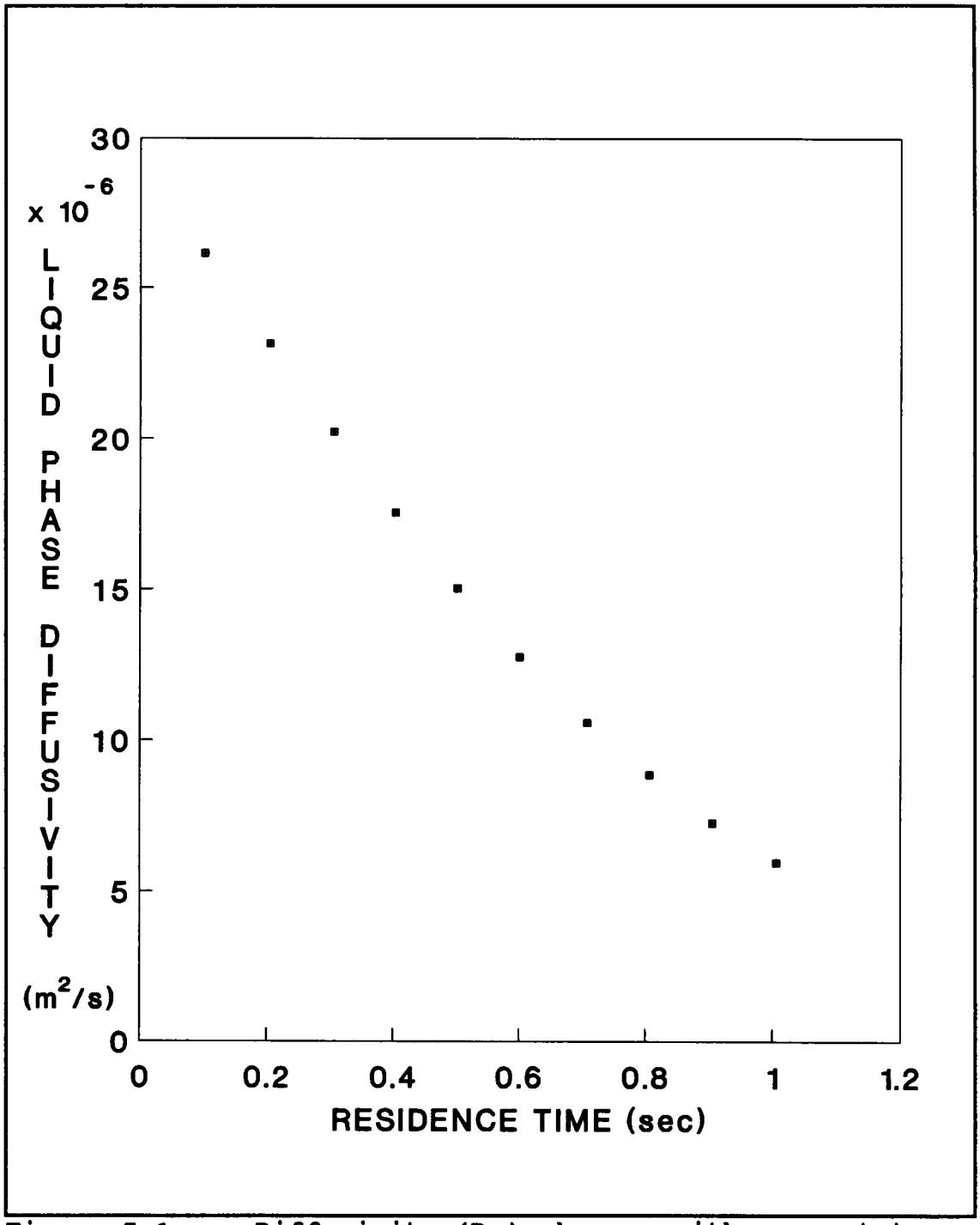

Figure 5.1 Diffusivity (D_{AL}) changes with respect to time and is described by equation 4.9

TABLE 5.1

The effect of product formation on diffusivity and model efficiency predictions

DATA SET	D_{ALo} x 10^5	D_{AL} x 10^6	θ	E_o %	E %
1	2.95	2.27	.923	69.2	69.2
2	2.89	2.16	.926	70.6	70.7
3	2.92	2.14	.926	69.3	69.1
4	3.01	2.29	.924	68.1	68.2
5	3.15	2.60	.917	61.6	61.6
6	2.91	2.61	.911	54.5	54.4
7	2.76	2.32	.916	56.7	56.6
8	2.91	2.41	.917	60.8	60.7
9	2.91	2.52	.914	55.4	55.6
10	2.94	2.85	.903	47.0	47.0
11	2.93	2.70	.908	51.1	51.0
12	3.24	2.90	.911	54.6	54.6

D_{ALo} = Diffusivity in continuous phase, cm^2/s
D_{AL} = diffusivity in slurry, cm^2/s
θ = volume fraction of solid in slurry, cm^3 solid/cm^3 droplet
E_o = model calculated efficiency using D_{ALo}, %
E = model calculated efficiency using D_{AL}, %

C. Absorbent Surface Area Correction.

The model UTSDM1 assumes the absorbent particles to be spherical. By considering the $Ca(OH)_2$ particle spherical, the $Ca(OH)_2$ dissolution rate is very likely underestimated. The work done by Danturluri (6) that stated a relationship between specific absorbent particle diameter and specific surface area (Table 4.1 and Equation 4.11) was incorporated into UTSDM1. A statistical analysis was performed on MODEL A and compared with the same analysis on UTSDM1. The difference between model SO_2 removal efficiency and experimental efficiency was determined and the 90% confidence interval was found. For UTSDM1, the confidence interval was determined to be -7.46 < (model efficiency - experimental efficiency) < -3.87. As expected, since only the SO_2 removal during the constant rate period was being modeled, the confidence interval did not include zero. For MODEL A, the 90% confidence interval was determined as -1.54 < (model efficiency - experimental efficiency) < 2.24. Here, the confidence interval includes zero which implies that the model is a good representation of what is occurring in a FGD spray dryer. Although MODEL A is a good model of absorption in a spray dryer, MODEL A is just designed to model the constant rate period. A graphical representation of the efficiency results predicted by MODEL A can be seen in Figures 5.2 - 5.13 which use the 12 data sets seen in Appendix C.

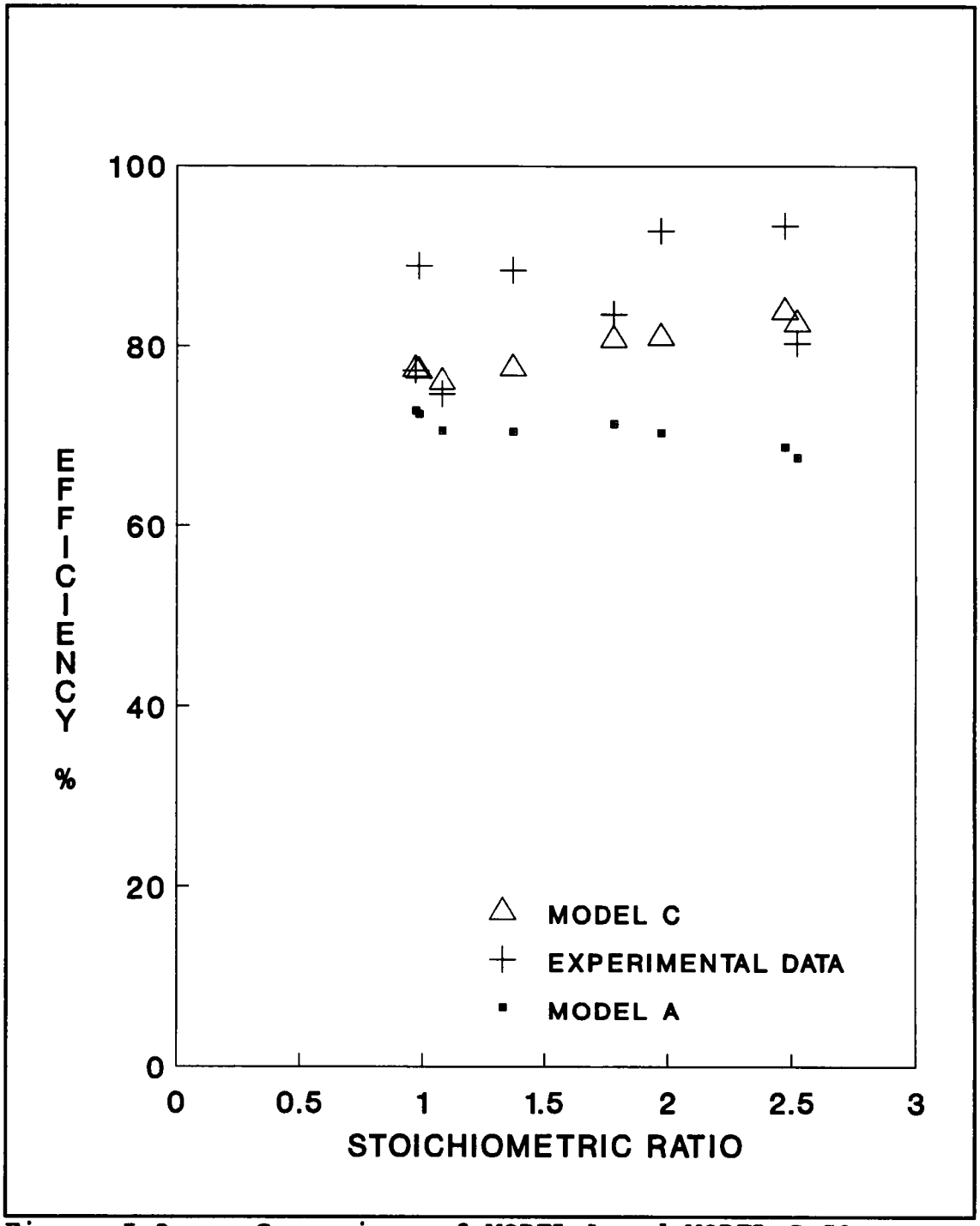

Figure 5.2 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 1

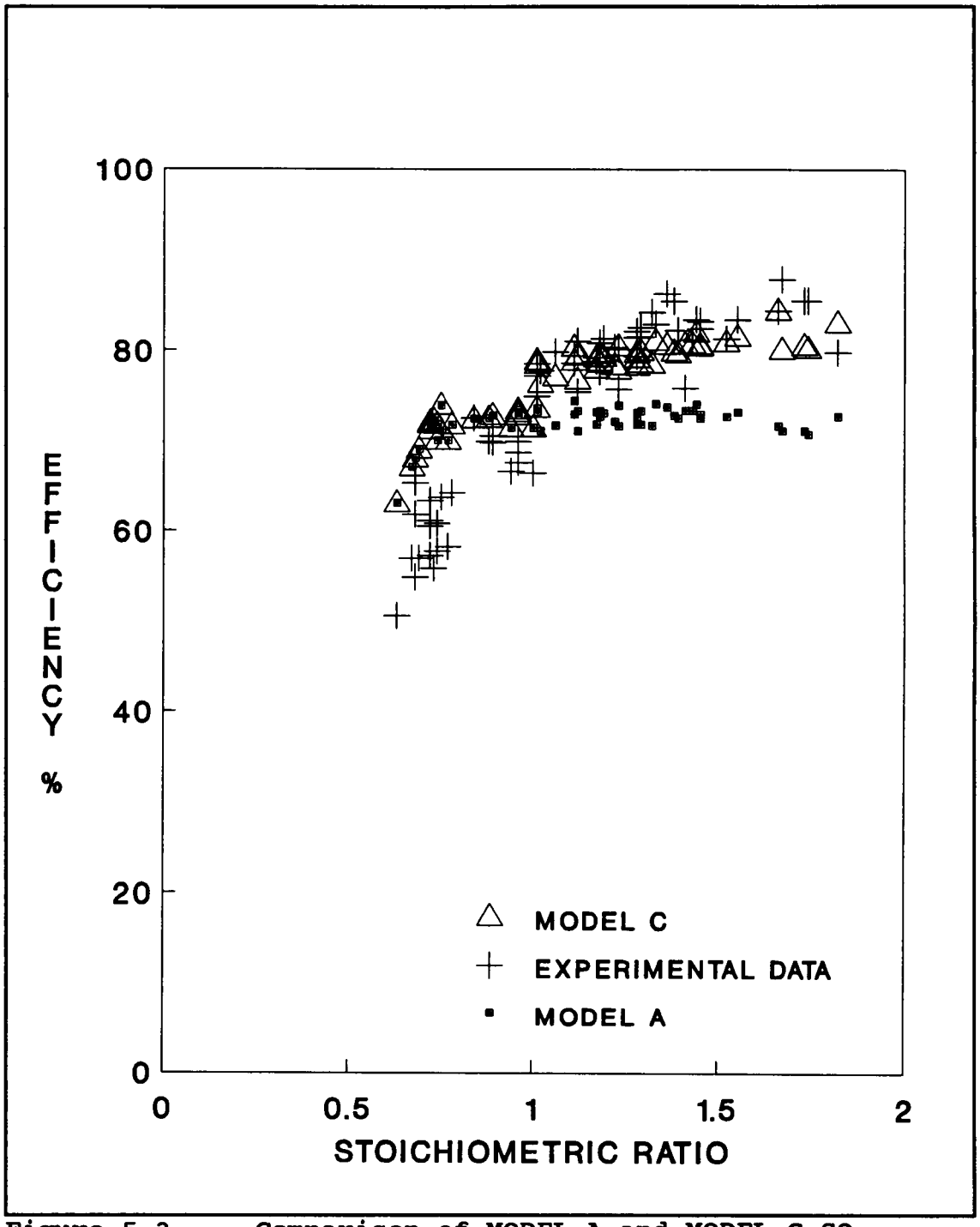

Figure 5.3 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 2

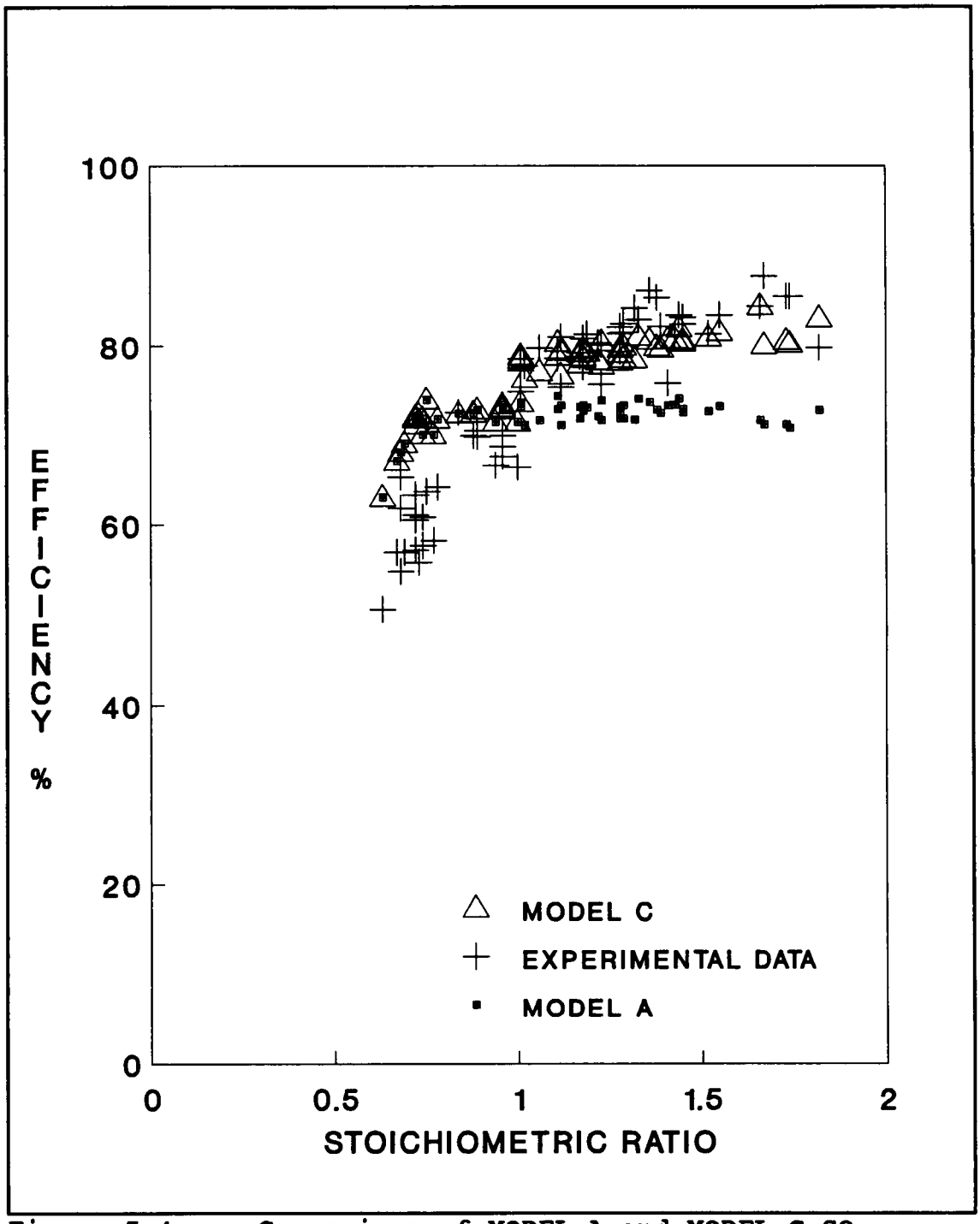

Figure 5.4 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 3

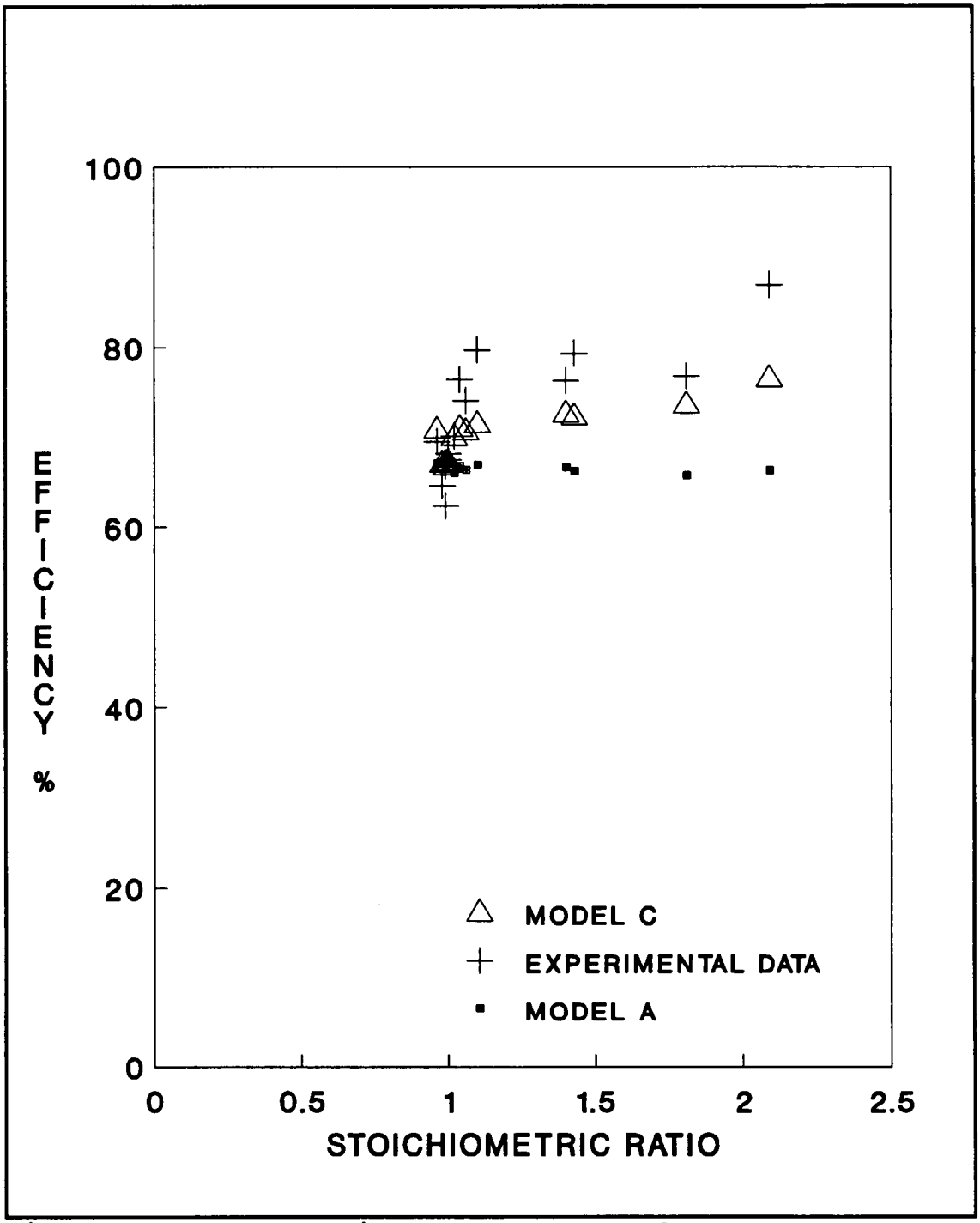

Figure 5.5 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 4

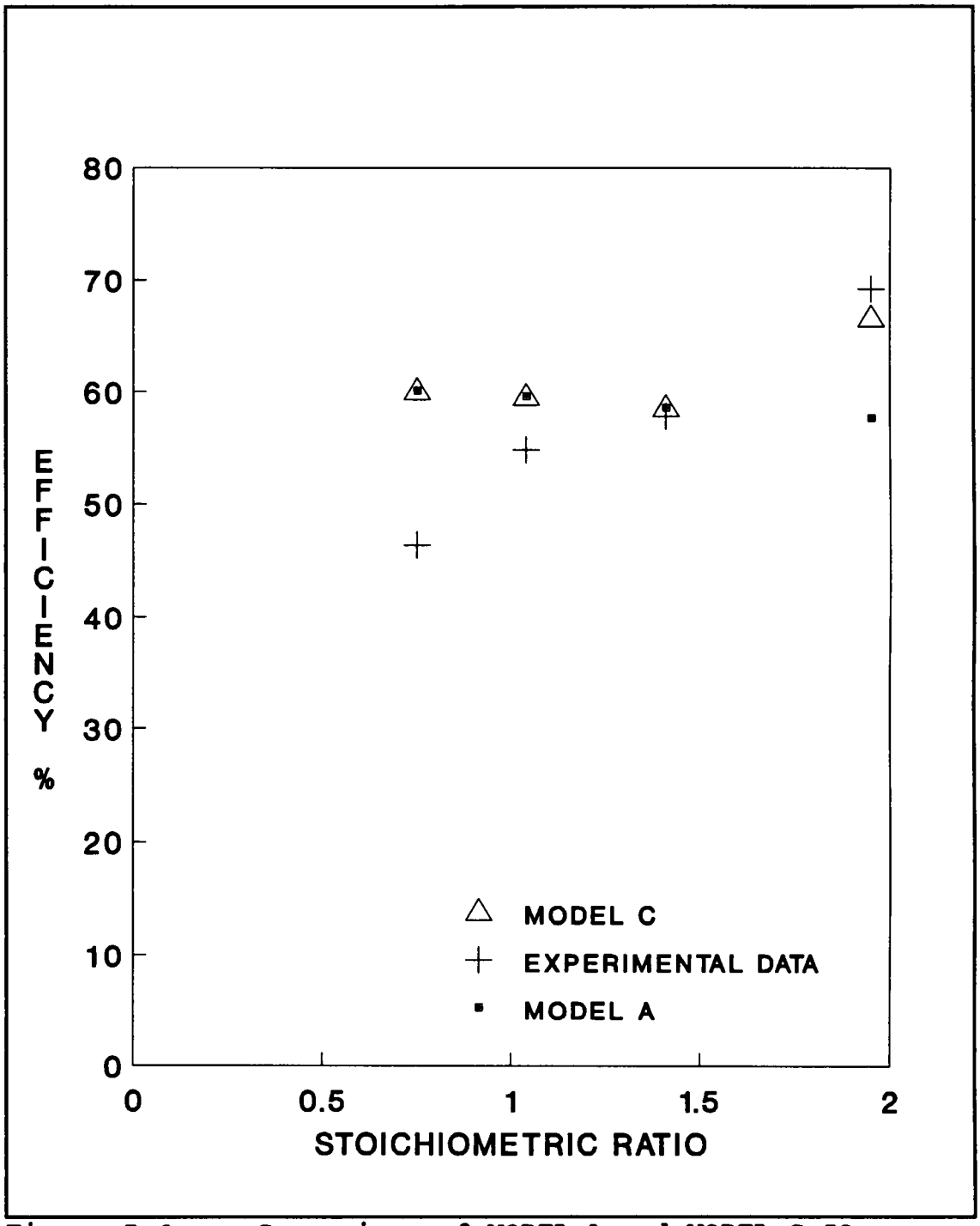

Figure 5.6 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 5

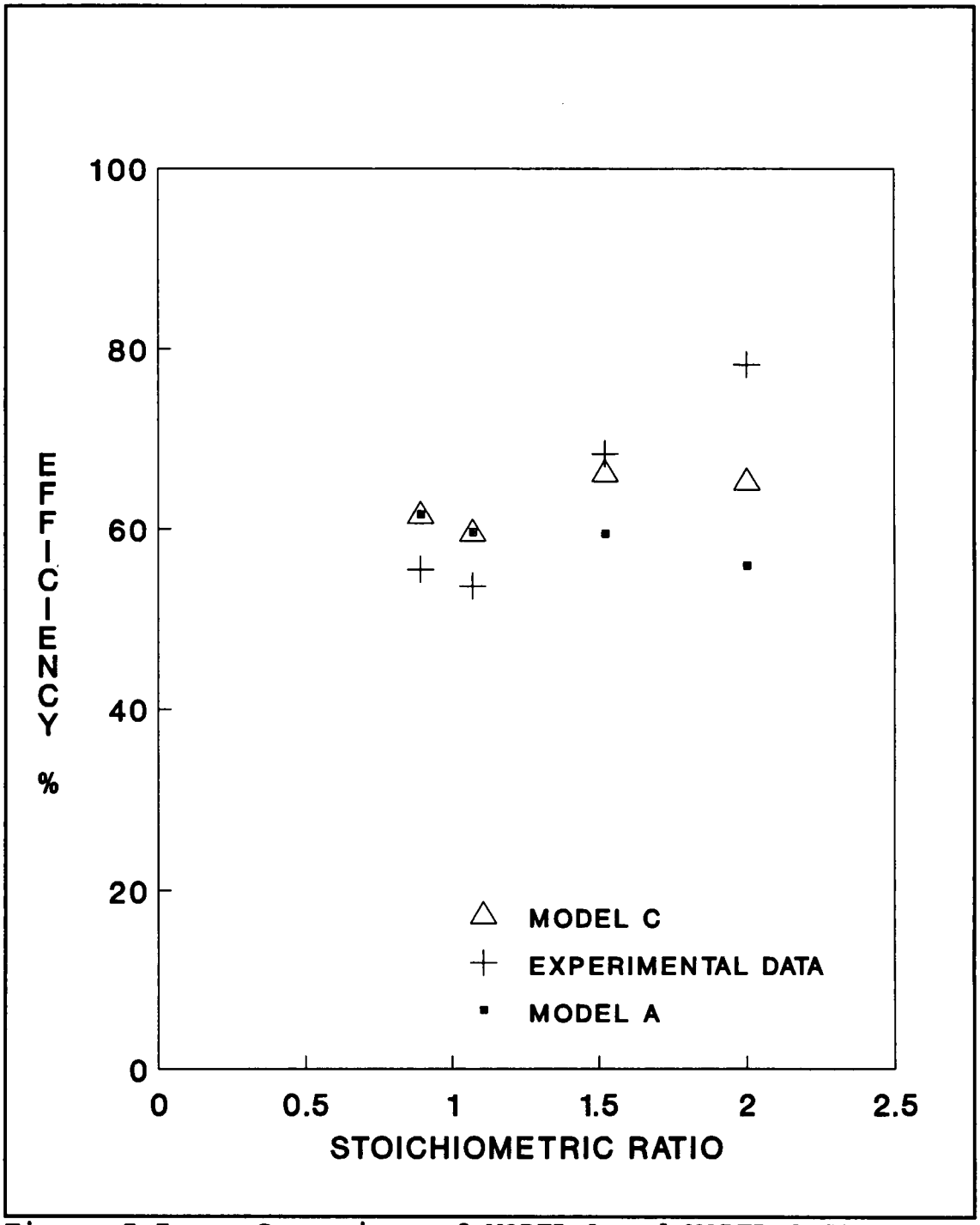

Figure 5.7 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 6

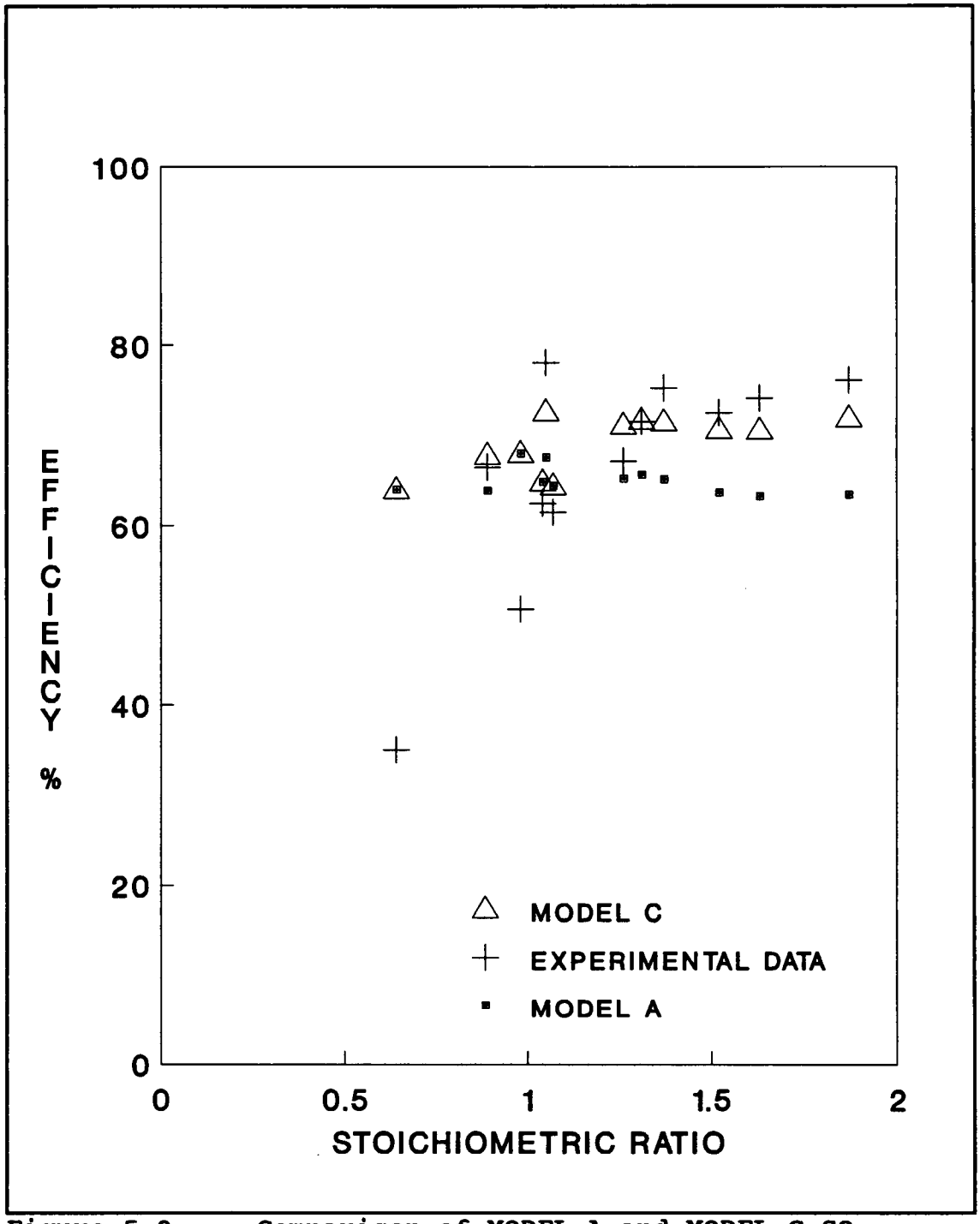

Figure 5.8 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 7

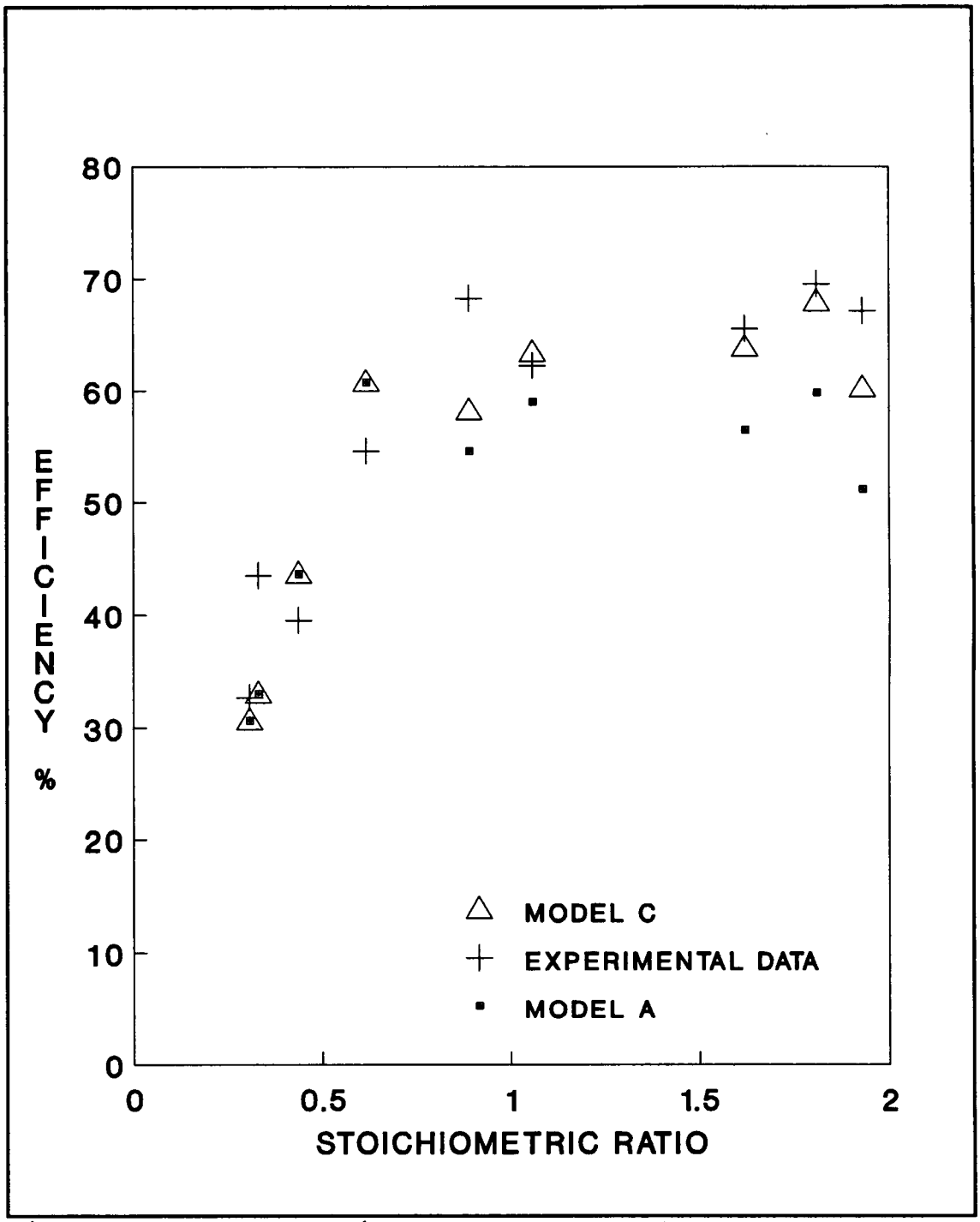

Figure 5.9 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 8

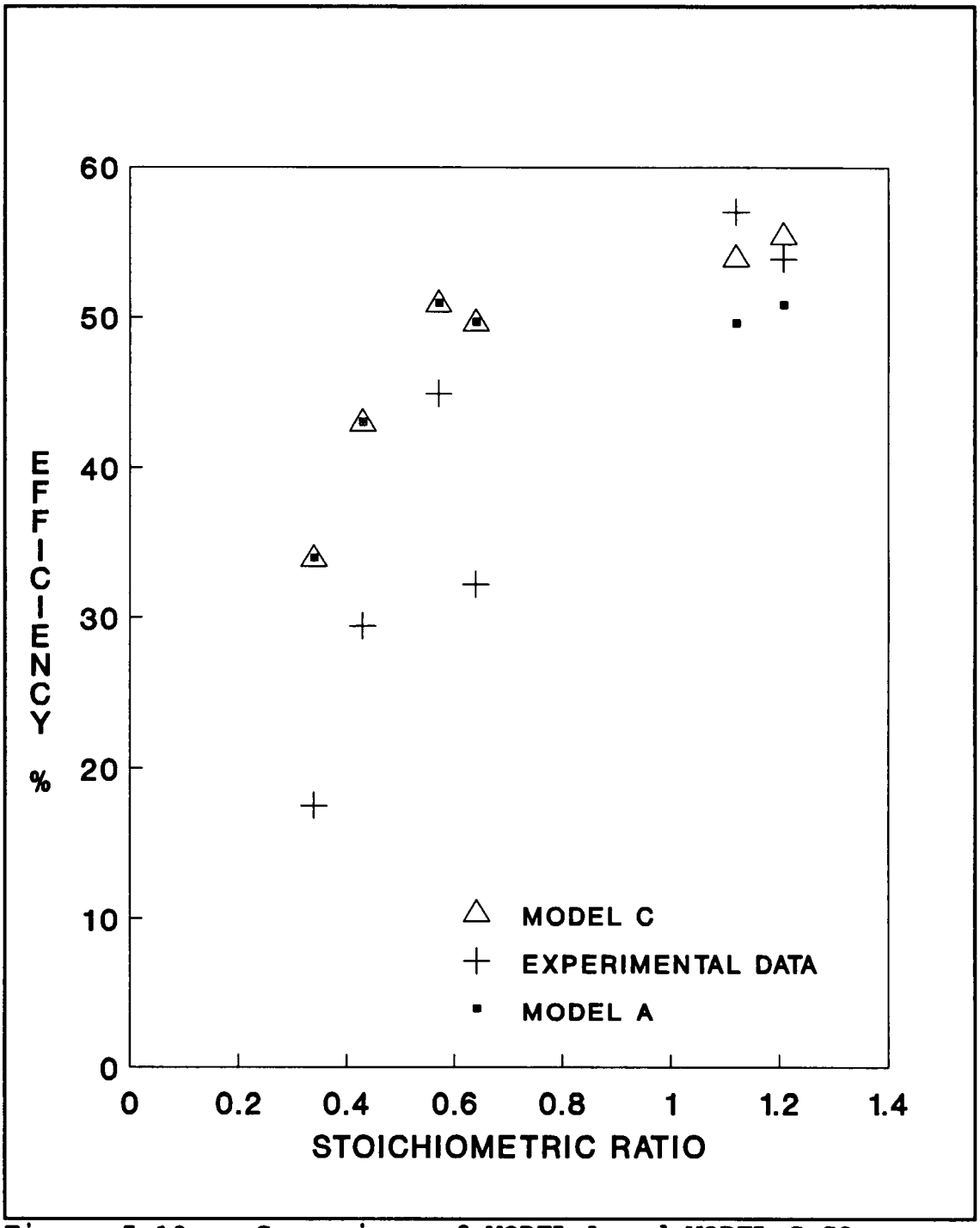

Figure 5.10 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 9

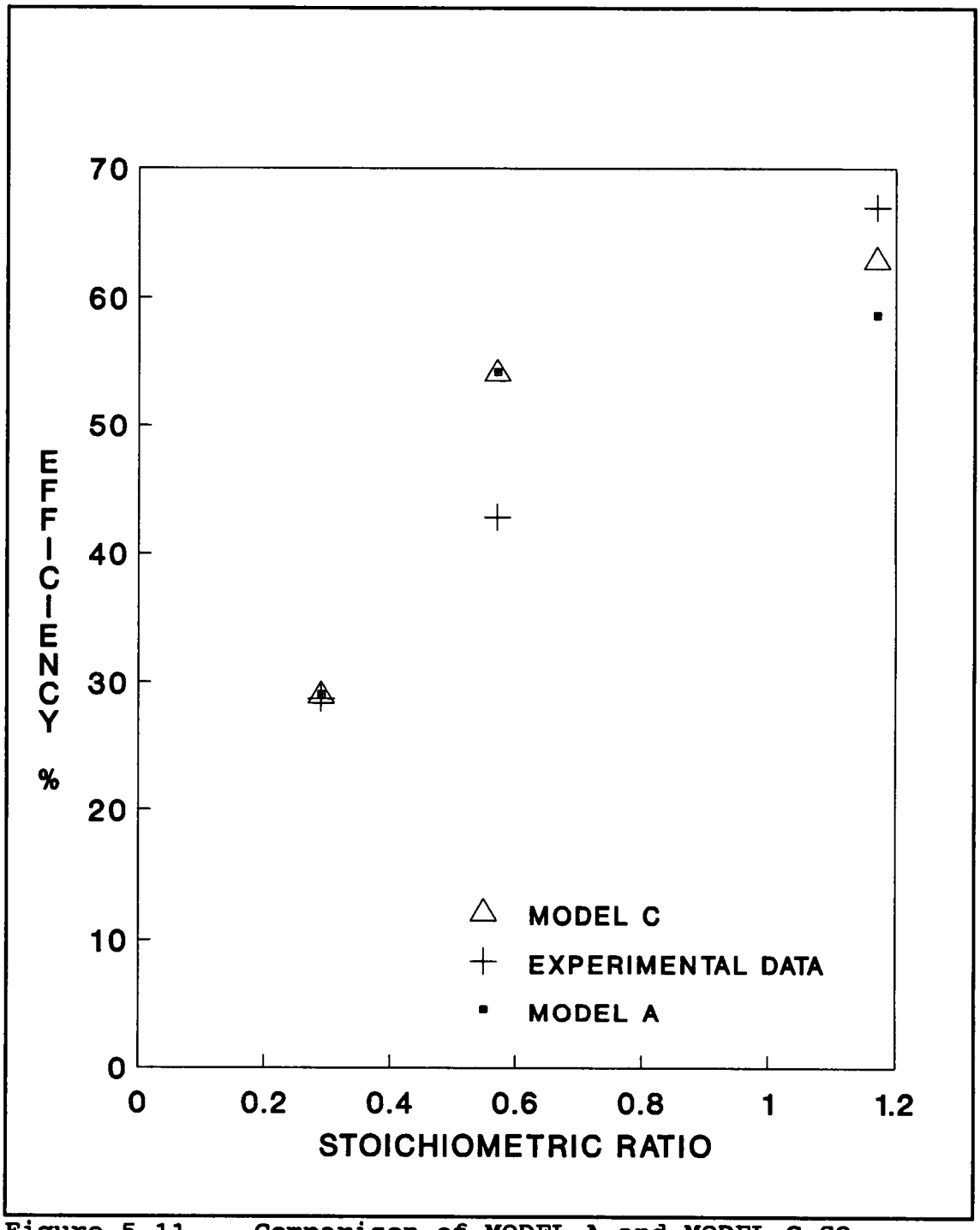

Figure 5.11 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 10

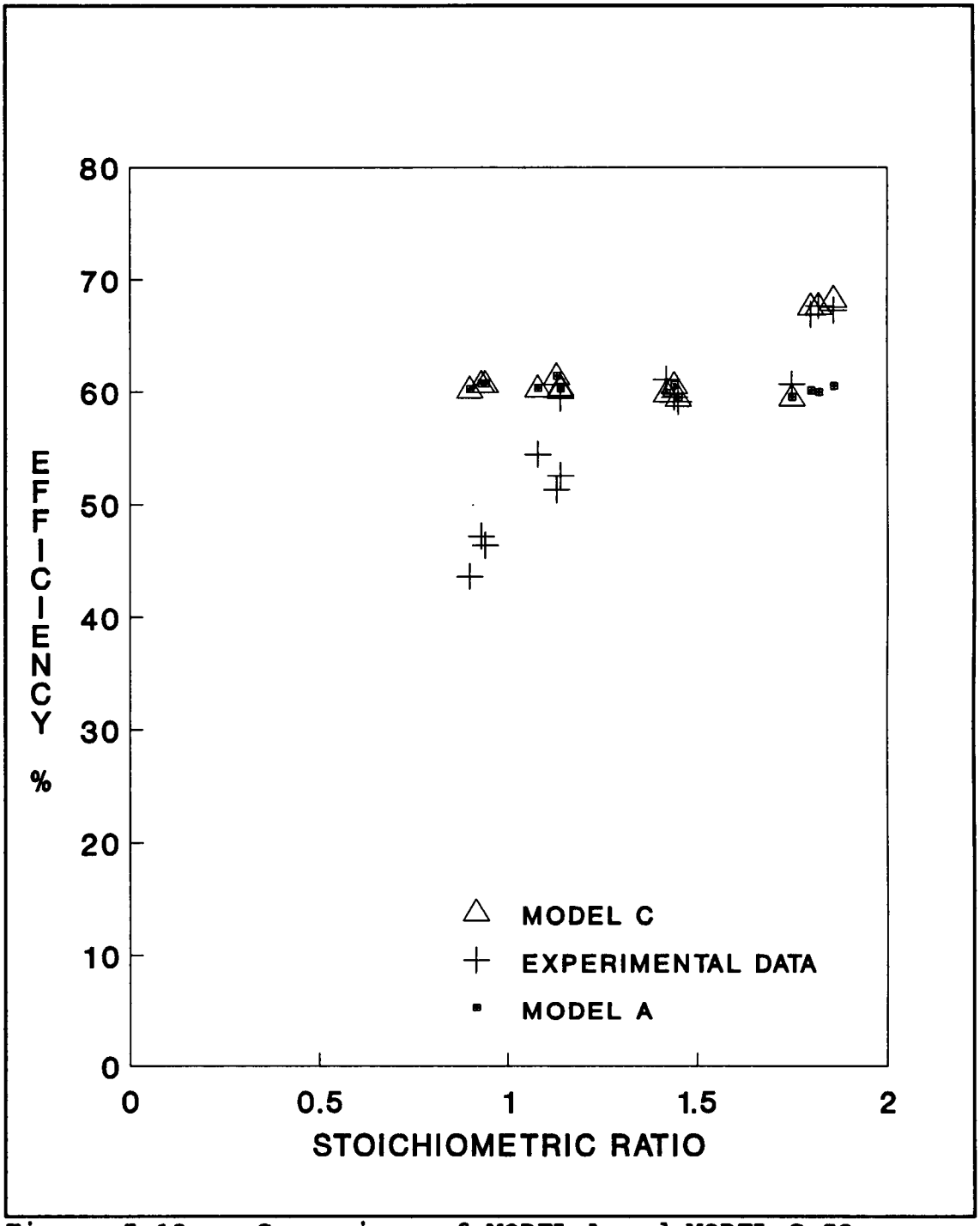

Figure 5.12 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 11

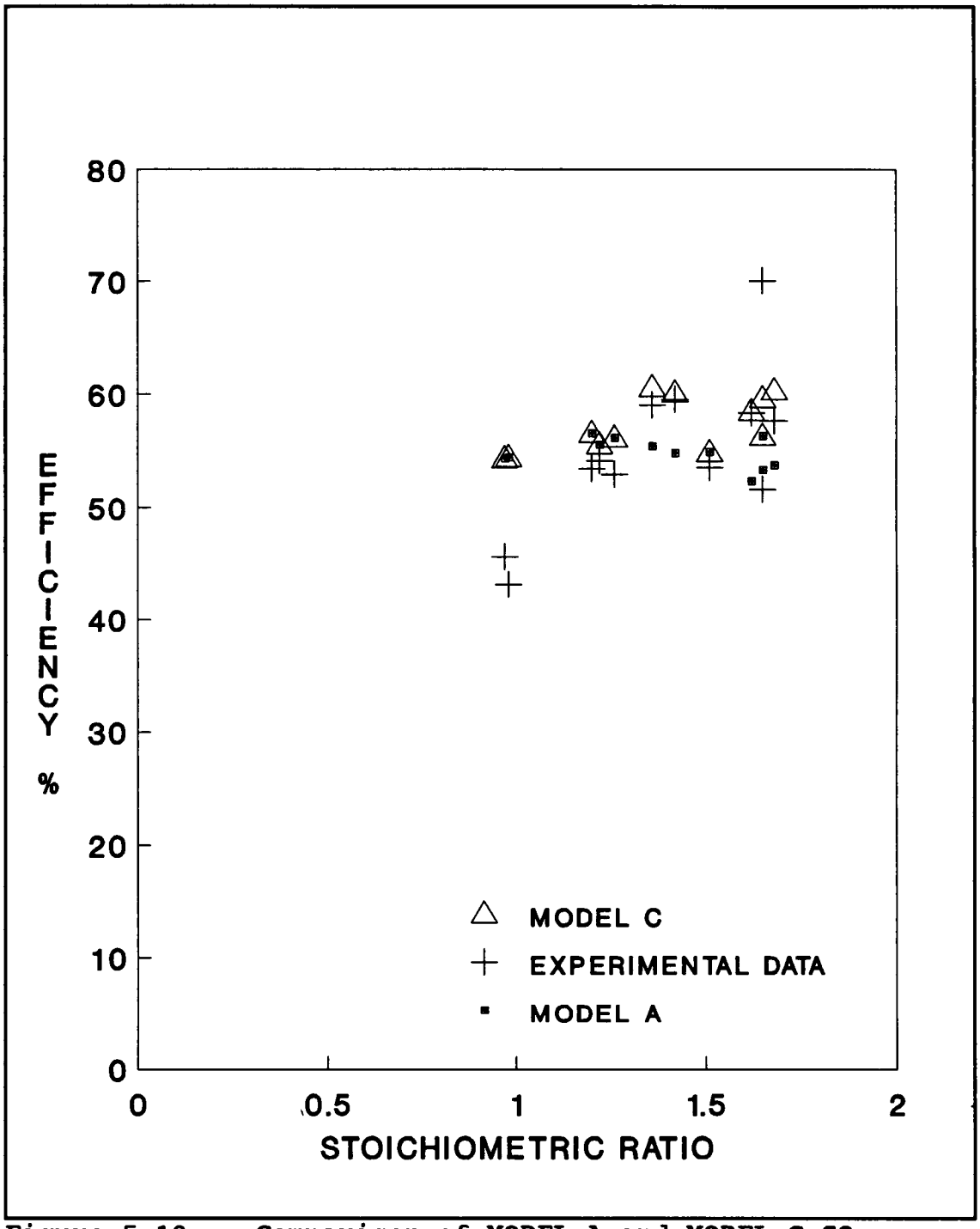

Figure 5.13 Comparison of MODEL A and MODEL C SO_2 removal efficiencies to experimentally measured efficiencies for data set 12

An analysis was done on MODEL A in an effort to better understand the over prediction of SO_2 absorption during the constant rate period. Graphs were constructed (Figures 5.14 through 5.17) of model SO_2 efficiency minus experimental SO_2 removal efficiency versus four influential model parameters (stoichiometric ratio, percent water in inlet gas, approach to saturation temperature, and average temperature in the spray dryer). It is observed from Figure 5.14 that below a stoichiometric ratio of one the model tends to over predict. Above a stoichiometric ratio of one, the model behavior shows an underprediction of SO_2 absorption within the spray dryer during the constant rate period.

D. Falling Rate Period.

MODEL A exhibited a confidence interval which included zero and thus provided an adequate overall prediction of SO_2 absorption in a spray dryer. But, from Figure 5.14 it was seen that above a stoichiometric ratio of one, there was a need for a continuation of the modeling effort to include the falling rate period. MODEL A with the addition of the falling rate period was named MODEL C.

MODEL B was used to find the effective diffusivity of SO_2 through the solid product phase. It can be seen from Figures 5.18 - 5.21 that the optimal effective diffusivities show no trends when compared to the stoichiometric ratio,

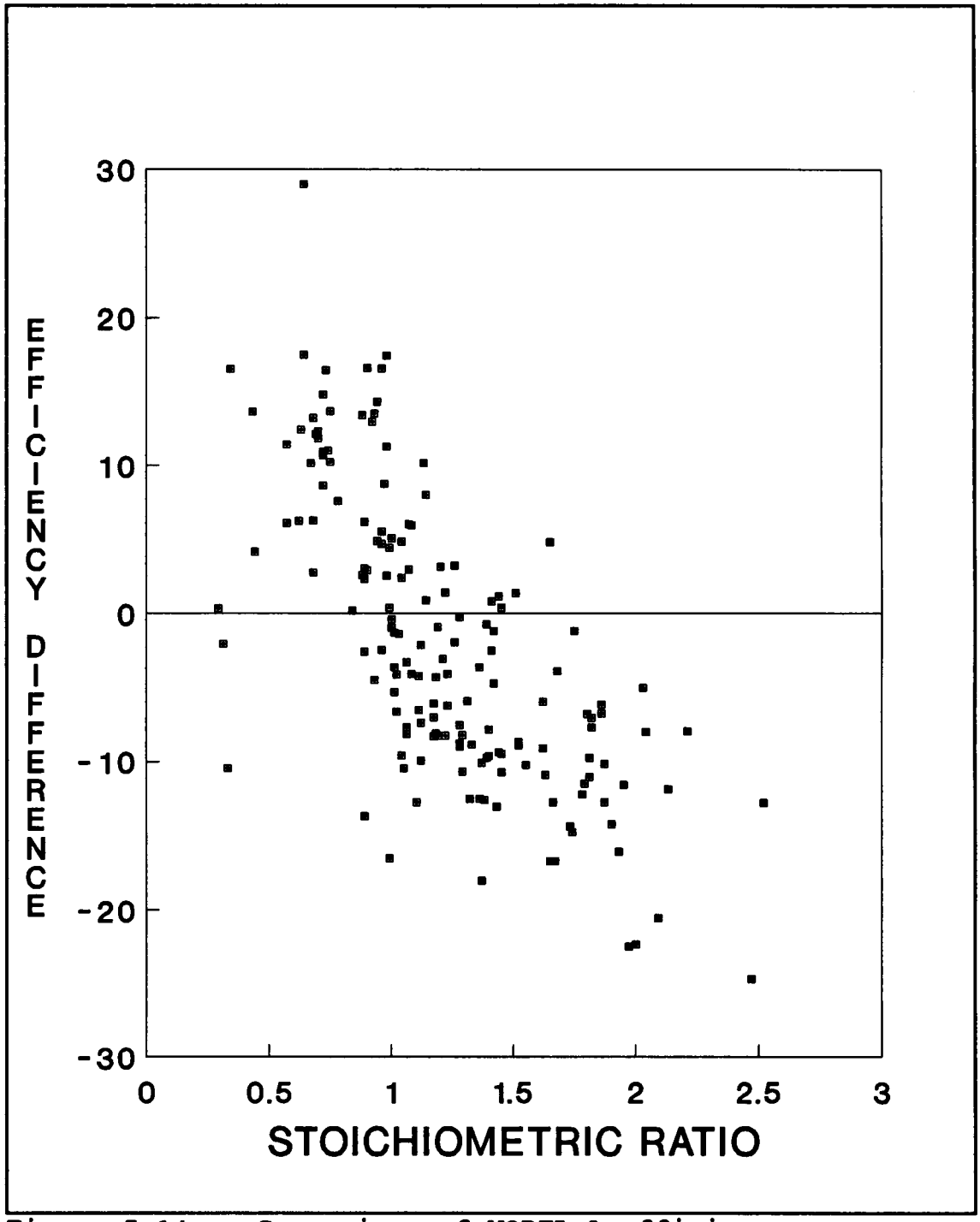

Figure 5.14 Comparison of MODEL A efficiency - experimental efficiency versus stoichiometric ratio

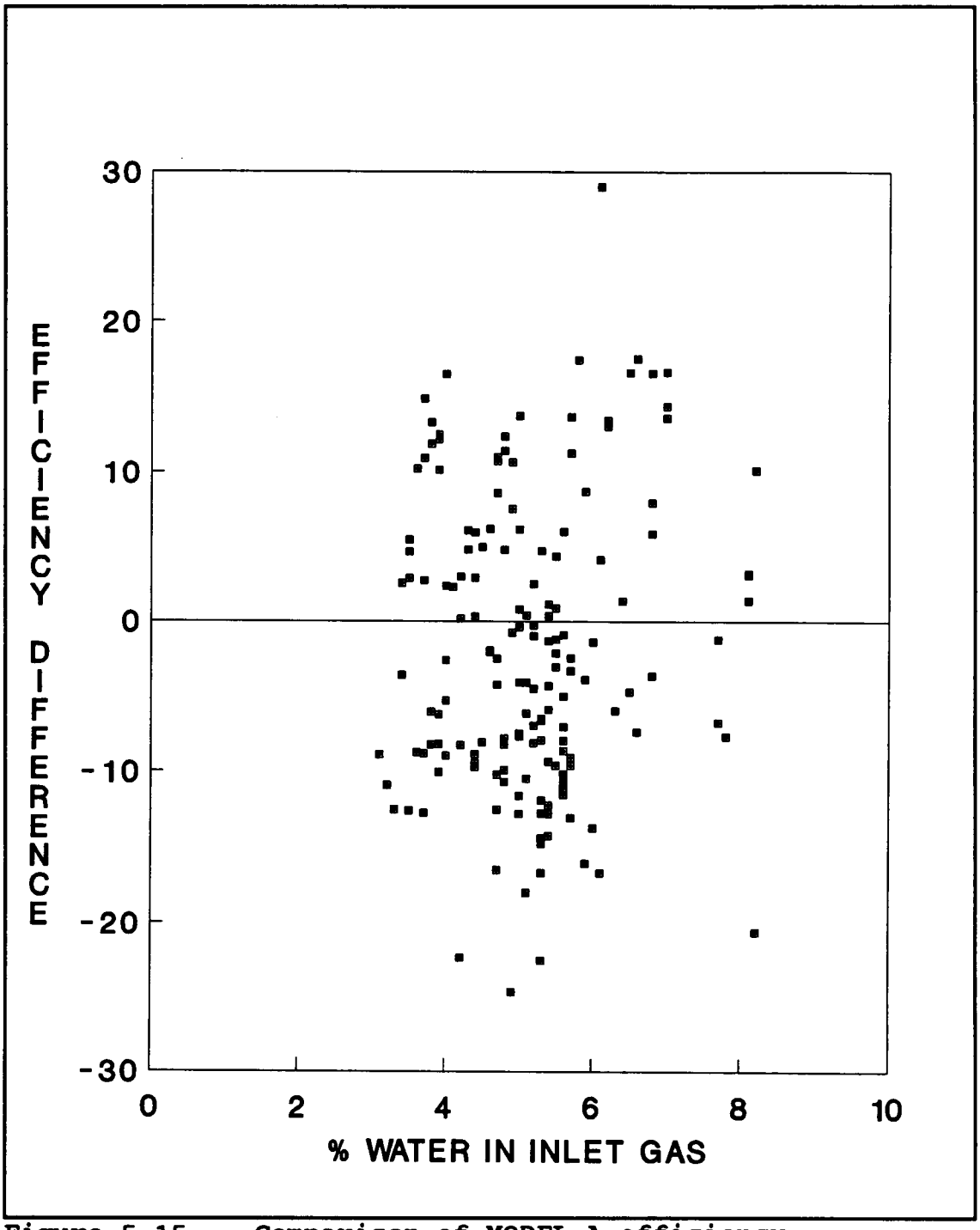

Figure 5.15 Comparison of MODEL A efficiency - experimental efficiency versus percent water in inlet gas

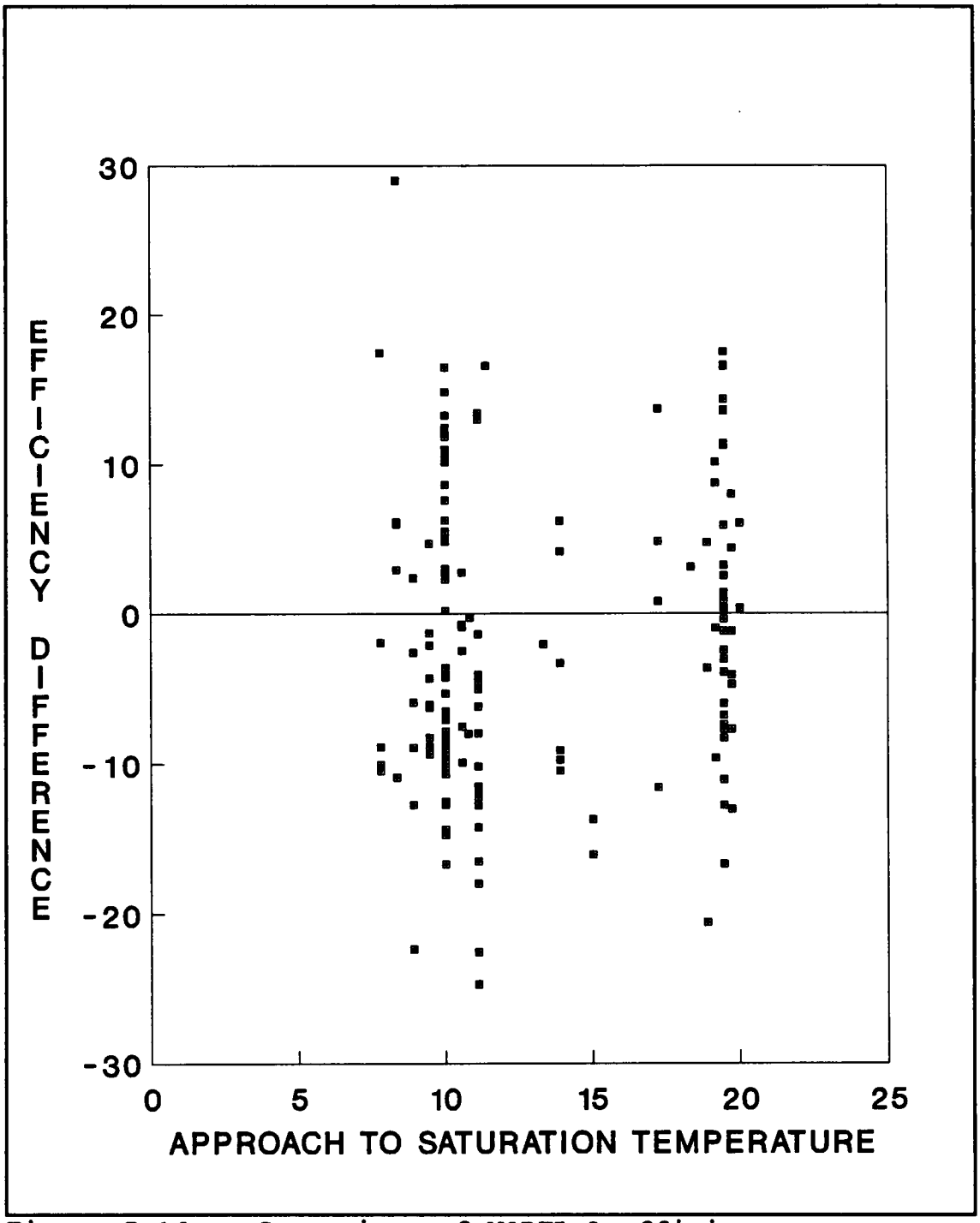

Figure 5.16 Comparison of MODEL A efficiency - experimental efficiency versus the approach to saturation temperature (°C)

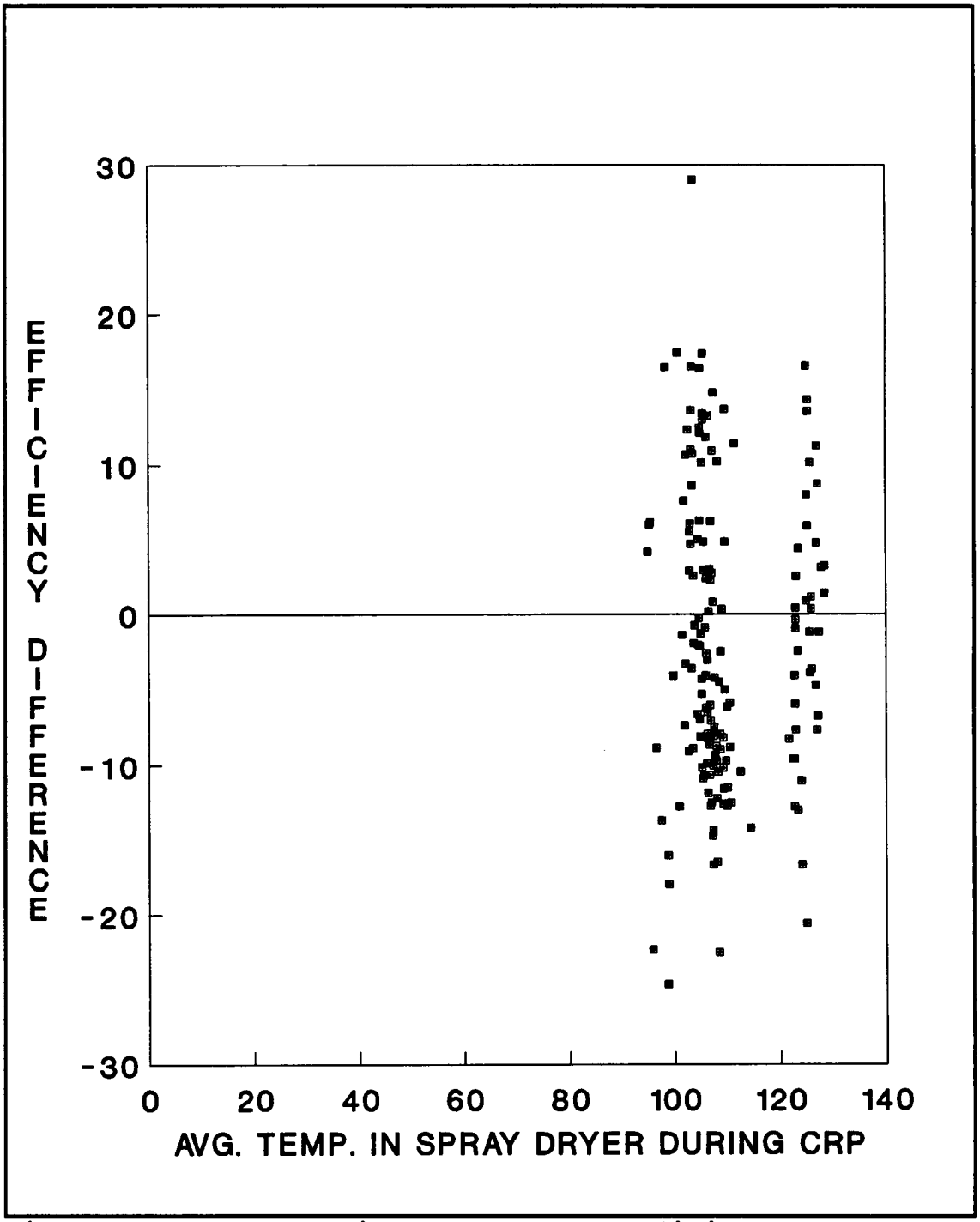

Figure 5.17 Comparison of MODEL A efficiency - experimental efficiency versus the average temperature in the spray dryer (°C)

approach to saturation temperature, percent water in inlet gas, or average gas temperature in the spray dryer during the falling rate period. Therefore, an average was taken of the diffusivities calculated. The average diffusivity was found to be 1.4×10^{-4} m^2/s. It is expected that the effective diffusivity would be of comparable magnitude or smaller than gas-phase diffusivities. Typical gas-phase diffusivities are of the order of magnitude of 1×10^{-5} m^2/s, indicating that the effective diffusivity found was an order of magnitude higher than expected. Factors which would cause the higher effective diffusivity found include:

1) the constant rate period portion of the model underestimates the SO_2 absorption in this stage; this would increase the required amount of SO_2 removal during the falling rate period, thereby increasing the effective diffusivity found
2) the droplet surface area within the model is calculated based on a spherical drop; the surface area of a drying droplet has the potential to be much greater than that of a sphere, which would increase the actual effective diffusivity

Even though the effective diffusivity predicted by MODEL B was higher than expected, when used in MODEL C practical sulfur dioxide removal efficiencies were achieved. When the stoichiometric ratio was greater than or equal to one, MODEL C incorporated the average diffusivity (D_e = 1.4

x 10^{-4} m^2/s) and SO_2 absorption efficiencies for the simulation were calculated using the twelve data sets in Appendix C. The results can be seen in Figures 5.2 - 5.13 (shown previously). For a stoichiometric ratio greater than or equal to one, a confidence interval was calculated for the difference between model calculated SO_2 removal efficiency and experimental SO_2 removal efficiency for the spray dryer. At 90% confidence, the interval was found to be -2.02 < (model efficiency - experimental efficiency) < -.69742, indicating that the model tends to slightly underpredict for the falling rate period. This slight underprediction is expected. The experimental efficiencies include the SO_2 removal throughout the entire spray dryer. This includes the constant rate period, the falling rate period, and the beginning of the dry period where SO_2 absorption is also predicted. MODEL C only considers the constant and falling rate periods.

The same analysis was done using MODEL C as was done using MODEL A in an effort to discover any trends in model parameters. The difference between model SO_2 removal efficiency and experimental efficiency was plotted against the same four parameters. The graphs can be seen in Figures 5.22 - 5.25. No trends were observed.

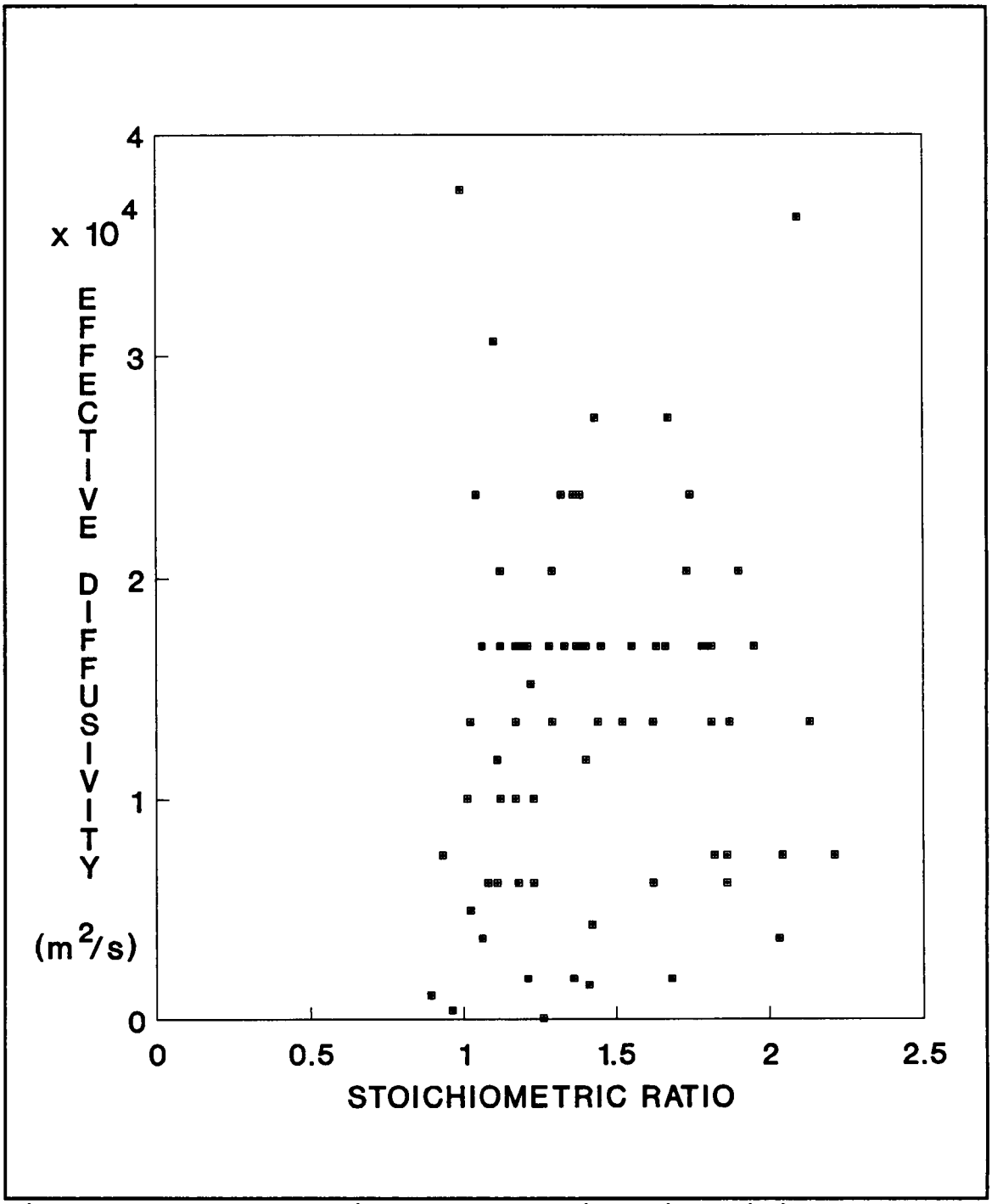

Figure 5.18 Comparison of effective diffusivity calculated versus the stoichiometric ratio

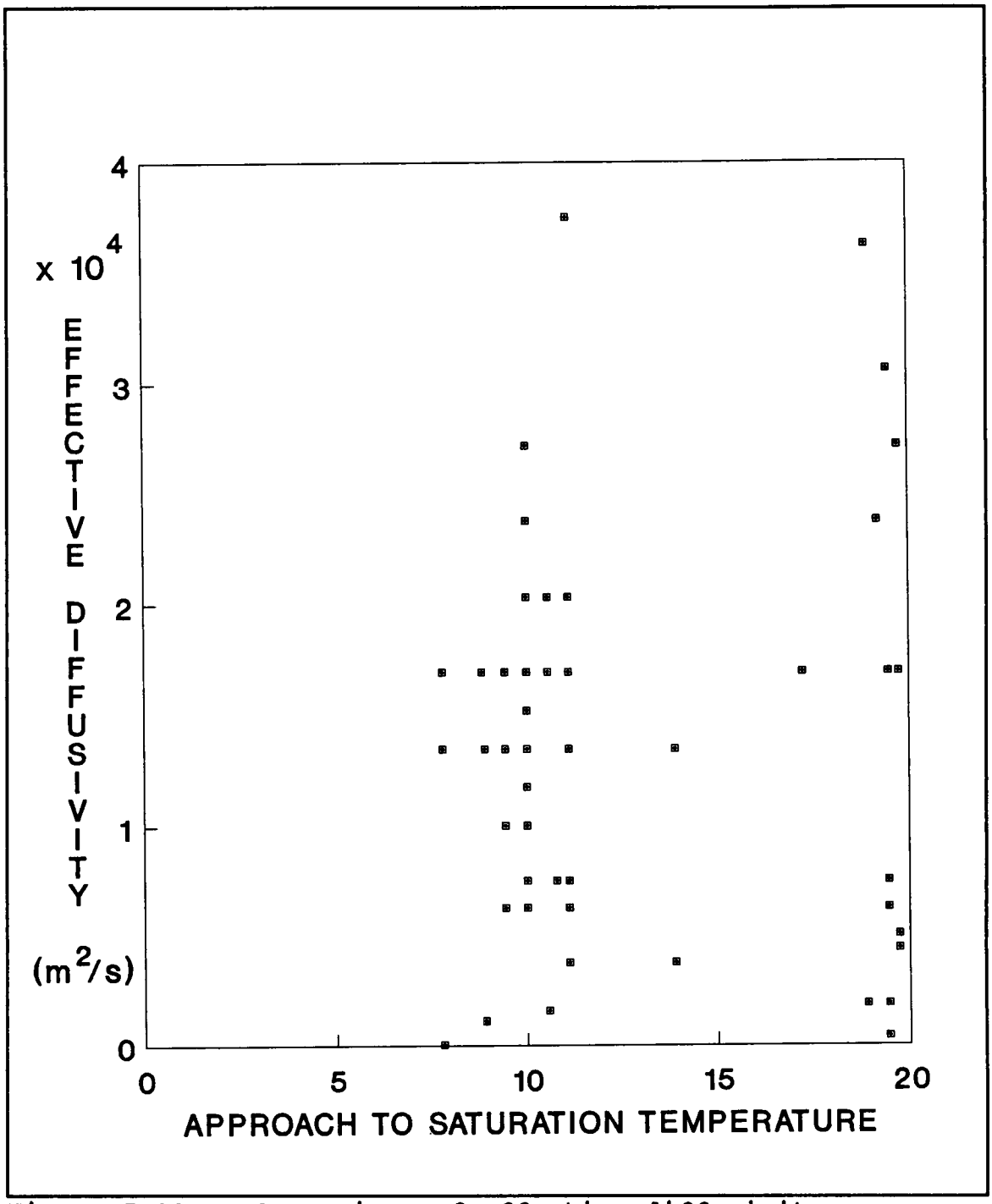

Figure 5.19 Comparison of effective diffusivity calculated versus the approach to saturation temperature (°C)

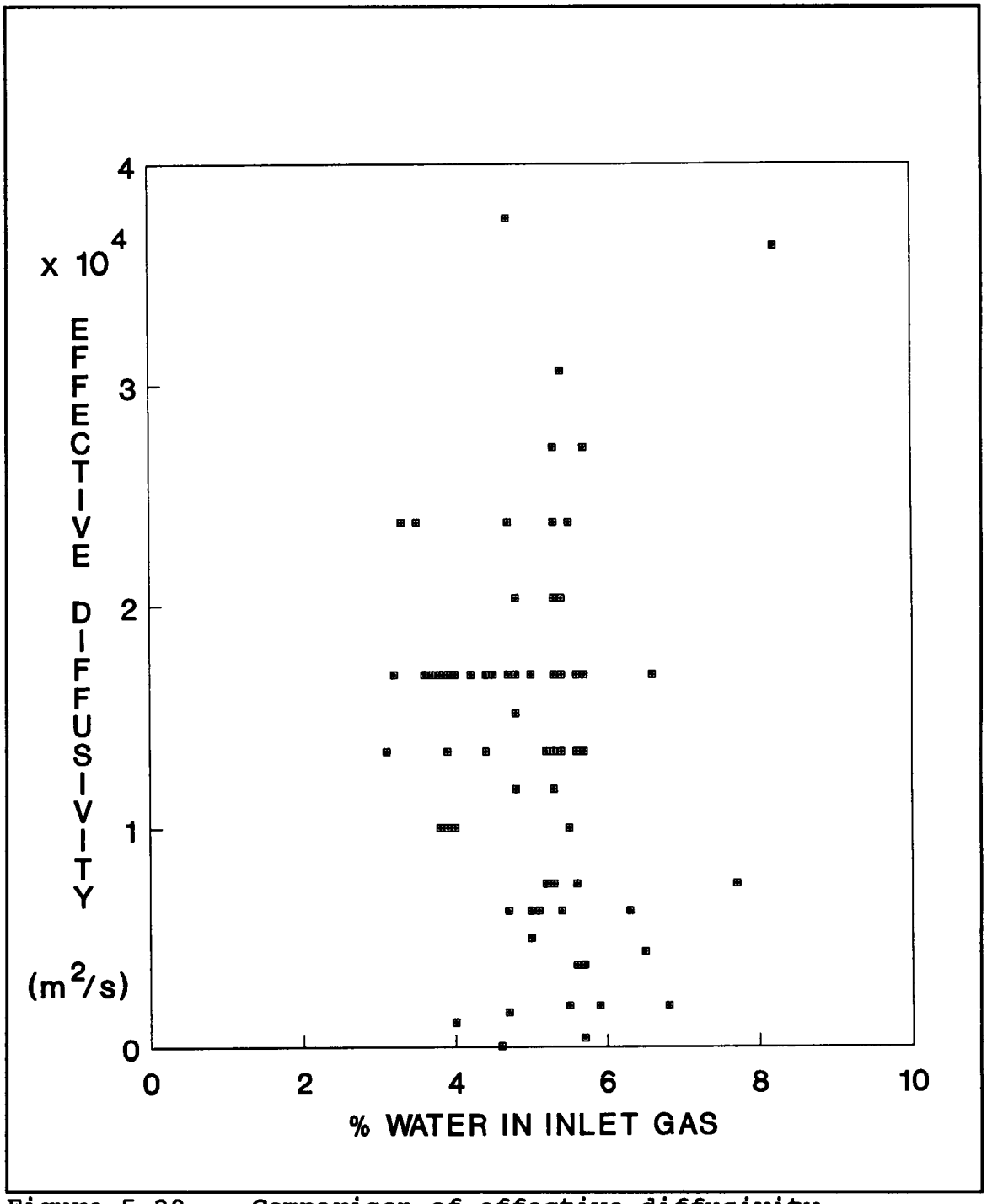

Figure 5.20 Comparison of effective diffusivity calculated versus the percent water in the inlet gas

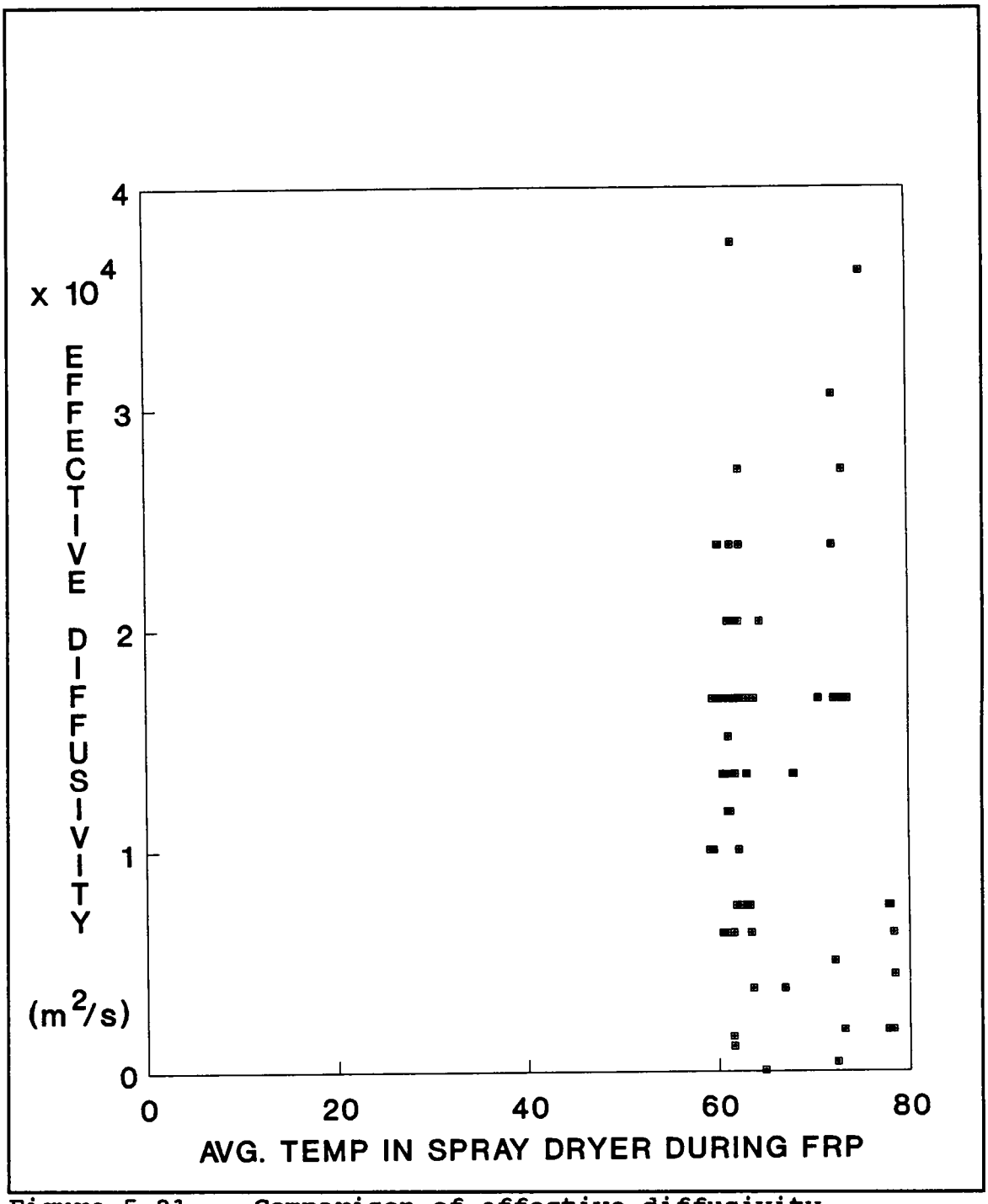

Figure 5.21 Comparison of effective diffusivity calculated versus the average gas temperature in the spray dryer during the falling rate period (°C)

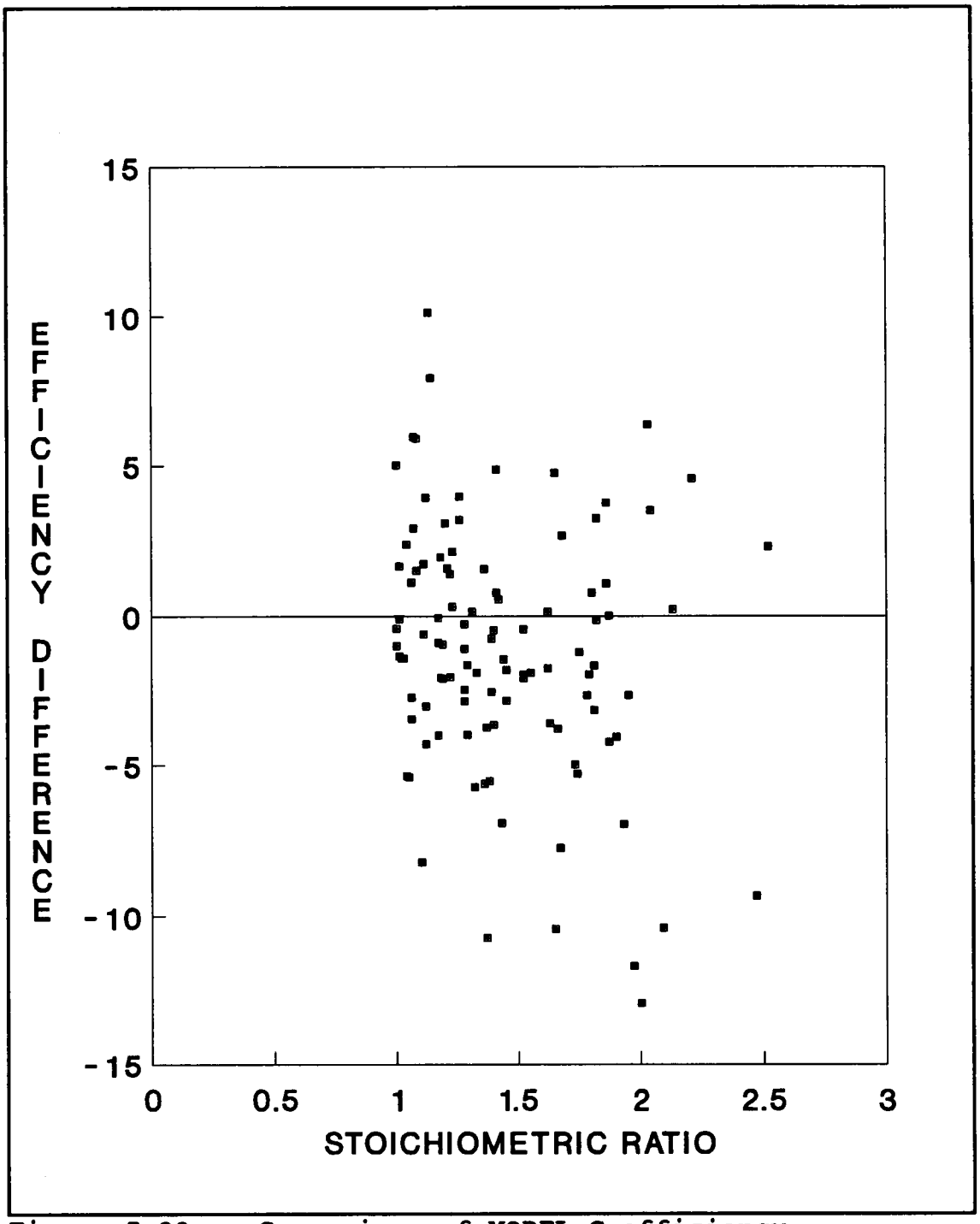

Figure 5.22 Comparison of MODEL C efficiency - experimental efficiency versus stoichiometric ratio

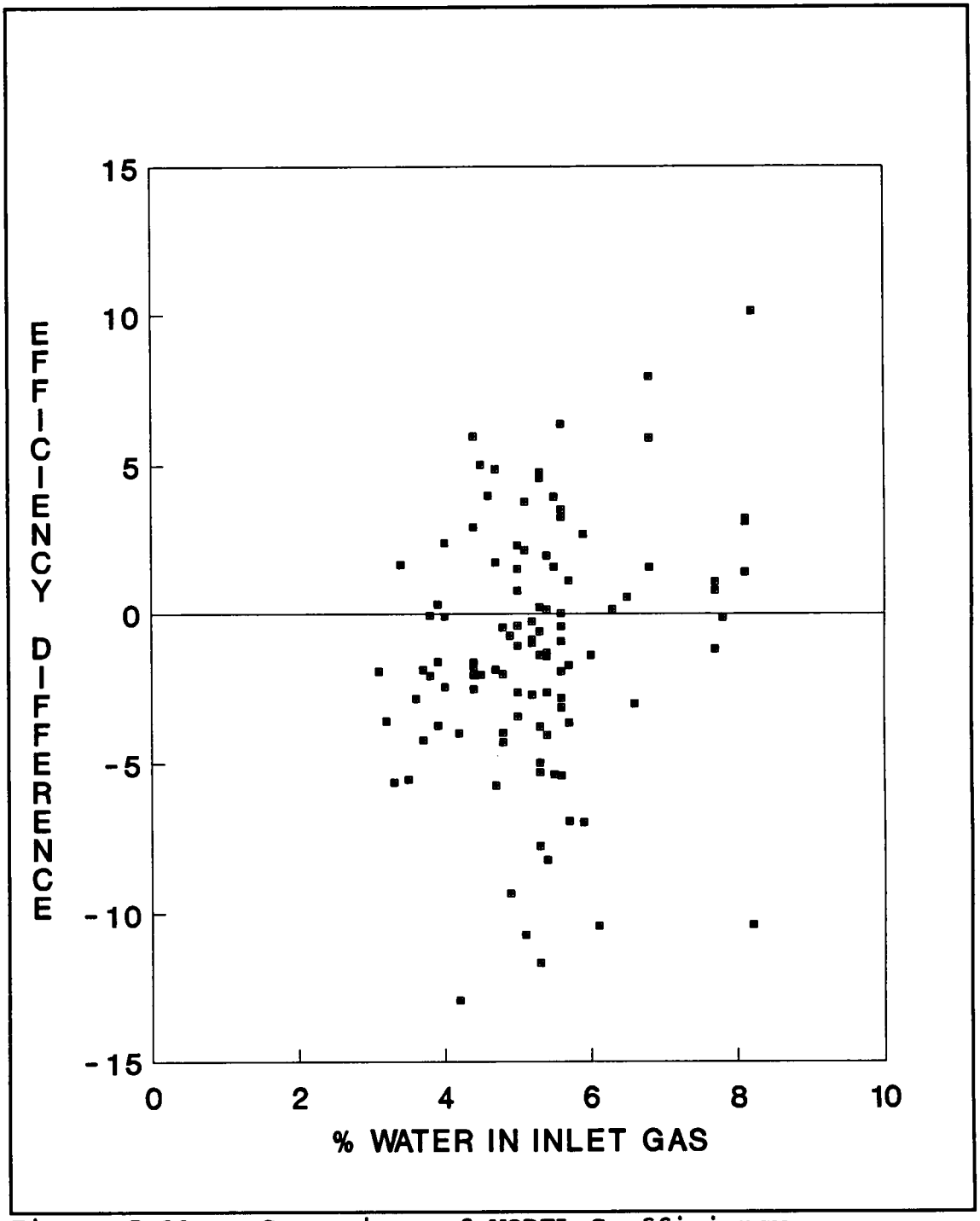

Figure 5.23 Comparison of MODEL C efficiency - experimental efficiency versus percent water in inlet gas

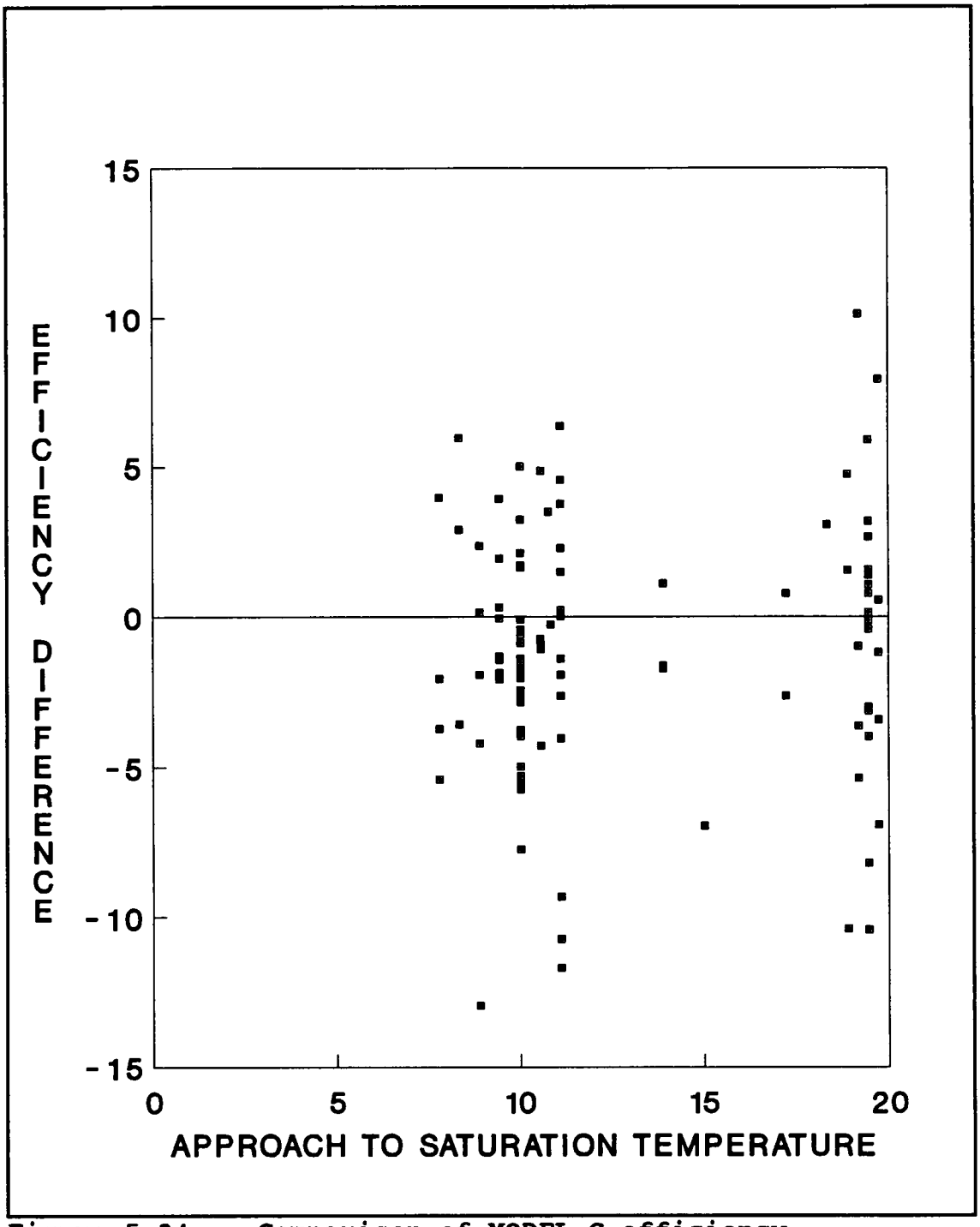

Figure 5.24 Comparison of MODEL C efficiency - experimental efficiency versus the approach to saturation temperature (°C)

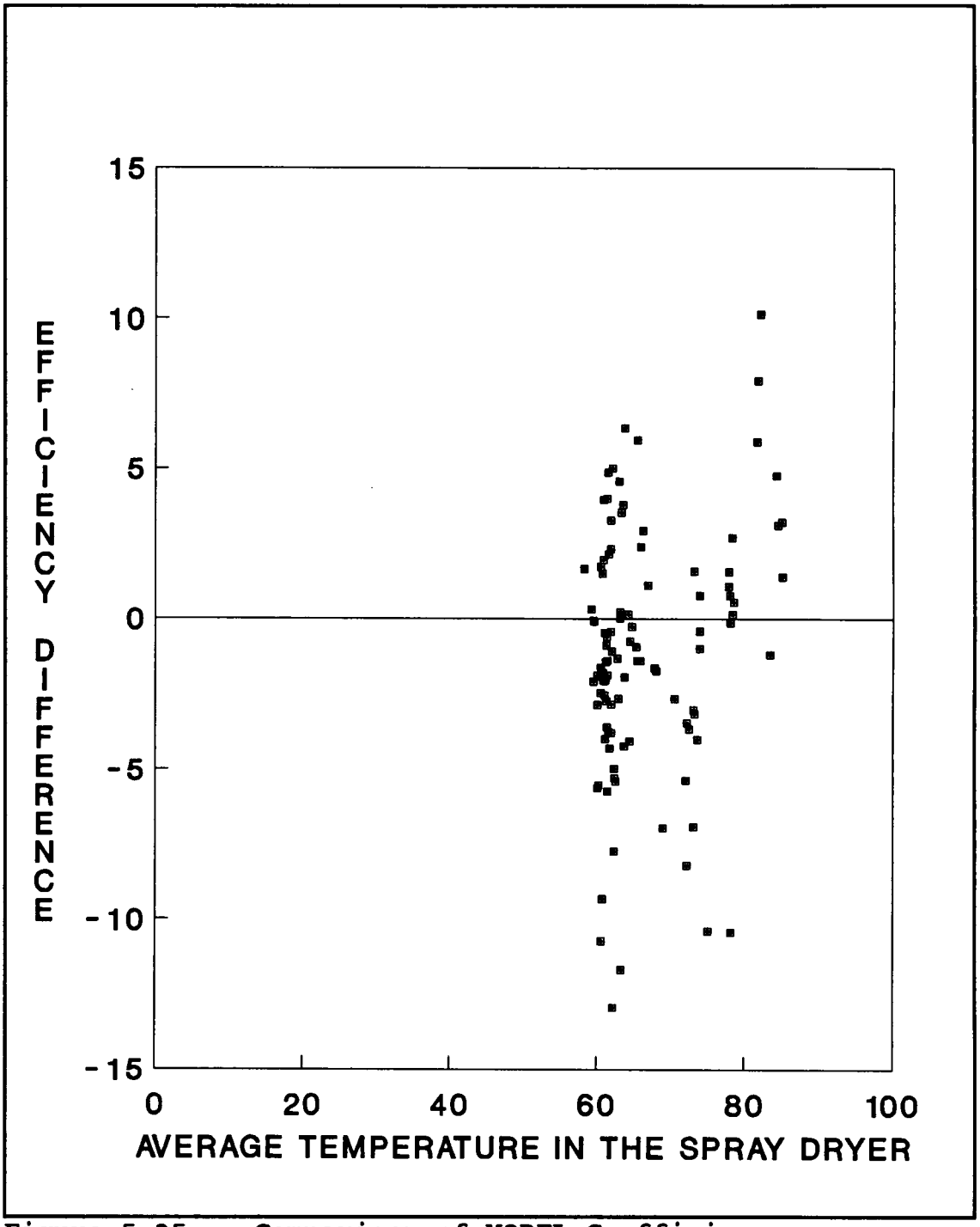

Figure 5.25 Comparison of MODEL C efficiency - experimental efficiency versus the average temperature (°C) in the spray dryer

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The computer simulation SPRAYMOD was developed by the Research Triangle Institute under contract to the EPA to determine SO_2 removal efficiency in a spray dryer. The material and enthalpy balance calculations for the plug flow system of SPRAYMOD were used in developing the mathematical model UTSDM1. UTSDM1 superimposed SO_2 absorption using the constant rate period with the existing SPRAYMOD model describing spray dryer operations. UTSDM1 is based on film theory developed by Partridge (5) and uses a combined individual resistance equation.

After two changes were made in the UTSDM1 calculations for the constant rate period, MODEL C was developed by incorporating the falling rate period into the model. The absorbent surface area and the diffusivity of SO_2 in the liquid phase calculations were the two changes made in UTSDM1. The absorbent surface area was no longer calculated assuming a spherical absorbent particle. In MODEL C, the absorbent surface area is dependent on slaking operations and specific absorbent particle diameter. The liquid phase diffusivity in MODEL C was calculated taking account for effects of reaction product solid in the droplet. MODEL C is based on film theory and it assumes that the $Ca(OH)_2$

particles are evenly dispersed throughout the spherical slurry droplet. A series resistance equation is used to predict SO_2 removal in the falling rate period. The absorption model developed combined the individual resistances for the gas phase mass transfer, liquid phase mass transfer, and absorbent dissolution into a single flux relationship.

When work originated on the model UTSDM1, the model underpredicted SO_2 removal efficiency in a spray dryer. This was the desired result because UTSDM1 only modeled the constant rate period. When the absorbent surface area calculation was corrected and absorbent geometry was no longer assumed spherical, the model (MODEL A) was in good agreement with experimental spray dryer data. But, a trend was observed that showed model overprediction with stoichiometric ratios less than one and under prediction with stoichiometric ratios greater than one. As a result of this trend, the modeling effort continued by concentrating on the cases where the stoichiometric ratio was greater than or equal to one, and a relationship for the falling rate period was included into the model. The new model was called MODEL C. The iterative MODEL B was used to determine an effective diffusivity. The diffusivity was independent of all process variables and therefore taken as the constant 1.4×10^{-4} m^2/s.

In an effort to continue this modeling process, concentration should first be centered on the factors which would cause the higher effective diffusivity found. More study should be given to the gas-solid reaction occurring during the dry stage. In addition, concern should be given to the enthalpy balance during the falling rate period. Presently, the current model predicts a linear increase in droplet temperature throughout the spray dryer. During the falling rate period this is not a correct assumption. Further model development could be to incorporate spray dryer and/or baghouse product recycle.

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APPENDICES

APPENDIX A

DERIVATION OF THE FALLING RATE PERIOD MODEL

Derivation of the Falling Rate Period Model:

$$-r_A = \frac{4\pi R_c \, R_d \, D_E \, (P_{AS} - P_{Ai})}{(R_d - R_c) \, RT} \qquad (A.1)$$

$$-r_A = \pi d_d^2 \, k_{AG} \, (P_{AG} - P_{Ai}) \qquad (A.2)$$

$$-r_A = \pi d_d^2 \, k_{AL} \, (C_{Ai} - 0) \, (x_o / x) \qquad (A.3)$$

$$-r_A = \pi d_c^2 \, k_{BL} \, (C_B - 0) \, \frac{x_o}{x_o - x} \qquad (A.4)$$

$$-r_A = k_s \, (SA) \, (C_s - C_B) \qquad (A.5)$$

$$P_{Ai} = H_A \, C_{Ai} \qquad (A.6)$$

$$\frac{k_{AL}}{k_{BL}} = \frac{\frac{D_{AL}}{x_o}}{\frac{D_{BL}}{x_o}} = \frac{D_{AL}}{D_{BL}} \qquad (A.7)$$

rearranging (A.5)

$$C_B = C_s + \frac{r_A}{k_s \, (SA)} \qquad (A.8)$$

rearranging (A.3)

$$x = \frac{\pi d_c^2 \, k_{AL} \, (C_{Ai} - 0) \, x_o}{-r_A} \qquad (A.9)$$

rearranging (A.2) gives

$$P_{AS} = P_{AG} + \frac{r_A}{\pi d_d^2 \, k_{AG}} \qquad (A.10)$$

substitute x_o from (A.7) into (A.9)

$$x = \frac{\pi d_d^2 \, c_{Ai} \, D_{AL}}{-r_A} \qquad (A.11)$$

substitute (A.11) and x_o from (A.7) into (A.4)

$$-r_A = \frac{\pi d_d^2 \, C_B \, D_{BL}}{\frac{D_{BL}}{k_{BL}} + \frac{d_c^2 \, CAi \, D_{AL}}{r_A}} \qquad (A.12)$$

which equals

$$-r_A \, (D_{BL} / k_{BL}) - \pi d_d^2 \, C_{Ai} \, D_{AL} = \pi d_c^2 \, C_B \, D_{BL} \qquad (A.13)$$

substitute (A.10) into (A.1)

$$\frac{-r_A \, (R_d - R_c) \, RT}{4\pi R_c \, R_d \, D_E} = P_{AG} + \frac{r_A}{\pi d_d^2 \, k_{AG}} - P_{Ai} \qquad (A.14)$$

substitute (A.6) into (A.14)

$$C_{Ai} = \frac{P_{AG}}{H_A} + \frac{r_A}{\pi d_d^2 \, k_{AG} \, H_A} + \frac{r_A \, (R_d - R_c) \, RT}{4\pi R_c \, R_d \, D_E \, H_A} \qquad (A.15)$$

substitute (A.15) and (A.8) into (A.13)

$$-r_A - \frac{D_{BL}}{k_{BL}} - \frac{\pi d_c^2 \, D_{AL} \, r_A}{\pi d_d^2 \, k_{AG} \, H_A} - \frac{\pi d_c^2 \, D_{AL} \, r_A \, (R_d - R_c) \, RT}{4\pi R_c \, R_d \, D_E \, H_A} - \frac{\pi d_c^2 \, D_{BL} \, r_A}{k_s \, (SA)} =$$

$$\frac{\pi d_c^2 \, D_{AL} \, P_{AG}}{H_A} + \pi d_c^2 \, D_{BL} \, C_s \qquad (A.16)$$

factor out $-r_A$ and divide through by area and D_{AL}

(A.17)

$$-N_A = \frac{\frac{P_{AG}}{H_A} + \frac{D_{BL}}{D_{AL}} C_s}{\frac{D_{BL}}{D_{AL} \, k_{BL}} + \frac{d_c^2}{d_d^2 \, k_{AG} \, H_A} + \frac{R_c \, (R_d - R_c) \, RT}{R_d \, D_E \, H_A} + \frac{\pi d_c^2 \, D_{BL}}{D_{AL} \, k_s \, (SA)}}$$

APPENDIX B

COMPUTER PROGRAMS

A. Introduction.

The model developed by Damle (2), SPRAYMOD, simulates the removal of SO_2 in a spray dryer using a lime absorbent. Partridge (5) retained the mass and energy balance from SPRAYMOD and developed a model for the constant rate period. This model, which is based on film theory, is called UTSDM1. The present study makes revisions to the constant rate period described by UTSDM1 and adds theory to account for the falling rate period. The new model is called MODEL C.

B. Computer Input Variables.

Several input variables are required for the model. These are summarized by the program simulation seen in Figure B.1. As seen in the simulation, there are four inlet gas conditions required. The needed gas conditions are; the inlet gas temperature, percent water in the inlet gas, the inlet SO_2 concentration , and the molecular weight of the dry inlet gas.

The inlet operating parameters needed are as follows: adiabatic saturation temperature at the spray dryer outlet, the stoichiometric ratio (moles of $Ca(OH)_2$ / moles of inlet SO_2), the mass fraction of reactive absorbent in fresh solids (which is 1.0 if there is no recycle), the recycle ratio (which is zero for no recycle), the mass fraction of active absorbent in recycle (which is also zero for no recycle), the residence time of the gas phase, the type of

Typical Input Data Set

Inlet Gas Conditions
- Inlet Gas Temperature (TI) - 160 C
- % Water in Inlet Gas (WI) - 6.5%
- Inlet SO_2 Concentration (SI) - 800 ppm
- Molecular Weight of Dry Inlet Gas (MG) - 28.9

Operating Conditions
- Approach to Saturation (AT) - 15 C
- Stoichiometric Molar Ratio (SR) - 1
- Mass Fraction of Absorbent in Fresh Solids (MF) - 1
- Recycle Solids Ratio by Mass (RR) - 0
- Mass Fraction of Absorbent in Recycle (MR) - 0
- Residence Time of Gas Phase (RT) - 10 sec
- Flow System in Spray Dryer - OP = 1 (Plug Flow) - OP = 2 (Backmix)

Absorbent Conditions
- Inlet Droplet Diameter (DO) - 50 μm
- Inlet Droplet Temperature (TW) - 60 C
- Form of Absorbent - Slurry (OS = 1)
- Absorbent Particle Diameter (DP) - 4 μm
- Molecular Weight of Absorbent (MS) - 74
- Density of Solid Absorbent (SG) - 2.2 g/cm3
- Critical Moisture Content (XC) - 29.2 % (mass basis)
- Equilibrium Moisture Content (XE) - 6 % (mass basis)
- Dry Absorbent Reaction Rate Coefficient (KR) - 0

Program Parameters
- Maximum Allowable Time Step (MT) - 0.1 sec
- Time Between Printouts (PT) - 0.5 sec
- Time Step Control Parameter (SC) - 0.01 sec

Figure B.1 Input to MODEL C

mixing occurring in the spray dryer (plug flow or backmix), and an assumed spray dryer efficiency. The assumed efficiency is only used initially in the backmix case.

There are also several $Ca(OH)_2$ conditions required as input data. The inlet droplet diameter is required and is calculated for the model using the following equation developed by Masters (29):

(B.1)

$$D_{vs} = \frac{1.4 \times 10^4 \ (m)^{0.24}}{(Nd)^{0.83} \ (nh)^{0.12}}$$

Other needed inputs to the model include the inlet droplet temperature, form of absorbent (slurry or solution), absorbent mean particle diameter, molecular weight of absorbent (74 g/mole for $Ca(OH)_2$), the density of solid absorbent (2.2 g/cm^3), critical and equilibrium moisture content, and the dry absorbent reaction rate coefficient. In this study, an average value of 3.25 μm was used for the absorbent particle diameter (5).

For the dried droplet, equilibrium moisture content is defined as the water content that would exist if the flue gas were at 100 percent saturation (100 percent relative humidity). This value was approximated by assuming that the moisture content of the product was linearly related to the relative humidity. The average moisture content found in the UT system was approximately 3 percent. The relative

humidity was found to be between 40 and 50 percent. Thus, using a 50 percent relative humidity and a 3 percent moisture content in the product, the equilibrium moisture content for this study was evaluated to be approximately 6 percent (5).

The critical moisture content is defined as the moisture content of water in the droplet when the falling rate period begins. For this study, the critical moisture content was chosen to be 29.2 percent by mass or 47.6 percent by volume (5).

Also added to MODEL C was a condition to the enthalpy balance limiting the difference between the gas temperature and the droplet temperature to never be less than three. It was found that when the $Ca(OH)_2$ was almost completely converted, the solid product layer formed started to impede the loss of heat (28). This instability was accounted for by limiting this temperature difference to never be less than three. Using this stipulation, it was observed that the outlet temperature of both gas and droplet most accurately match know experimental temperatures.

```
10 REM ************************************************************
20 REM
30 REM Program - MODEL C
40 REM
50 REM           Predicts Efficiency of Sulfur Dioxide
60 REM           Removal in a Spray Dryer using Sorbent Spray
70 REM
80 REM           Program for material and energy balance, sorbent solution,
90 REM           and dry particle reaction stage calculations was developed
90 REM           by:  Dr. Ashok S. Damle
100 REM               Research Triangle Institute
110 REM               P. O. Box 12194
120 REM               Research Triangle Park, NC 27709
130 REM
140 REM          Constant rate period model developed
150 REM          by:  George P. Partridge Jr., Wayne T. Davis, and
160 REM               Gregory D. Reed
170 REM               Civil Engineering Department
180 REM               The University of Tennessee
190 REM               Knoxville, Tennessee 37996-2010
200 REM
210 REM          and  Robert M. Counce
220 REM               Chemical Engineering Department
230 REM               The University of Tennessee
240 REM               Knoxville, Tennessee 37996
250 REM
260 REM          Falling rate period model developed
270 REM          by:  Laura W. Lackey, Robert M. Counce, and
280 REM               J.J. Perona
290 REM               Chemical Engineering Department
300 REM               The University of Tennessee
310 REM               Knoxville, Tennessee 37996
320 REM
330 REM          and  Wayne T. Davis
340 REM               Civil Engineering Department
350 REM               The University of Tennessee
360 REM               Knoxville, Tennessee 37996
370 REM
380 REM ************************************************************************
390 REM
400 REM       START DATA INPUT
410 REM
420 REM
430 REM
440 REM      Initialize Default Values
450 REM
460 II = 0!
470 ZZ = 0!
480 AA=0!
490 BB=0!
500 TI=150:WI=10:AT=10:SI=800:DO=60:DP=4:TW=60:MF=1!
510 MG=28.9:MS=74!:SR=1!:RR=0!:OS=1:MR=.3:SG=2.2
520 XC=50:XE=10:RK=0:RT=10:OP=2:NA$="":MT=.1:PT=.5:SC=.01
530 PRINT" Insert Data Disk in Drive A ! "
540 REM
550 PRINT"No. of cases to be calculated? (";N;") - ";:INPUT N
560 CLS
570 PRINT"":PRINT"":PRINT"":PRINT"":PRINT""
580 PRINT"":INPUT"   Enter Datafile Name - ";E$
590 REM
600 OPEN "I", 1, E$
610 INPUT# 1, NA$,TI,WI,SI,MG,AT,SR,MF,RR,MR,RT,OP,DO,TW,OS,DP,MS,SG,XC,XE,RK,MT,PT,SC,P1
620 II = 0!:AA = 0!:XC = 29.2
630 CC = 0!:BB = 0:TFRP=17
640 REM
650 REM      Calculate Surface Area of Lime Particles
```

```
660 SPS1 = -6.4825 + 103.9471*(1/DP)
670 P1I = P1
680 TI=TI+273.15:WI=WI*.01:SI=SI*.000001:LX=(MF+RR*MR)/(1+RR)
690 DO=DO*.0001:TW=TW+273.15:DP=DP*.0001:XC=XC*.01:XE=XE*.01
700 DS = 2.9:MWP = 132.64
710 DE =.00014
720 DE = DE * 10000
730 III = 0:DEL = 9.999999E-16:DEH = 12:DSH = 2.9
740 REM
750 REM
760 REM ************************************************************************
770 REM
780 REM          Calculate Adiabatic Saturation Temperature
790 REM
800 REM ************************************************************************
810 REM
820 WP=WI*760
830 HI=WP*18!/MG/(760-WP)
840 CS=.24+.45*HI
850 T1=330!
860 L=597.64-.275*(T1+TI-546.3)
870 PS=EXP(20.426-5138.8/T1)
880 YP=PS*18!/MG/(760-PS)
890 E1=TI-T1-(YP-HI)*L/CS
900 IF ABS(E1)<.1 GOTO 1070
910 T2=T1+1
920 L=597.64-.275*(T2+TI-546.3)
930 PS=EXP(20.426-5138.8/T2)
940 YP=PS*18!/MG/(760-PS)
950 E2=TI-T2-(YP-HI)*L/CS
960 IF ABS(E2)<.1 GOTO 1080
970 T3=T1-E1*(T1-T2)/(E1-E2)
980 L=597.64-.275*(T3+TI-546.3)
990 PS=EXP(20.426-5138.8/T3)
1000 YP=PS*18!/MG/(760-PS)
1010 E=TI-T3-(YP-HI)*L/CS
1020 IF ABS(E)<.1 GOTO 1060
1030 IF ABS(E1)<ABS(E2) THEN T2=T1
1040 IF ABS(E1)<ABS(E2) THEN E2=E1
1050 E1=E:T1=T3:GOTO 970
1060 TS=T3:GOTO 1090
1070 TS=T1:GOTO 1090
1080 TS=T2:GOTO 1090
1090 TE=AT+TS
1100 TDE = TE - 3
1110 REM
1120 REM ************************************************************************
1130 REM
1140 REM          Overall Material and Energy Balances
1150 REM
1160 REM ************************************************************************
1170 REM
1180 PS=EXP(20.426-5138.8/TS)
1190 HS=PS*18!/MG/(760-PS)
1200 TM=(TI+TE)/2
1210 L=597.64-.55*(TM-273.15)
1220 CS=.24+.45*HS
1230 HO=HS-(TE-TS)*CS/L
1240 WO=HO/(HO+18!/MG)
1250 PS=EXP(20.426-5138.8/TE)
1260 RH=WO*760/PS
1270 XU=RH*XE
1280 GW=1.01*(HO-HI)
1290 GS=SI*SR*MS*(1!+RR)/MF/MG/(1!-WI)
1300 ES=SR*(1!+RR*MR/MF)
1310 XF=GW/(GW+GS)
1320 WO=.52356*DO^3*SG/(1!+(SG-1!)*XF)
1330 TN=GW/XF/WO
1340 IF OS=2 GOTO 1450
```

```
1350 NP=((DO/DP)^3)*(1!-XF)/(1!+(SG-1!)*XF)
1360 SPS = SPS1*10000
1370 SFA = WO*(1-XF)*SPS
1380 REM
1390 REM
1400 REM ************************************************************************
1410 REM
1420 REM    Initialize All Droplet and Gas Phase Variables
1430 REM
1440 REM ************************************************************************
1450 REM
1460 WW=XF*WO
1470 CM=WO*(1!-XF)*LX/MS
1480 CI=WO*(1!-XF)*(1!-LX)/MS
1490 I = 1!
1500 IF OP=2 GOTO 1600
1510 TG=TI:XW=WI:XS=SI:TD=TW:TIMEC=0:SM = 0:ST=0
1520 II = 0:AA = 0
1530 CC = 0:BB = 0:ABC = 0
1540 GOTO 1780
1550 REM
1560 REM       For Backmixed Flow Option Assume SO2 Removal
1570 REM       Efficiency of the Spray Dryer and Calculate
1580 REM       Outlet SO2 Concentration
1590 REM
1600 GOTO 1620
1610 P1=0!:P2=1!
1620 P2=0!
1630 IF ES<1! THEN P2=ES
1640 P1=P1/100!
1650 I=0
1660 REM
1670 REM        Start Trial and Error Sequence to Determine
1680 REM            SO2 Removal Efficiency
1690 REM
1700 I = I + 1!
1710 IF I>1 GOTO 1740
1720 P1=P1*100
1730 P1=P1/100
1740 REM
1750 XS=SI*(1!-P1)*(1!-WO)/(1!-WI):TG=TE:XW=WO:TD=TW
1760 REM
1770 REM
1780 T=0!:TP=0!:ST=0!:D=DO:WD=WO:W=WW:X=XF:UT=0!:III=0
1790 GOTO 4000
1800 REM
1810 REM ************************************************************************
1820 REM
1830 REM    Solve Material and Energy Balance Equations
1840 REM       for Droplet and Gas Phase
1850 REM
1860 REM ************************************************************************
1870 REM
1880 TM=(TD+TG)/2!
1890 DS=2.951E-05*TM^1.5
1900 DW=5.062E-05*TM^1.5
1910 CT=.012194/TM
1920 CO=1.82E-07*TM+.0000079
1930 PW=EXP(20.426-5138.8/TD)
1940 XD=PW/760!
1950 IF XD>1! THEN XD=.9999
1960 IF X<XE THEN XD=XD*X/XE
1970 REM
1980 REM       Rate of Water Evaporation
1990 REM
2000 IF X < XU OR T > (TIMEC + TFRP) GOTO 2210 ELSE GOTO 2030
2010 WM=0! : FW=0!
2020 GOTO 2050
2030 WM=6.2832*DW*CT*D*LOG((1!-XW)/(1!-XD))
```

```
2040 IF X<XC THEN WM=WM*(X-XU)/(XC-XU)
2050 RL=(CM-ABS(ST))/CM
2060 TCD = TD - 273.15
2070 IF TCD > 45 GOTO 2090
2080 SGW = 1.006615 - .0003616*TCD:GOTO 2120
2090 IF TCD > 65 GOTO 2110
2100 SGW = 1.012141 - .000483*TCD:GOTO 2120
2110 SGW = 1.0204777# - .0006102*TCD
2120 STM = (-ST)*MWP
2130 DELW = STM/(STM + W)
2140 E = (DELW/DS)/((DELW/DS) + ((1-DELW)/SGW))
2150 REM
2160 REM
2170 REM       Check for Dry or Wet State of Droplet
2180 REM
2190 IF X<.01 GOTO 2210
2200 IF X > .01 GOTO 2400
2210 II = II + 1!
2220 IF II<2 GOTO 2240
2230 GOTO 2290
2240 TNC = I
2250 REM
2260 TDC = T
2270 REM        Rate of SO2 Absorption in
2280 REM        Dry Particle Stage
2290 REM
2300 IF RL>1E-08 GOTO 2320
2310 SM=0! : GOTO 2330
2320 SM=-RK*XS*CT*RL*CM
2330 FW=WM*18!
2340 FS=SM*64!
2350 GOTO 3230
2360 REM
2370 REM       Rate of SO2 Absorption in
2380 REM       Wet Particle Stage
2390 REM
2400 REM
2410 FW=WM*18
2420 IF RL>1E-08 GOTO 2460
2430 F=0!:SM=0!:FS=0!
2440 GOTO 3230
2450 REM
2460 IF OS=2 GOTO 3230
2470 VS=(1-X)/(1+(SG-1)*X)
2480 LP=DP:LP=(RL*(LP^3!))^.3333
2490 SFAN = SFA:SFAN = RL*SFAN*(LP^2/DP^2)
2500 CL=.00188-1.174E-05*(TD-273.15)
2510 PV = ABS(ST) * MWP/DSH
2520 IF X > XC GOTO 2550
2530 DC = (DFRP^3 - PV/.5236)^(1/3)
2540 NPF = NP * (DC^3/DFRP^3)
2550 REM
2560 REM       Calculate Film Thickness
2570 REM
2580 BT=(1!/VS^.333)-1!:FILMT=.5*BT*LP:FILMTL=.5*LP
2590 REM
2600 REM       Calculate Dissolution Rate Reduction due to
2610 REM         Product Precipitation and Inert Solids
2620 REM
2630 RF=1!+(2.108*ABS(ST)+CI)/(CM-ABS(ST)):RF=1!
2640 PN=(1.3272*(20!-TCD)-.001053*(TCD-20!)^2!)/(TCD+105!)
2650 DAL1=(5.1735E-08*TD)/(1.002*10!^PN)
2660 DAL = DAL1*(1 - E)
2670 DBL=(5.472E-08*TD)/(1.002*10!^PN)
2680 KG=(2!*DS)/D
2690 KAL=DAL/FILMT:KALL=(13.1595*DAL)/D:IF KAL<KALL THEN KAL=KALL
2700 IF X > XC GOTO 2720
2710 KAL1=DAL1/FILMT:KALL=(13.1595*DAL1)/DFRP:IF KAL1<KALL THEN KAL1=KALL
2720 IF TCD>45! GOTO 2750
```

```
2730 RHO=1.006615-.0003616*TCD
2740 GOTO 2790
2750 IF TCD>65! GOTO 2780
2760 RHO=1.012141-.000483*TCD
2770 GOTO 2790
2780 RHO=1.020478-.0006102*TCD
2790 IF TCD>45! GOTO 2820
2800 KO=.13846*TCD-.55
2810 GOTO 2860
2820 IF TCD>65! GOTO 2850
2830 KO=.18376*TCD-2.6176
2840 GOTO 2860
2850 KO=.2281143*TCD-5.492191
2860 KO=KO*(10!^4!):IF FILMT>FILMTL THEN FILMT=FILMTL
2870 HA=((2.88745E-04)*(KO-760!))/(RHO*TD)
2880 REM          CHECK FOR FALLING RATE PERIOD
2890 IF X<XC GOTO 2920
2900 R=1/(KG*HA)+1/KAL+(3.141593*FILMT*RF*D^2!)/(SFAN*DAL)
2910 C=(CT*XS)/HA+(DBL*CL)/(DAL*MS):GOTO 3170
2920 III = III + 1
2930 IF III=1 AND (XS*1000000!)<S2 THEN GOTO 4090
2940 IF III<2 THEN TIMEC = T:TGC = TG:TDC = TD
2950 DT1 = TGC - TDC
2960 DT2 = TE - TDE:TMF = (TGC + TE)/2
2970 DELT = (DT1 - DT2)/LOG(DT1/DT2)
2980 COF= 1.82E-07*TMF + .0000079
2990 LT = 597.64 - .55*(TMF - 273.15)
3000 TBTC = TMF - 273.15
3010 IF TBTC > 45 GOTO 3030
3020 SGW1 = 1.006615 - .0003616*TBTC
3030 IF TBTC > 65 GOTO 3050
3040 SGW1 = 1.012141 - .000483*TBTC:GOTO 3060
3050 SGW1 = 1.020477 - .0006102*TBTC
3060 REM SPECIFIC GRAVITY OF WATER CALCULATED ABOVE
3070 XEP = XE/100
3080 SS = (XEP/SGW1) + ((1 - XEP)/DSH)
3090 DSF = XEP*SGW1 + (1-XEP)*DSH
3100 IF III<2 THEN TFRP = (LT*(XC - XE)*DSF*DFRP^2)/(12*COF*DELT)
3110 RD=DFRP/2:RP=LP/2:RC=DC/2:GC=82.06:KG=(2*DS)/DFRP
3120 R1 = 1/KAL1 + (DC^2/(DFRP^2*KG*HA)) + (RC*(RD-RC)*GC*TD)/(RD*DE*HA)
3130 R2 = (3.141593*DC^2*FILMT)/(DAL1*SFAN)
3140 R = R1 + R2
3150 C = (CT*XS)/HA + (DBL*CL)/(DAL1*MS)
3160 F=-((3.141593*DFRP^2!)*C)/R:GOTO 3180
3170 F=-((3.141593*D^2)*C)/R
3180 SM=F
3190 FS=F*64.06:IF X<XC GOTO 3210
3200 GOTO 4500
3210 REM        RATE OF HEAT TRANSFER
3220 REM
3230 IF WM=0! AND ABS(TG-TD)<.2 THEN Q=0! :GOTO 3310
3240 EP=1.289*WM/CO/D
3250 IF EP<9.999999E-06 THEN EP=9.999999E-06
3260 Q=6.2832*CO*D*(TG-TD)*EP/(EXP(EP)-1)
3270 REM
3280 REM       Calculate Derivative Functions and
3290 REM          set Time Step DT
3300 REM
3310 F1=(Q-WM*10080)/WD
3320 F2=-FW-FS
3330 IF F1=0! THEN D1=1000:GOTO 3350
3340 D1=SC*(TD-273!)/ABS(F1)
3350 IF F2=0! THEN D2=1000:GOTO 3370
3360 D2=SC*WD/ABS(F2)
3370 DT=D1
3380 IF D2<D1 THEN DT=D2
3390 IF DT>MT THEN DT=MT
3400 REM
3410 IF OP=2 GOTO 3590
```

```
3420 REM
3430 REM        Calculate Change in Gas Phase Variables
3440 REM           ( for OP=1 )
3450 REM
3460 CS=.24+(.446*18!*XW)/(MG*(1!-XW))
3470 DG=Q*DT*TN/CS
3480 IF (TG-TD)<3 GOTO 3500
3490 TG=TG-DG
3500 SD=SM*DT*TN*(1!-XW)*MG
3510 XS=XS+SD
3520 DX=WM*DT*TN*(1!-XW)*MG
3530 XW=XW+DX
3540 XS=XS/(1!+DX):XW=XW/(1!+DX)
3550 REM
3560 REM        Calculate Change in Droplet Variables during
3570 REM             Time Step DT
3580 REM
3590 T=T+DT
3600 ST=ST+SM*DT
3610 UT=-ST/CM
3620 IF (TG-TD)<3 GOTO 3640
3630 TD=TD+F1*DT
3640 IF OS = 2 GOTO 3810
3650 REM
3660 REM       For Slurry Option (OS = 1)
3670 REM       Ca(OH)2 + SO2 + H2O = CaSO3.2H2O  Reaction is
3680 REM       Assumed and the Change in Weight of Droplet and
3690 REM       Water Content are Calculated Accordingly.
3700 REM
3710 WD=WD+F2*DT
3720 W=W-FW*DT+18!*SM*DT
3730 IF W<0 THEN W=0
3740 GOTO 3850
3750 REM
3760 REM       For Solution Option (OS=2)
3770 REM       Na2CO3 + SO2 = Na2SO3 + CO2  Reaction is Assumed
3780 REM       and the Change in Weight of Droplet and Water
3790 REM       Content are Calculated Accordingly.
3800 REM
3810 WD=WD+F2*DT+44!*SM*DT
3820 W=W-FW*DT
3830 IF W<0 THEN W=0
3840 REM
3850 X=W/WD
3860 IF X<XC THEN ABC = ABC + 1
3870 IF ABC < 2 THEN DFRP = D
3880 D=((WD+(SG-1)*W)/SG/.52356)^(1!/3!)
3890 REM
3900 REM        Check for Zero SO2 Removal During Last Time Step
3910 REM
3920 IF SM=0! GOTO 4000
3930 REM
3940 REM        Check for End Time and Printout Times
3950 REM
3960 IF T>RT THEN PRINT "T>RT"
3970 IF T>RT GOTO 4000
3980 IF T<TP GOTO 1880
3990 TP=T+TP
4000 REM
4010 REM
4020 IF T=0 GOTO 1880
4030 IF SM = 0 THEN PRINT "SM = 0"
4040 IF SM=0! GOTO 4120
4050 IF T>RT GOTO 4120
4060 GOTO 1880
4070 REM
4080 DE = 0
4090 PRINT"CONSTANT RATE PERIOD OVER PREDICTS SO2 REMOVAL"
4100 REM      Calculate SO2 Removal Efficiency
```

```
4110 REM
4120 EF=ES*UT
4130 PRINT:PRINT:PRINT:PRINT:PRINT
4140 IF OP=1 GOTO 4340
4150 P2=EF
4160 IF P2>1! THEN P2=1!
4170 P3=ABS(P1-P2)
4180 IF P3<.02 GOTO 4280
4190 IF I=1 THEN PA=P1:PB=(P1+P2)/2:GOTO 4260
4200 PC=(P1+P2)/2
4210 IF ABS(PC-PB)<ABS(PB-PA) GOTO 4250
4220 IF (PB-PC)/(PB-PA) > 0! THEN PC=(PA+PB)/2
4230 IF (PB-PC)/(PB-PA) < 0! THEN PC=1.5*PB-PA/2
4240 P2=2!*PC-P1
4250 PA=PB:PB=PC
4260 P1=(P1+P2)/2!
4270 GOTO 1690
4280 EF=(P1+P2)/2:XS=SI*(1!-EF)*(1!-WO)/(1!-WI)
4290 REM
4300 REM
4310 CC = CC + 1!
4320 REM
4330 IF CC<2! GOTO 4010
4340 GOTO 4350
4350 REM
4360 REM       Check for Remaining Datasets
4370 REM
4380 N=N-1!
4390 ZZ = ZZ + 1!
4400 IF ZZ>1! GOTO 4430
4410 OPEN "DATA" FOR OUTPUT AS #2
4420 GOTO 4440
4430 REM
4440 PRINT# 2,
CHR$(34);NA$;CHR$(34);TI,WI,SI,MG,AT,SR,MF,RR,MR,RT,OP,DO,TW,OS,DP,MS,SG,XC,XE,RK,MT,PT,SC,P1I,TE,TS
,WO,RH,TNC,TGC,T,TG,TD,DFRP,X,XW,XS,UT,I,EF
4450 PRINT"No. of cases still to be calculated = ";N
4460 IF N>0 GOTO 610
4470 CLOSE #1
4480 CLOSE #2
4490 STOP
4500 COND=(.1218*SFAN*(DAL^2!))/(FILMT*(D^3!)*(KAL^2!))
4510 IF COND<1! GOTO 4570
4520 PRINT" SOLID DISSOLUTION IN LIQUID FILM IS IMPORTANT"
4530 PRINT" MODEL DOES NOT APPLY - N = ";N
4540 PRINT" COND = ";COND
4550 PRINT" TIME = ";T
4560 GOTO 4380
4570 REM
4580 GRATE=KG*3.141593*(D^2!)*CT*XS
4590 DRATE=SFAN*(DBL/(FILMT*RF))*(CL/MS)
4600 CONCB=(CL/MS)+((F*FILMT*RF)/(SFAN*DBL))
4610 MODELR=-F
4620 IF GRATE>MODELR GOTO 4670
4630 F=-GRATE
4640 SM=F
4650 FS=F*64.06
4660 GOTO 4710
4670 IF CONCB>0! GOTO 4710
4680 F=-DRATE
4690 SM=F
4700 FS=F*64.06
4710 REM
4720 GOTO 3210
```

```
10 PRINT" THIS PROGRAM CREATES A SEQUENTIAL INPUT DATA FILE FOR SPRYAMOD-M"
20 GOTO 40
30 CLS
40 PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" "
50 PRINT"       Dataset Name - ";NA$;"  ";:INPUT NA$
60 PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" "
70 PRINT"            Do you want to redo this screen  ";
80 REDO$="":INPUT REDO$ : R$ = LEFT$ (REDO$,1)
90 IF R$ = "y" OR R$ = "Y" GOTO 30
100 CLS
110 PRINT" ":PRINT" "
120 PRINT"  Inlet Gas Conditions - ":PRINT" ":PRINT" "
130 PRINT" ":PRINT"Finished entering data ? If yes, enter TI=0.0"
140 PRINT"     Inlet Gas Temperature (";TI;"C) - ";:INPUT TI
150 IF TI=0! THEN CLOSE: END
160 PRINT" ":PRINT"     % Water Vapor in Inlet Gas (";WI;") - ";:INPUT WI
170 PRINT" ":PRINT"     Inlet SO2 Concentration (";SI;"ppm) - ";:INPUT SI
180 PRINT:PRINT"     Molecular Weight of Dry Inlet Gas (";MG;") - ";:INPUT MG
190 PRINT" ":PRINT" "
200 PRINT"                    Do you want to redo this screen ";
210 REDO$="":INPUT REDO$ : R$ = LEFT$ (REDO$,1)
220 IF R$ = "y" OR R$ = "Y" GOTO 100
230 CLS:PRINT"":PRINT"":PRINT"  Operating Parameters -":PRINT" "
240 PRINT"     Approach to Saturation (";AT;"C) - ";:INPUT AT
250 PRINT"     Stoichiometric Molar Ratio (";SR;") - ";:INPUT SR
260 PRINT"     Mass Fraction of Reagent in Fresh Solids (";MF;") - ";:INPUT MF
270 PRINT"     Recycle Solids Ratio by Mass (";RR;") - ";:INPUT RR
280 PRINT"     Mass Fraction of Reagent in Recycle (";MR;") - ";:INPUT MR
290 PRINT"     Residence Time of Gas Phase (";RT;"sec) - ";:INPUT RT
300 PRINT"     Gas Flow Pattern (Plug Flow=1,Backmixed=2) (";OP;") - ";:INPUT OP
310 PRINT" ":PRINT"                    Do you want to redo screen ";
320 REDO$="":INPUT REDO$ : R$ = LEFT$ (REDO$,1)
330 IF R$ = "y" OR R$ = "Y" GOTO 230
340 CLS:PRINT"":PRINT"  Sorbent Properties - ":PRINT" "
350 PRINT"     Inlet Droplet Diameter (";DO;"um) - ";:INPUT DO
360 PRINT"     Inlet Droplet Temperature (";TW;"C) - ";:INPUT TW
370 PRINT"     Form of Sorbent (Slurry=1,Solution=2) (";OS;") - ";:INPUT OS
380 IF OS = 2 GOTO 400
390 PRINT"     Sorbent Particle Diameter (";DP;"um) - ";:INPUT DP
400 PRINT"     Molecular Weight of Sorbent (";MS;") - ";:INPUT MS
410 PRINT"     Density of Solid Sorbent (";SG;"gm/cm3) - ";:INPUT SG
420 PRINT"     Critical Moisture Content (";XC;"%) - ";:INPUT XC
430 PRINT"     Equilibrium Moisture Content (";XE;"%) - ";:INPUT XE
440 PRINT"     Dry Sorbent Reaction Rate Coeff. (";RK;"cm3/gmole/sec) - ";:INPUT RK
450 PRINT" ":PRINT"                  Do you want to redo this screen ";
460 REDO$="":INPUT REDO$ : R$ = LEFT$ (REDO$,1)
470 IF R$ = "y" OR R$ = "Y" GOTO 340
480 CLS:PRINT" ":PRINT" "
490 PRINT"  Program Parameters -":PRINT" ":PRINT" "
500 PRINT"     Maximum Allowable Time Step (";MT;"sec) - ";:INPUT MT
510 PRINT" ":PRINT"     Time between Output Printouts (";PT;"sec) - ";:INPUT PT
520 PRINT" ":PRINT"     Time Step Control Parameter (";SC;") - ";:INPUT SC
530 PRINT" ":PRINT"     Assumed Efficiency of Spray Dryer (";P1;"%) - ";:INPUT P1
540 PRINT" ":PRINT" ":PRINT"                  Do you want to redo this screen ";
550 REDO$="":INPUT REDO$ : R$ = LEFT$ (REDO$,1)
560 IF R$ = "y" OR R$ = "Y" GOTO 480
570 PRINT"":PRINT"          Would you like to review complete data set";
580 RE$="":INPUT RE$ : R$ = LEFT$ (RE$,1)
590 IF R$ = "y" OR R$ = "Y" GOTO 30
600 CLS:PRINT"":PRINT"":PRINT"":PRINT""
610 PRINT"                  DATA INPUT DONE"
620 REM
630 PRINT"":INPUT"  Enter a Datafile Name for This Dataset - ";E$
640 PRINT" Are you creating a new file ? Y/N"
650 A$ =INKEY$:IF A$ ="" THEN 650
660 IF A$ = "N" OR A$ = "n" THEN 690
670 OPEN E$ FOR OUTPUT AS #1
680 GOTO 700
690 OPEN E$ FOR APPEND AS #1
```

```
700 PRINT# 1,
CHR$(34);NA$;CHR$(34);TI,WI,SI,MG,AT,SR,MF,RR,MR,RT,OP,DO,TW,OS,DP,MS,SG,XC,XE,RK,MT,PT,SC,P1
710 CLOSE #1
720 GOTO 30
```

```
10 REM ******************************************************
20 REM
30 REM THIS PROGRAM READS THE OUTPUT DATA FILE FOR SPRAYMOD-M
40 REM
50 REM ******************************************************
60 REM
70 PRINT"No. of cases to be read ? (";N;") - ";:INPUT N
80 OPEN "DATA" FOR INPUT AS 2
90 INPUT
#2,NA$,TI,WI,SI,MG,AT,SR,MF,RR,MR,RT,OP,DO,TW,OS,DP,MS,SG,XC,XE,RK,MT,PT,SC,P1I,TE,TS,WO,RH,TNC,TGC,
T,TG,TD,DFRP,X,XW,XS,UT,I,EF,DC,TIMEC,TIMEF,DE
100 REM ************************************************************************
110 REM
120 REM     Printout Data Values
130 REM
140 REM ************************************************************************
150 REM
160 TI=TI-273.15:WI=WI*100!:SI=SI*1000000!
170 DO=DO*10000!:TW=TW-273.15:DP=DP*10000!
180 XC=XC*100!:XE=XE*100!:DE=DE/10000
190 LPRINT""
200 LPRINT"            *** SPRAY DRYER MODEL PREDICTIONS ****"
210 LPRINT"":LPRINT"":LPRINT"   Input Dataset - ";NA$
220 LPRINT"":LPRINT"   Inlet Gas Conditions - ":LPRINT""
230 LPRINT"      Inlet Gas Temperature - ";TI;"C"
240 LPRINT"      % Water in Inlet Gas - ";WI;"%"
250 LPRINT"      Inlet SO2 Concentration - ";SI,"ppm"
260 LPRINT"      Molecular Weight of Dry Inlet Gas - ";MG
270 LPRINT"":LPRINT"   Operating Parameters - ":LPRINT""
280 LPRINT"      Approach to Saturation - ";AT;"C"
290 LPRINT"      Stoichiometric Molar Ratio - ";SR
300 LPRINT"      Mass Fraction of Sorbent in Fresh Solids - ";MF
310 LPRINT"      Recycle Solids Ratio by Mass - ";RR
320 LPRINT"      Mass Fraction of Sorbent in Recycle - ";MR
330 LPRINT"      Residence Time of Gas Phase - ";RT;"sec"
340 IF OP=2 GOTO 370
350 LPRINT"      Flow System in Spray Dryer - Plug Flow"
360 GOTO 380
370 LPRINT"      Flow System in Spray Dryer - Completely Backmixed"
380 LPRINT"":LPRINT"   Sorbent Properties - ":LPRINT""
390 LPRINT"      Inlet Droplet Diameter - ";DO;"um"
400 LPRINT"      Inlet Droplet Temperature - ";TW;"C"
410 IF OS=1 GOTO 440
420 LPRINT"      Form of Sorbent - Solution"
430 GOTO 460
440 LPRINT"      Form of Sorbent - Slurry"
450 LPRINT"      Sorbent Particle Diameter - ";DP;"um"
460 LPRINT"      Molecular Weight of Sorbent - ";MS
470 LPRINT"      Density of Solid Sorbent - ";SG;"gm/cm3"
480 LPRINT"      Critical Moisture Content - ";XC;"%"
490 LPRINT"      Equilibrium Moisture Content - ";XE;"%"
500 LPRINT"      Dry Sorbent Reaction Rate Coefficient - ";RK;"cm3/gmole/sec"
510 LPRINT"      Assumed Spray Dryer Efficiency - ";P1I;"%"
520 LPRINT"":LPRINT"   Program Parameters - ":LPRINT""
530 LPRINT"      Maximum Allowable Time Step - ";MT;"sec"
540 LPRINT"      Time between Printouts - ";PT;"sec"
550 LPRINT"      Time Step Control Parameter - ";SC
560 LPRINT"":LPRINT""
570 REM       Print Exit Gas Conditions
580 REM
590 LPRINT"   Exit Gas Temperature and Humidity ":LPRINT""
600 LPRINT"      Exit Gas Temperature - ";TE-273.15;"C"
610 LPRINT"      Adiabatic Saturation Temperature - ";TS-273.15;"C"
620 LPRINT"      % Water Vapor in Exit Gas - ";WO*100;"%"
630 LPRINT"      % Relative Humidity of Exit Gas - ";RH*100;"%"
640 LPRINT"":LPRINT""
650 LPRINT"Dry Particle Stage Calculations Started At Trial No.";TNC
660 LPRINT"  "
665 LPRINT "CONSTANT RATE PERIOD TIME = ";TIMEC
```

```
666 LPRINT "FALLING RATE PERIOD TIME = ";TIMEF
670 LPRINT"TIME(SEC)=";T
680 LPRINT"  "
690 LPRINT "AVG TEMP IN SPRAY DRYER DURING FRP(C) = ";(TG+TGC)/2-273.15
700 LPRINT "DROP TEMP(C)=";TD-273.15;"   DROP DIAMETER(UM)=";DFRP*10000!
705 LPRINT "EFFECTIVE DIFFUSIVITY(M^2/S)=";DE
710 LPRINT "% WATER IN DROPLET=";X*100;"      WATER MOLE FRACTION IN GAS=";XW
715 LPRINT "CORE DIAMETER(UM) = ";DC*10000
720 LPRINT"SO2 CONCENTRATION IN GAS PHASE(PPM)=";XS*1000000!;"      % LIME USED IN DROP=";UT*100
730 LPRINT"  "
740 LPRINT"Trials Required = ";I
750 LPRINT " "
760 LPRINT"% SO2 REMOVAL EFFICIENCY=";EF*100
770 LPRINT"EXIT SO2 CONCENTRATION(PPM)=";XS*1000000!
780 LPRINT" "
790 LPRINT" "
800 LPRINT" "
810 N = N - 1!
820 IF N>0! GOTO 90
830 CLOSE #2
840 STOP
```

APPENDIX C

SPRAY DRYER PILOT PLANT DATA AND OPERATING PARAMETERS

LIST OF ABBREVIATIONS

ACFM3	Actual cubic feet per minute of gas flow measured at Port 3 (after the baghouse)
CS1	SO_2 concentration at Port 1 corrected for air leakage into pilot plant dryer system (ppm)
DT	Approach to saturation (°F)
DVS	Calculated slurry droplet diameter using equation developed by Master(25), μm
F1	Fractional moisture content in flue gas at Port 1
GPM	Slurry feed rate to pilot spray dryer (gpm)
ID	Data identification number
SCFM1C	Standard cubic feet per minute at Port 1 corrected for air leakage into pilot spray dryer system
SLC	Slurry concentration (lb/gal CaO)
SPREFF	SO_2 removal efficiency across pilot spray dryer for pilot data (%)
SR	Stoichiometric molar ratio
T2	Temperature of flue gas at Port 2 (°F)
TEMP1C	Temperature of flue gas at Port 1 corrected for air leakage into pilot spray dryer system (°F)
TW2	Wet bulb temperature at spray dryer outlet (°F)

DATA SET 1

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
10188201	136	0.000	0.210	891	735	313
10118202	134	0.127	0.226	880	738	306
10198203	134	0.262	0.210	881	737	306
10118204	133	0.450	0.230	886	740	307
10118205	133	0.700	0.269	889	740	303
10118206	133	0.820	0.260	898	736	303
10198204	134	0.500	0.220	884	736	306
07128202	137	0.367	0.262	887	731	279
07128201	137	0.840	0.260	885	731	279
07098205	134	0.375	0.288	885	747	276
07098204	134	0.189	0.240	881	749	276
07098203	133	0.694	0.245	879	748	274

ID	CS1	SPREFF	SR	DVS	F1	DT
10188201	1027	5.3	0.000	77.7	0.052	20
10118202	1163	41.7	0.230	79.3	0.048	20
10198203	1091	54.9	0.470	78.2	0.048	20
10118204	1037	77.3	0.927	80.2	0.052	20
10118205	979	83.5	1.780	83.7	0.054	20
10118206	1013	92.8	1.970	83.2	0.053	20
10198204	1044	88.9	0.985	79.4	0.047	20
07128202	840	74.6	1.080	82.6	0.050	20
07128201	811	80.3	2.520	83.2	0.050	20
07098205	725	88.4	1.370	84.5	0.051	20
07098204	710	62.8	0.586	80.6	0.051	20
07098203	633	93.3	2.470	81.8	0.049	20

DATA SET 2

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
83021702	129	0.00	.160	813	673	305
83021703	129	0.00	.150	818	671	303
83021401	130	0.49	.191	758	619	313
83021402	130	0.49	.247	733	603	309
83021403	129	0.49	.182	710	584	307
83021701	129	0.00	.190	814	675	295
83022101	129	0.59	.271	806	690	302
83022102	129	0.59	.235	806	691	300
83022103	129	0.59	.242	806	691	300
83022104	130	0.59	.277	806	691	299
83022105	129	0.59	.247	806	691	298
83022203	130	0.60	.240	804	676	308
83022204	130	0.60	.260	800	677	312
83022205	130	0.60	.250	800	676	318
83022301	129	0.00	.196	817	672	299
83022302	128	0.00	.227	817	673	296
83022303	128	0.00	.182	817	673	293
83022401	133	0.60	.210	819	664	295
83022402	132	0.60	.260	821	660	310
83022403	133	0.60	.246	820	662	303
83022404	133	0.60	.240	819	664	298
83055405	133	0.60	.200	820	664	293
83022406	133	0.60	.200	820	664	295
83022501	129	0.60	.237	811	675	310
83022502	129	0.60	.237	811	675	312
83022503	128	0.60	.251	812	673	317
83022801	127	0.60	.260	812	683	306
83022802	127	0.60	.250	812	683	306
83022803	127	0.60	.240	812	684	304
83022804	127	0.60	.224	812	684	305
83020701	130	0.80	.240	815	681	301
83020107	127	0.00	.240	820	711	309
83020106	127	0.00	.240	822	710	311
83020105	127	0.00	.230	822	710	311
83020104	127	0.00	.240	832	718	311
83020103	127	0.00	.240	803	693	309
83020102	127	0.00	.240	804	692	308
83020101	130	0.00	.210	806	692	304
83020301	130	0.59	.240	807	684	305
83020302	129	0.59	.210	816	691	303
83020303	130	0.59	.210	764	648	302
83020304	129	0.59	.230	816	690	305
83020305	129	0.59	.230	806	681	305
83020401	131	0.69	.250	842	698	301
83020402	131	0.69	.220	817	683	300
83020403	131	0.69	.213	773	649	300

83020404	130	0.69	.218	837	698	305
83020405	130	0.69	.227	806	672	304
53020702	130	0.80	.240	785	654	300
83020703	130	0.80	.242	818	678	301
83020704	130	0.80	.212	788	651	300
83020706	130	0.52	.232	841	695	300
83020707	129	0.52	.236	798	662	297
83020708	129	0.52	.200	809	669	297
83020709	129	0.52	.215	776	644	296
83040401	128	0.40	.228	823	678	296
83040402	128	0.40	.218	823	678	294
83040403	128	0.40	.225	823	678	294
83040404	127	0.43	.222	822	678	295
83040405	128	0.43	.203	822	678	296
83040601	132	.317	.25	825	671	311
83040602	133	.317	.226	824	673	307
83040603	132	.314	.237	824	672	308
83040604	132	.314	.229	814	665	304
83040605	132	.314	.205	804	657	302
83041101	129	0.43	.238	839	680	300
83041102	128	0.43	.237	825	681	305
83041103	128	0.43	.236	823	682	304
83041104	128	0.44	.227	823	682	303
83041105	128	0.44	.264	803	666	299
83041106	128	0.44	.266	793	658	295
83041201	127	.318	.249	822	684	305
83041202	127	.318	.220	812	677	300
83041203	127	.318	.240	812	675	308
83041204	127	0.33	.254	801	667	308
83041205	127	0.33	.248	792	660	299
83041206	127	0.33	.221	802	668	300
83050307	131	.368	.212	810	652	293
83050306	131	.368	.213	821	660	293
83050305	131	.363	.205	822	659	298
83050304	131	.363	.207	821	661	290
83050303	131	.363	.223	822	660	292
83050302	131	.363	.223	822	661	288
83050301	131	.363	.225	825	660	287

ID	CS1	SPREFF	SR	DVS	F1	DT
83021702	1058	0	0	72.9	.038	19
83021703	1100	3.5	0	71.7	.039	19
83021401	983	82.3	1.06	76.8	.045	19
83021402	980	75.8	1.41	81.7	.047	19
83021403	949	78.6	1.11	75.9	.047	18
83021701	1104	-2.2	0	75.9	.041	19
83022101	1207	84.2	1.32	83.7	.047	18
83022102	1140	81.3	1.21	80.9	.048	18
83022103	1168	80.3	1.22	81.5	.048	18
83022104	1192	81	1.12	80.2	.048	19

83022105	1126	82.5	1.29	81.9	.048	18
83022203	1143	81.4	1.28	81.3	.036	18
83022204	1149	85.4	1.38	82.9	.035	18
83022205	1124	86.2	1.36	82.1	.033	18
83022301	1100	.9	0	76.5	.044	18
83022302	1040	1.7	0	79.2	.045	17
83022303	1020	3.8	0	75.1	.046	17
83022401	1117	78.8	1.17	78.7	.052	18
83022402	1052	83.4	1.55	82.9	.047	18
83022403	1198	80.2	1.28	81.8	.05	19
83022404	1212	75.7	1.23	81.3	.051	18
83022405	1222	77.7	1.02	77.8	.053	18
83022406	1172	79.8	1.06	77.8	.052	18
83022501	1133	82.1	1.28	81.1	.04	18
83022502	1127	81.5	1.29	81.1	.039	18
83022503	1158	82.9	1.33	82.2	.037	17
83022801	1133	82.2	1.39	82.9	.044	18
83022802	1044	82.4	1.45	82.1	.044	18
83022803	1170	81	1.24	81.3	.045	18
83022804	1143	80.8	1.18	80	.045	18
83020701	1164	87.8	1.67	81.6	.053	18
83020107	1074	.6	0	80.3	.03	18
83020106	1089	2.3	0	80.3	.029	18
83020105	1112	3.8	0	79.5	.029	18
83020104	1144	2.1	0	80.3	.029	18
83020103	1160	7.1	0	80.3	.03	18
83020102	1172	-.9	0	80.3	.03	18
83020101	1169	9.3	0	77.8	.032	21
83020301	1018	81.2	1.4	81.3	.048	18
83020302	1005	80.1	1.23	78.7	.039	17
83020303	1181	75	1.12	78.7	.039	18
83020304	1159	79.2	1.17	80.5	.038	17
83020305	1153	81.3	1.19	80.5	.038	17
83020401	936	79.8	1.82	82.3	.056	18
83020402	1053	8302	1.45	79.8	.056	18
83020403	1023	81.3	1.52	79.2	.056	18
83020404	1031	8304	1.44	79.6	.054	17
83020405	1016	83	1.58	80.4	.055	17
83020702	1160	85.5	1.74	81.6	.053	18
83020703	1136	85.5	1.73	81.8	.053	18
83020704	1079	84.4	1.66	79.2	.053	18
83020706	1074	79.4	1.11	80.5	.053	18
83020707	1086	77.6	1.18	80.9	.054	17
83020708	1063	74.9	1.01	77.7	.054	17
83020709	1067	75.4	1.12	79.1	.055	17
83040401	1056	69.9	0.88	80	.034	18
83040402	979	69.9	.9	79.1	.035	18
83040403	947	67.6	.96	79.7	.035	18
83040404	1010	68.7	.96	79.5	.035	17
83040405	875	77.2	1.01	77.8	.034	18
83040601	1091	63.7	.75	81.7	.036	18
83040602	1075	65.3	.68	79.7	.037	19

83040603	998	68	.76	80.6	.037	18
83040604	1068	58.2	.7	79.9	.038	18
83040605	1007	56.9	.67	77.8	.039	18
83041101	1023	78.5	1.01	80.9	.04	18
83041102	1164	70.5	.89	80.8	.041	18
83041103	1155	69.8	.89	80.7	.042	18
83041104	1199	72.5	.84	80	.042	18
83041105	1280	66.6	.94	82.9	.043	18
83041106	1220	66.4	1	83.1	.045	18
83041201	1168	54.8	.68	81.6	.038	18
83041202	1131	50.6	.63	79.2	.039	18
83041203	1082	61.1	.72	80.9	.037	18
83041204	1194	57.2	.72	82	.037	18
83041205	1171	55.8	.73	81.5	.04	18
83041206	1083	56.9	.69	79.3	.039	18
83050307	1139	61.1	.72	78.6	.047	18
83050306	1132	63.3	.72	78.7	.047	18
83050305	1150	61.8	.68	77.9	.046	18
83050304	1115	57.7	.7	78.1	.048	18
83050303	1141	60.8	.74	79.5	.047	18
83050302	1173	60.5	.72	79.5	.049	18
83050301	1092	64.2	.78	79.7	.049	18

DATA SET 3

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
84012701	136	.64	.235	688	558	292
84012703	133.5	.46	.234	689	565	292
84012704	134.5	.46	.214	684	561	294
83121402	135	.5	.22	657	547	296
83121501	136	.689	.24	681	549	308
93121502	136	.682	.24	675	547	306
83121503	135.4	.68	.24	663	544	304
83121601	136	.701	.26	705	605	296
83121602	136	.701	.26	705	604	296
84020201	139.5	.537	.154	669	548	286
84020202	138	.537	.149	664	546	294
84020203	138	.537	.155	660	542	294
84020204	138	.537	.159	691	567	293
84020304	136	.554	.181	682	559	280
84021504	134	.698	.243	697	567	302
84021505	134	.698	.238	686	565	289
84030501	140	.69	.265	714	562	322
84031301	138	.698	.235	719	581	308
84020204	138	.537	.159	691	567	293
84020304	136	.554	.181	682	559	280
84021504	134	.698	.243	697	567	302
84021505	134	.698	.238	686	565	289
84030501	140	.69	.265	714	562	322
84031301	138	.698	.235	719	581	308

ID	CS1	SPREFF	SR	DVS	F1	DT
84012701	955	79.5	1.87	81	.056	20
84012703	941	72.2	1.39	80.6	.049	19
84012704	947	72	1.28	78.9	.052	19.5
83121402	1169	71.8	1.19	79.5	.056	19
83121501	1117	76.5	1.86	81.5	.051	20
83121502	1017	75.6	20.3	81.4	.056	20
83121503	1015	78.8	2.04	81.4	.056	19.4
83121601	976	81.1	2.13	83	.053	20
83121602	940	77.5	2.21	83	.053	20
84020201	1082	53	.96	73	.065	20.5
84020202	1150	57	.88	72.4	.062	20
84020203	1154	57.5	.92	73.1	.062	20
84020204	1134		.91	73.6	.062	20
84020304	1205	69.5	1.03	75.9	.06	20
84021504	961		2.14	81.7	.045	20
84021505	1085		1.87	81.3	.049	20
84030501	1180	85.8	1.9	83.4	.054	20
84031301	1089	82.5	1.79	81.1	.056	20

84020204	1134		.91	73.6	.062	20
84020304	1205	69.5	1.03	75.9	.06	20
84021504	961		2.14	81.7	.045	20
84021505	1085		1.87	81.3	.049	20
84030501	1180	85.8	1.9	83.4	.054	20
84031301	1089	82.5	1.79	81.1	.056	20

DATA SET 4

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
84121102	158	.71	.194	736	606	340
84121303	157	.45	.189	743	604	342
84121304	157	.45	.19	737	604	343
84121305	157	.45	.189	729	598	342
84121302	157.5	.45	.193	746	604	342
84121307	157	.45	.194	730	598	342
84121308	157	.45	.194	730	598	342
84121401	154.5	.45	.19	732	602	342
84121402	155	.45	.19	729	599	342
84121403	155.5	.45	.188	731	603	342
84121404	156	.45	.189	731	604	342
84121405	156	.45	.189	729	604	342
84121406	156	.45	.189	730	605	342
84121407	156	.46	.191	728	604	342
84121408	155.5	.46	.194	729	604	342
84121701	156.5	0	.195	752	596	342
84121702	157	0	.195	745	593	342
84121703	156.5	0	.197	745	595	343
84121704	156.5	0	.19	747	596	342
84121705	157	0	.191	742	593	342
84121706	157	0	.192	738	590	342
84121707	156	0	.192	741	593	342
8412708	156	0	.192	738	590	342
85011401	157.5	.92	.195	752	591	341
85011402	158	.92	.194	749	591	340
85011501	157.5	.9	.196	774	631	341
85011502	157.5	.9	.194	775	633	340
85011503	157.5	.92	.192	769	630	340
85011504	157	.92	.19	765	625	340
85011702	157	.55	.192	846	679	340
85011703	156.5	.55	.192	838	676	340
85011704	156.5	.55	.193	832	673	339
85011705	157	.55	.192	825	668	341
85011706	156	.55	.194	824	667	340
85011707	156	.55	.194	832	673	341
85011708	156	.55	.194	825	669	340
85011709	156	.55	.193	823	667	340
85011803	157.5	.71	.193	825	665	340
85011801	156.5	.71	.192	821	665	339
85011802	157	.71	.192	828	668	341
85011804	157	.71	.192	829	668	340
85021301	156	.63	.192	775	631	339

ID	CS1	SPREFF	SR	DVS	F1	DT
84121102	1036		1.51	77.4	.059	35
84121303	1016		.95	76.6	.055	35
84121304	1005		.97	76.7	.057	35
84121305	1016	69.5	.96	76.6	.057	35
84121302	1003	62.4	.99	76.9	.055	35.5
84121307	1015	61	.99	77	.055	35
84141308	1042		.96	77	.055	35
84121401	1019		.96	76.7	.049	34.5
84121402	982	67.5	1	76.7	.05	35
84121403	988		988	76.5	.05	34.5
84121404	987	64.6	.98	76.7	.052	35
84121405	1004		.97	76.6	.052	35
84121406	979	66.8	.99	76.6	.051	35
84121407	1027		.98	76.8	.052	35
84121408	1013	68.2	1	77.1	.052	34.5
84121701	1042	-.7	0	76.4	.061	34.5
84121702	1023		0	76.4	.061	35
84121703	1040	.7	0	76.6	.059	34.5
84121704	1013		0	75.9	.059	34.5
84121705	974	-.3	0	76	.057	36
84121706	988		0	76.1	.057	36
84121707	968	1.7	0	76.1	.057	35
84121708	1013	0	0	76.1	.057	35
85011401	999	86.9	2.09	77.8	.082	34
85011402	1005		2.07	77.7	.082	34
85011501	1063	76.8	1.81	77.9	.056	35
85011502	1070		1.78	77.7	.056	35
85011503	1014	88	1.91	77.5	.056	35
85011504	941		2.04	77.3	.056	34.5
85011702	976	79.7	1.1	77	.054	35
85011703	984		1.09	77	.054	34.5
85011704	1042	7604	1.04	77.1	.055	34.5
85011705	1030		1.06	77	.054	35
85011706	1022		1.08	77.2	.05	35.5
85011707	1031	74.1	1.06	77.2	.05	35.5
85011708	1074	70.1	1.02	77.2	.05	35.5
85011709	1.67		1.03	77.1	.05	35.5
85011803	990	79.3	1.43	77.3	.057	35.5
85011801	1006	76.3	1.4	77.2	.057	34.5
85011802	1014		1.39	77.2	.057	35
85011804	996		1.41	77.2	.057	35
85021301	980	71	1.35	77.1	.057	34

DATA SET 5

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
01208102	148	0.72	0.221	833	653	296
01208103	148	1.28	0.223	837	665	291
01218102	148	1.02	0.202	834	667	287
01228102	149	0.59	0.189	828	668	298

ID	CS1	SPREFF	SR	DVS	F1	DT
01208102	1620	54.8	1.04	76.2	0.048	31
01208103	1518	69.3	1.95	77.1	0.050	31
01218102	1504	57.8	1.41	75.0	0.050	31
01228102	1531	46.4	0.75	73.2	0.050	31

DATA SET 6

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
11078001	123	1.350	0.265	824	671	261
11078002	125	1.010	0.247	807	665	259
11078003	125	0.837	0.232	816	677	262
11068004	122	1.69	0.267	818	680	255

ID	CS1	SPREFF	SR	DVS	F1	DT
11078001	2411	68.3	1.52	80.5	0.044	14
11078002	2416	53.6	1.07	78.7	0.044	15
11078003	2216	55.5	0.89	77.3	0.043	15
11068004	2284	78.2	2	81.1	0.042	16

DATA SET 7

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
10138004	130	1.290	0.320	797	648	303
10208001	133	0.815	0.276	817	659	302
10208002	136	1.040	0.273	815	648	306
10208005	129	1.105	0.279	840	663	299
10218005	133	0.590	0.231	814	664	288
10318002	130	0.880	0.227	805	687	294
10318003	130	0.998	0.235	822	680	296
10318004	130	0.998	0.241	812	667	293
10318005	129	1.030	0.265	829	676	287
11058002	127	1.310	0.278	823	662	292
11058003	127	1.110	0.279	819	667	287
11068002	127	0.784	0.264	817	666	296

ID	CS1	SPREFF	SR	DVS	F1	DT
10138004	2353	76.2	1.87	88.2	0.037	16
10208001	2243	78.1	1.05	80.5	0.056	14
10208002	2300	71.6	1.31	80.6	0.054	16
10208005	2333	75.3	1.37	81.1	0.039	14
10218005	2196	35.0	0.64	76.8	0.061	15
10318002	2044	50.6	0.98	76.9	0.058	14
10318003	2212	62.5	1.04	77.7	0.040	16
10318004	2320	61.5	1.07	78.2	0.044	15
10318005	2202	67.2	1.26	80.0	0.046	14
11058002	2319	74.2	1.63	81.4	0.032	15
11058003	2100	72.6	1.52	81.1	0.031	16
11068002	2420	66.5	0.89	79.6	0.040	16

DATA SET 8

ID	T2	SLC	GPM	ACFM3	SCFM1C	TEMP1C
04288201	144	1.10	0.30	880	721	271
04298201	144	0.75	0.28	890	711	273
05068201	140	1.34	0.29	859	729	255
08028206	140	0.862	0.220	907	745	256
08028207	138	0.42	0.228	890	757	254
08068203	140	0.585	0.224	891	732	293
08098203	140	1.11	0.338	888	727	296
08098204	140	0.318	0.207	901	736	293
10228201	138	0.286	0.263	902	734	317

ID	CS1	SPREFF	SR	DVS	F1	DT
04288201	1949	65.6	1.62	86.5	0.057	25
04298201	1923	62.3	1.06	84.6	0.057	25
05068201	1903	67.2	1.93	87.8	0.059	27
08028206	1967	68.3	0.891	80.0	0.060	27
08028207	1943	39.5	0.436	79.5	0.061	25
08068203	2001	54.6	0.616	79.9	0.050	25
08098203	1961	69.6	1.81	89.1	0.044	25
08098204	2012	32.7	0.306	78.0	0.046	24
10228201	2149	43.5	0.33	82.5	0.051	25

DATA SET 9

ID	T2	SLC	GPM	AFCM3	SCFM1C	TEMP1C
07238201	147	1.126	0.250	894	735	275
07278201	150	0.755	0.14	882	744	270
07308201	150	0.377	0.225	895	735	273
08058205	149	0.405	0.138	886	744	255
08068202	151	1.34	0.173	908	744	261
08068206	151	0.853	0.15	908	744	260

ID	CS1	SPREFF	SR	DVS	F1	DT
07238201	2184	53.9	1.207	82.7	0.0547	35
07278201	1723	44.9	0.57	71.6	0.056	36
07308201	1846	29.4	0.43	79.7	0.057	35
08058205	2041	17.5	0.34	76.3	0.068	35
08068202	1916	57.0	1.12	76.1	0.066	35
08068206	1843	32.2	0.64	73.0	0.066	35

DATA SET 10

ID	T2	SLC	GPM	AFCM3	SCFM1C	TEMP1C
08068205	150	0.585	0.213	895	726	299
08098201	150	0.318	0.198	903	733	297
10258202	149	1.05	0.26	879	743	330

ID	CS1	SPREFF	SR	DVS	F1	DT
08068205	2087	42.8	0.566	80.0	0.048	35
08098201	2052	28.7	0.29	77.2	0.044	35
10258202	2146	1.17	83.5	83.5	0.042	35

DATA SET 11

ID	T2	SLC	GPM	AFCM3	SCFM1C	TEMP1C
85012501	156.5	.88	.192	849	649	340
85072502	158	.88	.192	833	640	340
85012503	157	.88	.192	831	639	340
85012504	157	.88	.192	825	635	339
85012505	156.5	.88	.192	829	636	340
85012506	157	.88	.192	827	634	340
85012507	157	.88	.192	827	634	340
85012802	159	0	.193	834	655	341
85012803	158.5	0	.192	818	643	340
85012901	159	1.46	.192	837	682	342
85012902	159	1.46	.194	833	682	340
85012903	158	1.46	.195	817	670	340
85012905	157	1.46	.186	810	666	340
85012906	157	1.46	.193	816	669	340
85012907	157	1.46	.19	810	664	340
85013102	161	1.84	.189	835	681	340
85013103	161	1.84	.189	834	681	340
85013103	161.5	1.84	.193	834	681	340
85013104	161	1.84	.191	825	673	339
85013105	161	1.84	.192	827	675	339
85013106	160.5	1.84	.19	819	669	339
85020101	160.5	1.09	.193	790	658	339
85020102	160.5	1.09	.193	790	658	338
85020103	160.5	1.09	.193	792	654	338
85020104	159.5	1.09	.192	797	658	339
85020105	159.5	1.09	.19	788	651	339

ID	CS1	SPREFF	SR	DVS	F1	DT
85012051	1890		.95	77.5	.069	33.5
85072502	1951	47.2	.93	77.5	.07	35
85012503	2032		.9	77.5	.07	35
85012504	2040	44.1	.9	77.5	.07	35
85012505	2008		.91	77.5	.07	34.5
85012506	1959	46.4	.94	77.5	.07	35
85012507	2017		.91	77.5	.07	35
85012802	1944		0	76.2	.07	36
85012803	1969	-1.5	0	76.1	.07	35.5
85012901	1964	59.5	1.44	79.2	.054	35
85012902	1990		1.44	78.4	.054	35
85012903	2015	59.1	1.45	78.5	.054	36
85012905	1987	59.4	1.41	77.7	.055	35
85012906	1994		1.45	78.3	.055	35
85012907	2032	61.1	1.42	78	.055	35

85013102	1959	66.9	1.8	78.4	.077	35
85013103	1896	67.3	1.86	78.4	.077	35
85013103	2057	60.7	1.75	78.8	.077	35.5
85013104	1996		1.8	78.6	.078	35
85013105	1979	67.7	1.82	78.7	.078	35
85013106	2004		1.79	78.5	.078	34.5
85020101	1941	51.3	1.13	77.9	.082	34.5
85020102	2003		1.1	77.9	.082	34.5
85020103	1950	52.5	1.14	77.9	.086	35.5
85020104	2034		1.08	77.8	.068	35.5
85020105	2018	54.4	1.08	77.6	.068	35

DATA SET 12

ID	T2	SLC	GPM	AFCM3	SCFM1C	TEMP1C
84121801	158	2.05	.187	748	593	341
84121802	158.5	2.05	.19	745	591	340
84121902	158	1.36	.192	733	602	342
84121903	158.5	1.36	.192	727	599	342
84121904	158.5	1.36	.191	728	600	342
84121905	159	1.36	.189	731	602	342
84121907	159	1.36	.19	711	586	342
85021401	160.5	1.89	.185	795	625	335
85021402	159	1.89	.19	785	623	335
85021403	158	1.89	.192	778	618	336
85021404	157	1.89	.192	787	625	334
85022501	159	1.64	.191	770	612	341
85022502	161	1.64	.19	767	612	341
85022503	161	1.64	.191	761	607	341
85022504	161	1.64	.191	771	615	341
85022505	161	1.64	.191	767	613	341
85022506	161	1.64	.191	766	612	341
85030401	160	2.21	.192	779	610	331
85030402	160.5	2.21	.189	777	612	325
85030403	157	2.21	.194	774	614	321
85030404	157	2.21	.189	774	613	321
85030405	157	2.21	.19	772	612	326
85022803	157	2.04	.192	769	609	340
85022805	155.5	2.04	.192	761	606	339
85022804	155.5	2.04	.19	764	607	340

ID	CS1	SPREFF	SR	DVS	F1	DT
84121801	2939	53.5	1.51	78.5	.064	35
84121802	2874		1.58	78.8	.064	35.5
84121902	3043	43.1	.98	78.1	.057	35
84121903	3005		1	78.1	.059	34.5
84121904	3068	45.6	.97	78	.059	34.5
84121905	3061		.96	77.8	.059	35
84121907	3178		.96	77.9	.059	35
85021401	2824	59	1.36	78.1	.068	34
85021402	3037		1.31	78.6	.068	35
85021403	2854	59.5	1.42	78.8	.065	35.5
85021404	2633		1.52	78.8	.066	34.5
85022501	2930	53.4	1.2	78.4	.081	33
85022502	2860		1.23	78.3	.081	35
85022503	2922	54.1	1.22	78.4	.081	35
85022504	2823		1.24	78.4	.081	35
85022505	2793	52.9	1.26	78.4	.081	35

85022506	2844		1.24	78.4	.081	35
85030401	2847	57.6	1.68	79.1	.059	35
85030402	2941		1.6	78.8	.061	35.5
85030403	2961	58.3	1.62	79.3	.063	35
85030404	2842		1.65	78.8	.063	35
85030405	2872	70	1.65	78.9	.061	35
85022803	2648		1.67	78.9	.052	36
85022805	2693	51.5	1.65	78.9	.053	34
85022804	2844		1.55	78.7	.052	34

VITA

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