CHAPTER V

VALIDATION OF PRESENT MODEL

The present mathematical model is an extension of W. Tanthapanichakoon and C. Srivotanai (1996), which is based on the model developed by S. Matsumoto et. al. (1984a). They assume most of the moisture removed is above the critical moisture content and the falling drying rate below the critical moisture content is proportional to the remaining free moisture content of the solids. However, intraparticle heat transfer resistance is assumed insignificant, so the simulated solid temperature is close to the wet-bulb temperature of the air and is significantly lower than the experimental results. To improve the prediction of the solid temperature at a moisture content below the critical moisture content, the semi-empirical equation proposed by R. Toei (1986) is adopted by W. Tanthapanichakoon and C. Srivotanai. In this work, the internal diffusion controlled model, which is proposed by S. Matsumoto (1984b), is combined with the above surface evaporation model to yield a more general model for the pneumatic conveying dryer. In this chapter, the results predicted by the extended model are compared with the experimental results to validate the model. For reference solid temperature predictions given by the previous model are also compared with the experimental values.

5.1 Experimental results

Previous experimental results are used to test the validity of the extended model. The results are obtained from a full-scale industrial pneumatic conveying dryer in a manioc flour mill in the Northeastern Region of Thailand. The pneumatic conveying dryer is 1 m in diameter and 57 m in length. Dry flour product size distribution is obtained by sieve analysis and the mean particle size of the product is 0.12 mm. Operational data have been accumulated almost daily over a 5-month period. Since most of the daily data are quite similar, only 10 different cases of the total data are selected for testing the validation of the model. The details of the selected data are summarized in Table 5.1. Because the gas velocity is not measured daily, the actual mass flow rate of air in the dryer is back-calculated by making an overall moisture balance around the dryer. Overall energy balance is next taken to double-check the reliability of the operating data. The percent error of the overall energy balance falls between –1.5% and 1.5%; the minus sign means the total outlet energy is lower than the total inlet energy. The other physical properties of the flour are specific heat of 0.44 kcal/kg K and true density of 1540 kg/m^3.

5.2 Identification of unknown model parameters

The present model contains a number of basic physical and transport properties of the drying material, such as density, specific heat, internal moisture diffusion coefficient and equilibrium moisture content. Film heat and mass transfer coefficients are also required, as well as properties of the humid air. Reported values on flour

Table 5.1 Operating conditions and drying results for 10 cases of flour drying

Run no.	1	2	3	4	5	6	7	8	9	10
Inlet conditions										
Air temperature (K)	469	461	478	469	481	473	471	453	473	473
Air humidity (%dry basis)	1.42	1.56	1.61	1.53	1.56	1.52	1.40	1.60	1.77	1.77
Flour temperature (K)	305	307	305	304	307	307	307	305	305	304
Moisture content (%dry basis)	52.67	56.74	57.48	57.48	54.32	58.23	56.99	56.25	61.81	58.73
Mass flow rate of air (kg/hr)	79764	75969	74147	82722	69317	73080	76390	77985	79348	71626
Air velocity (m/s)	37.7	35.4	35.8	39.2	33.7	34.9	36.3	35.7	37.9	34.2
Mass flow rate of flour (kg dry flour/hr)	6220	5092	5800	5830	6135	5759	5630	5216	5632	5684
Outlet conditions										
Air temperature (K)	392	391	389	392	387	389	389	382	391	388
Air humidity (%dry basis)	4.39	4.44	4.98	4.62	5.07	4.98	4.52	4.39	5.14	5.27
Flour temperature (K)	336	331	332	338	342	334	332	330	328	331
Moisture content (%dry basis)	14.55	13.90	14.42	13.64	14.68	14.29	14.68	14.68	14.42	14.68
Overall energy balance										
Percent error (%)	0.05	1.06	-1.44	1.17	-1.31	1.49	-1.29	-0.30	0.86	1.39

properties in the literature, general heat and mass transfer correlations, and relations for humid air properties are adopted in the simulation of the present model. However, two key properties, namely, the equilibrium moisture data and the internal moisture diffusion coefficient for cassava flour not known precisely, though they significantly influence the critical point, at which the drying rate is controlled by internal diffusion. Thus the equilibrium moisture data and internal moisture diffusivity are the model parameters that have to be determined first from the experimental data.

Fortunately, some equilibrium data of starch drying and internal moisture diffusion coefficient have been reported. Internal moisture diffusivity within starch granular is reported to be in the range of $5*10^{-10}$ and $3*10^{-9}$ m^2/s. These values are for the conditions of 10-50 % dry basis of moisture content and 298-413 K in starch temperature (A S. Mujumdar, 1995). Equilibrium data of starch are shown in Figure 5.1 (Perry, 1973). To simulate the model, both the value of the equilibrium moisture content and the slope of the equilibrium curve are required. Since the slope of the equilibrium moisture content curve is not only slightly nonlinear but also depends on the air temperature, whereas the equilibrium moisture content depends on both air humidity and temperature, the values of these parameters should be estimated at the critical moisture condition. Furthermore, the reported equilibrium data are for unknown kind of starch and not for flour. The equilibrium moisture content obtained from the desorption approach is always greater than the value obtained from the adsorption approach. In the present simulation, air temperature at the critical point is about 380-390 K. Thus, the slope of the equilibrium moisture content curve should be in the range of 0.35-0.5. So a value of 0.4 has been selected. The value of the internal moisture content will be

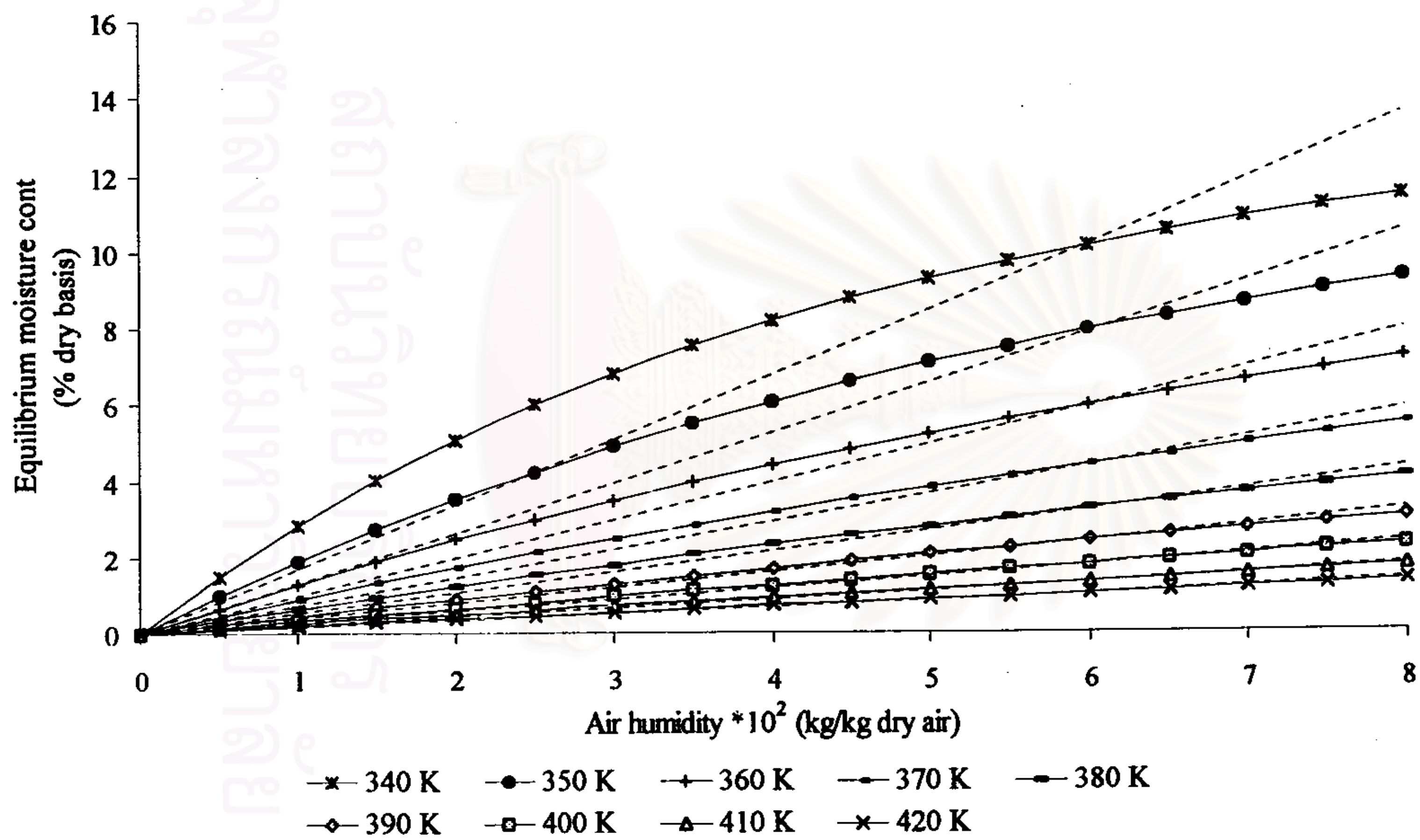

Figure 5.1 Equilibrium moisture content of starch (Perry, 1973)

determined after an insight into the model behavior has been obtained.

5.3 Estimation of unknown model parameters

According to the previous section, there are two types of unknown model parameters. In this section, the effect of these parameters, namely, the equilibrium moisture content, the slope of the equilibrium moisture content curve and the internal moisture diffusion coefficient, for flour drying are investigated. To observe the model behavior, the experimental data of case 4 in Table 5.1 is used as the reference case and each parameter is varied one at a time, as shown in Table 5.2.

Table 5.2 Reference value of parameters used to observe the model behavior

Parameters	
Internal moisture diffusivity (m^2/s)	$1*10^{-9}$
Equilibrium moisture content (% dry basis)	13
Slope of equilibrium curve	0.40

The effect of the variation in the equilibrium moisture content, which ranges from 12-14.5 % dry basis, on flour drying is shown in Figures 5.2 to 5.4. Figure 5.3 shows that the final product moisture content approaches the equilibrium moisture content. Furthermore, the figure reveals that the predicted critical moisture content is quite close to the equilibrium moisture content. Therefore, the dryer length in which surface evaporation predominates decreases as the equilibrium moisture content is increased as shown in Figure 5.2. A reduction in the dryer length with surface evaporation means an increase in the length with internal moisture diffusion controlled

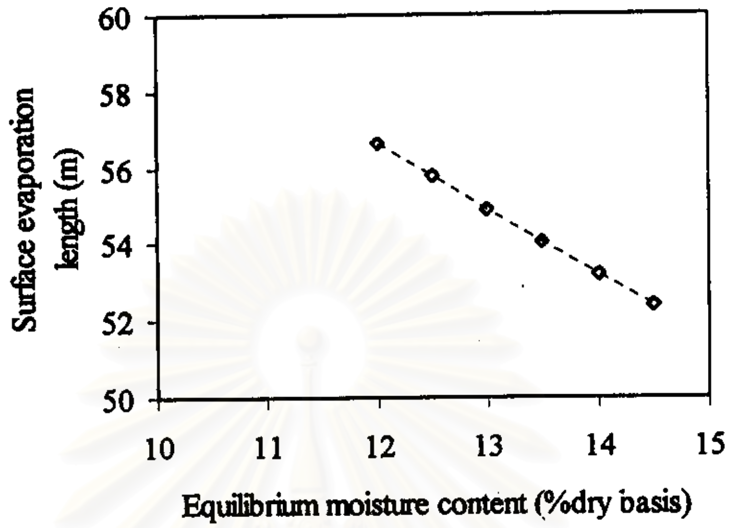

Figure 5.2 Effect of equilibrium moisture content on dryer length of surface evaporation period in flour drying simulations

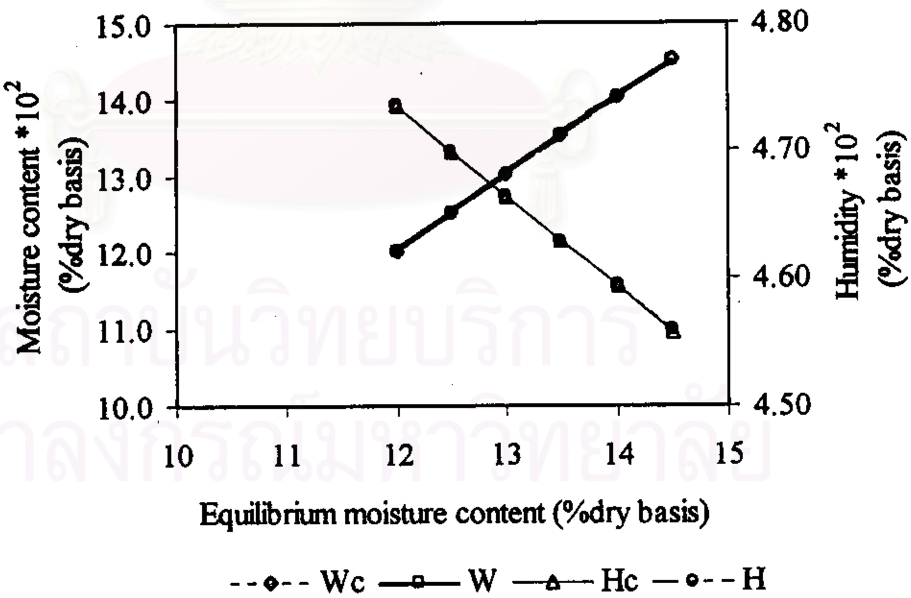

Figure 5.3 Effect of equilibrium moisture content on outlet moisture content and humidity in flour drying simulations

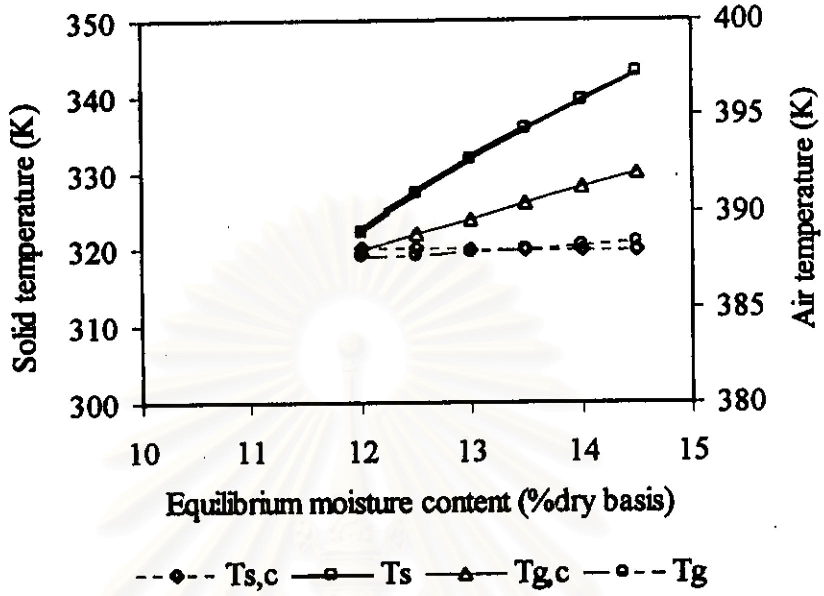

Figure 5.4 Effect of equilibrium moisture content on outlet solid and air temperatures in flour drying simulations

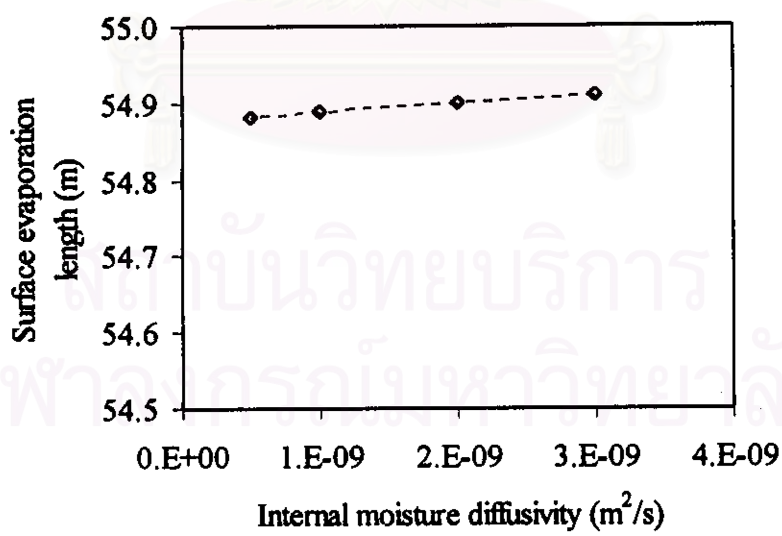

Figure 5.5 Effect of internal moisture diffusivity on dryer length of surface evaporation period in flour drying simulations

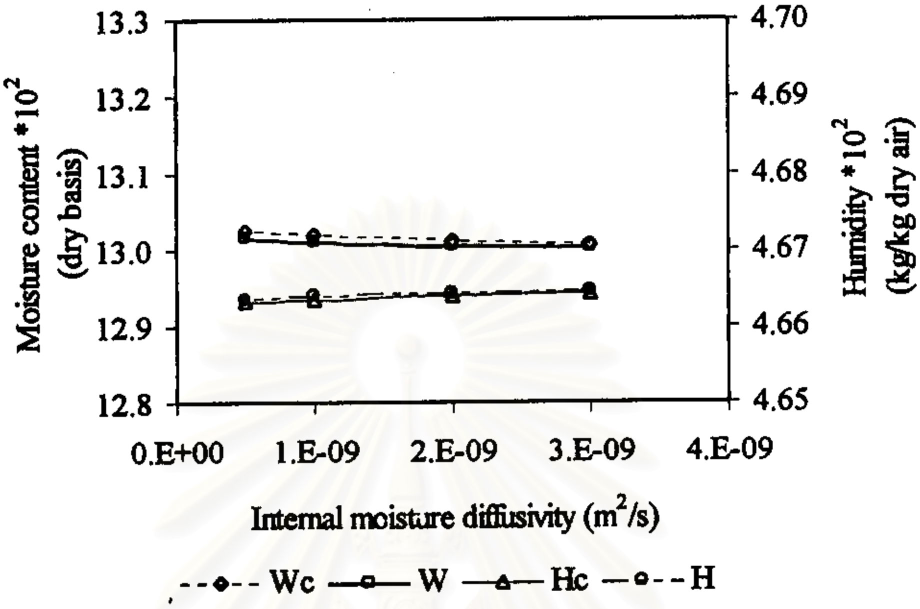

Figure 5.6 Effect of internal moisture diffusivity on outlet moisture content and humidity in flour drying simulations

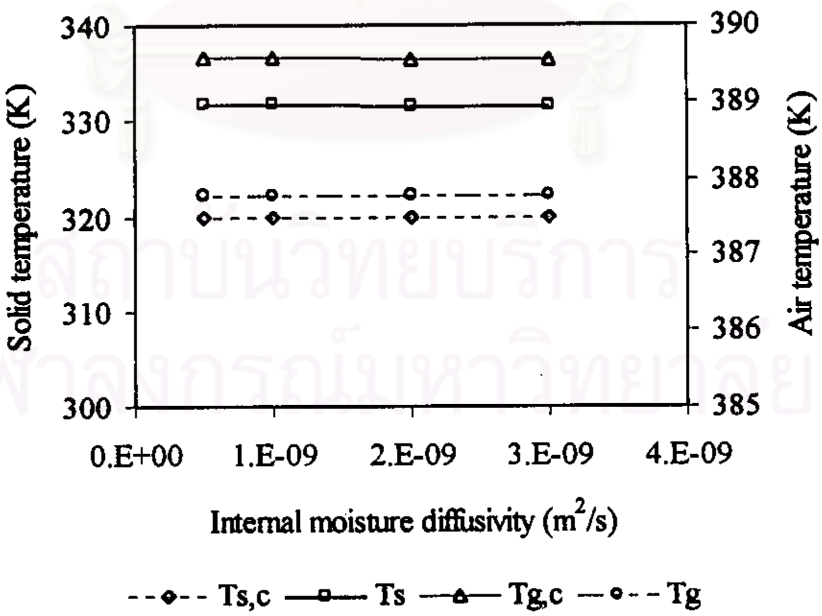

Figure 5.7 Effect of internal moisture diffusivity on outlet solid and air temperatures in flour drying simulations

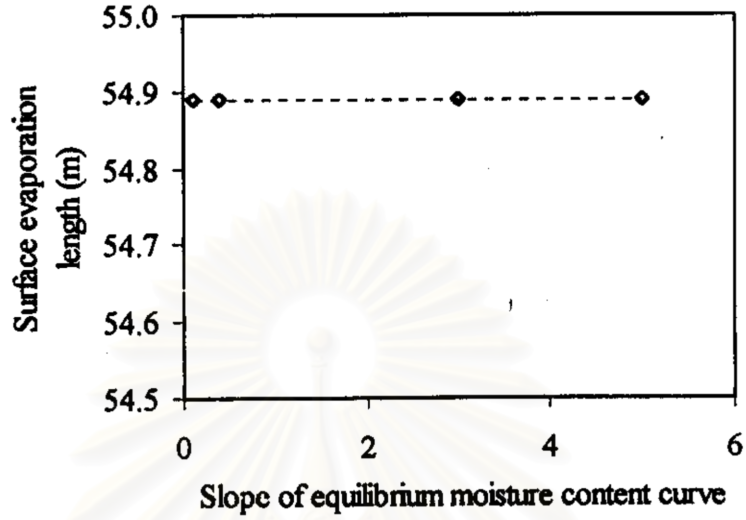

Figure 5.8 Effect of slope of equilibrium moisture content curve on dryer length of surface evaporation period in flour drying simulations

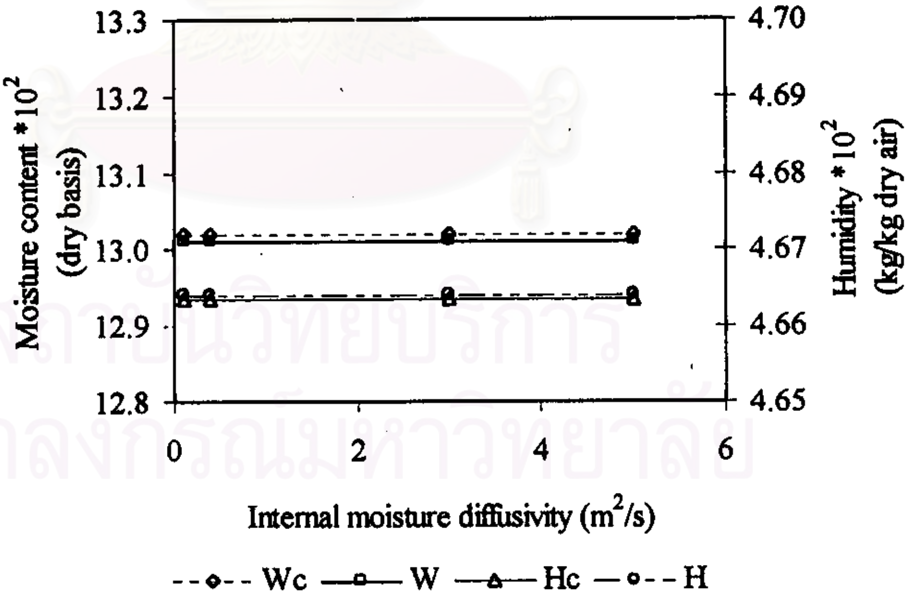

Figure 5.9 Effect of slope of equilibrium moisture content curve on outlet moisture content and humidity in flour drying simulations

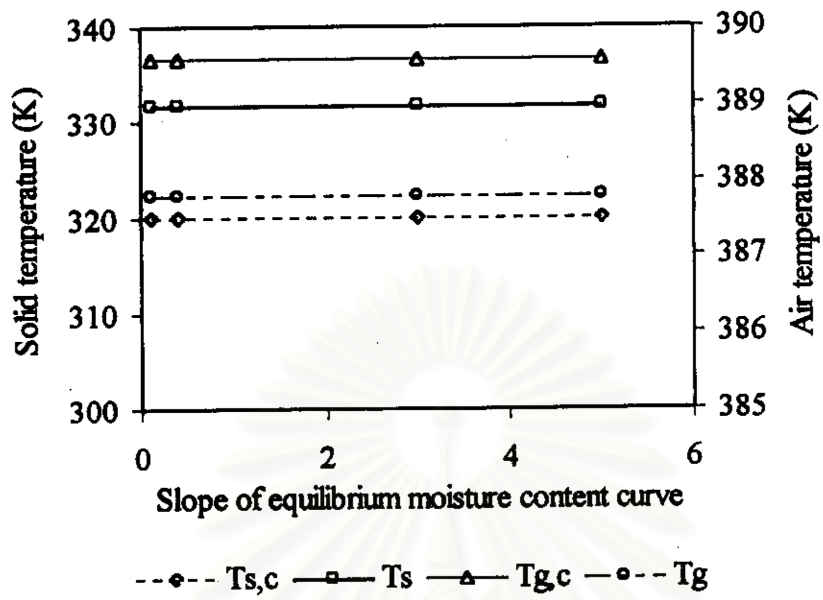

Figure 5.10 Effect of slope of equilibrium moisture content curve on outlet solid and air temperatures in flour drying simulations

rate. As shown in Figure 5.4, the final product temperature increases with the equilibrium moisture content while the air temperature slightly decreases.

Figures 5.5 to 5.7 show the effect of the internal moisture diffusion coefficient on the model behavior. The outlet and critical condition slightly change within the reported range of internal moisture diffusivity, $3*10^{-9}$ to $5*10^{-10}$ m^2/s. These show that the rate of internal diffusion, controlled by such factors as internal moisture diffusivity and particle diameter, is high enough so the internal moisture can replenish the evaporated moisture at the solid surface. Thus, the switching from the surface evaporation model to the internal diffusion controlled model occurs when the (critical) moisture content is close to the equilibrium moisture content. And after switching most heat transfer from the air is used to raise the flour temperature. This is the same explanation for the influence of the slope of the equilibrium moisture content curve.

That is the reason why the outlet and critical conditions are nearly independent of the slope, The effect of the slope of the equilibrium moisture content, which ranges between 0.1-5, is shown in Figures 5.8 to 5.10.

It can be concluded that the internal moisture diffusivity and the slope of the equilibrium moisture content within these ranges have little effect on the final simulation result. Thus, any value in these ranges can be chosen and $1*10^{-9}$ m^2/s and 0.4 are selected for the internal moisture diffusivity and the slope of the equilibrium moisture content curve in the simulation of flour drying, respectively. Consequently, the equilibrium moisture content, which has the most significant effect among the three key unknown parameters of the model, is varied to find the most suitable value compared to the experimental results.

A constant step size of $1*10^{-4}$ m is used in the numerical integration of the model. The equilibrium moisture content used in the simulation is 12, 12.5, 13, 13.5, 14 and 14.5 % dry basis. Figures 5.11 to 5.22 show the comparison between the simulation and experimental results. The difference between the simulation and experimental results at the dryer outlet is calculated. The equation used to calculate the sum of the differences is in the form:

$$S_x = \sqrt{\Sigma(x_{i,sim} - x_{i,exp})^2} \qquad (5.1)$$

Figures 5.23 to 5.26 illustrate, respectively, the S_x in case of the outlet moisture content, humidity and flour and air temperatures as the equilibrium moisture content is varied. The figures show that when the equilibrium moisture content increases, the simulated result of the outlet moisture content, humidity and air temperature approach

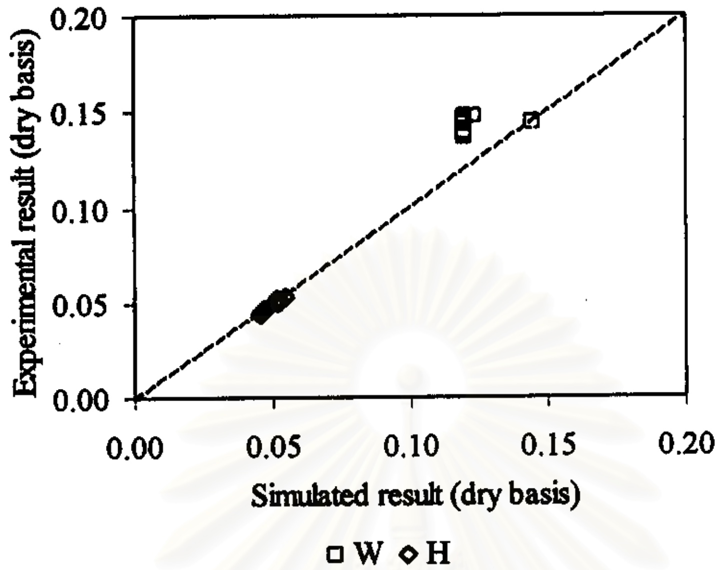

Figure 5.11 Comparison of outlet moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.12 kg/kg dry flour

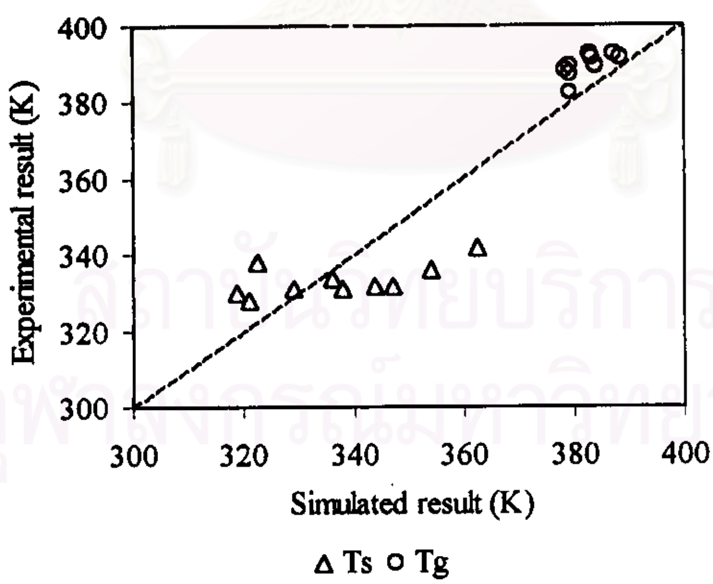

Figure 5.12 Comparison of outlet flour and air temperatures between experimental and simulated results when $W_{eq,0}$ = 0.12 kg/kg dry flour

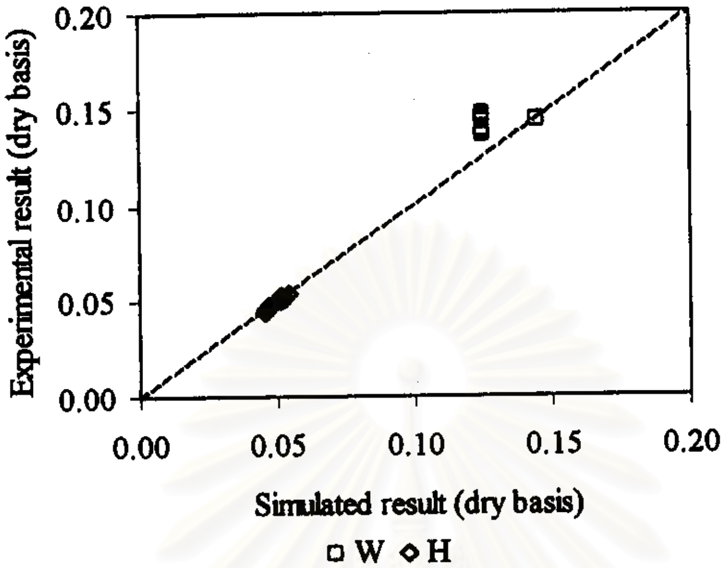

Figure 5.13 Comparison of outlet moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.125 kg/kg dry flour

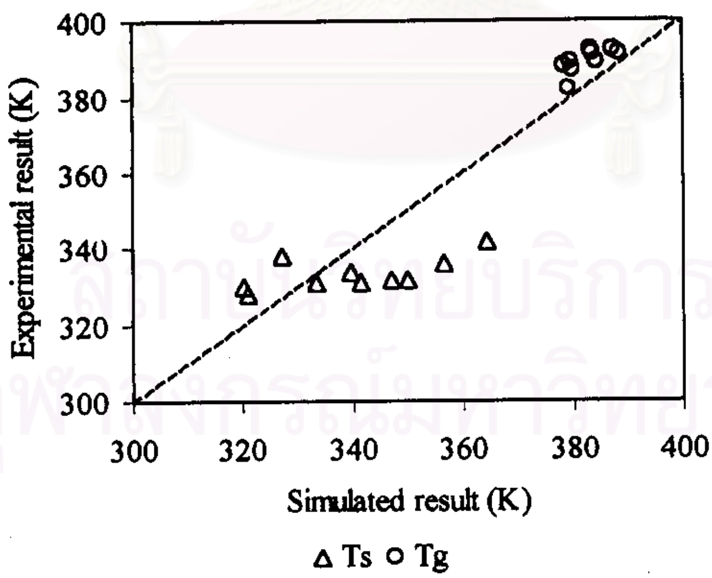

Figure 5.14 Comparison of outlet flour and air temperatures between experimental and simulation results when $W_{eq,0}$ = 0.125 kg/kg dry flour

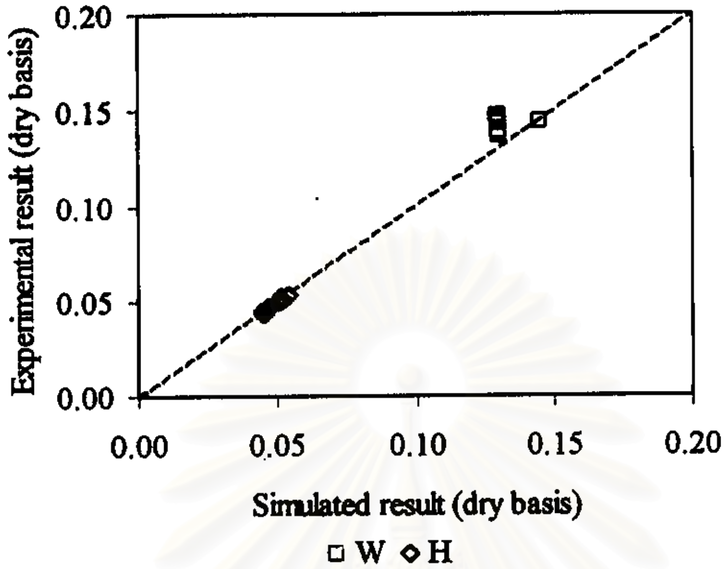

Figure 5.15 Comparison of outlet moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.13 kg/kg dry flour

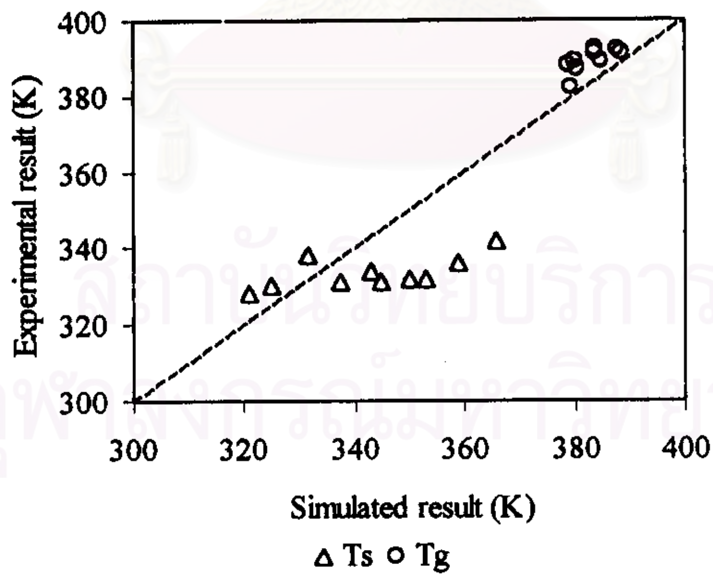

Figure 5.16 Comparison of outlet flour and air temperatures between experimental and simulated results when $W_{eq,0}$ = 0.13 kg/kg dry flour

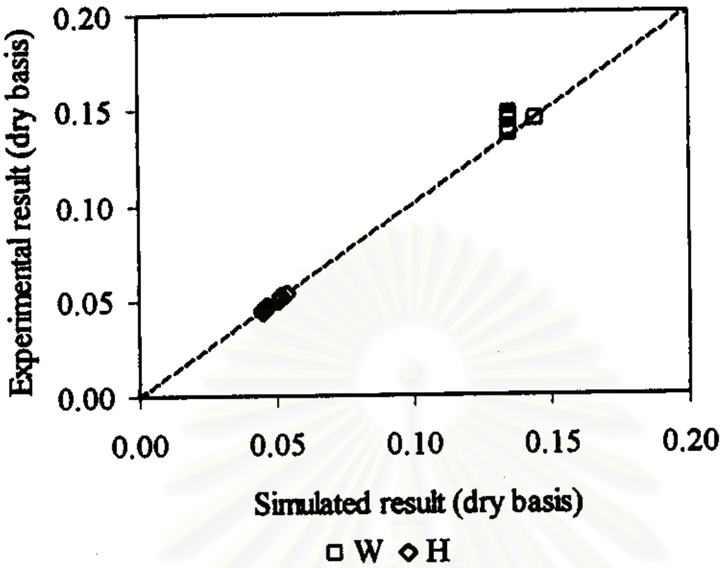

Figure 5.17 Comparison of outlet moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.135 kg/kg dry flour

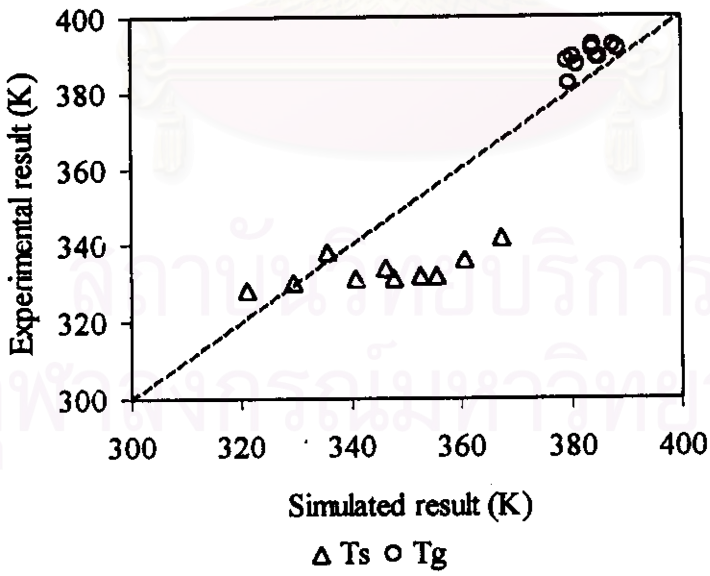

Figure 5.18 Comparison of outlet flour and air temperatures between experimental and simulated results when $W_{eq,0}$ = 0.135 kg/kg dry flour

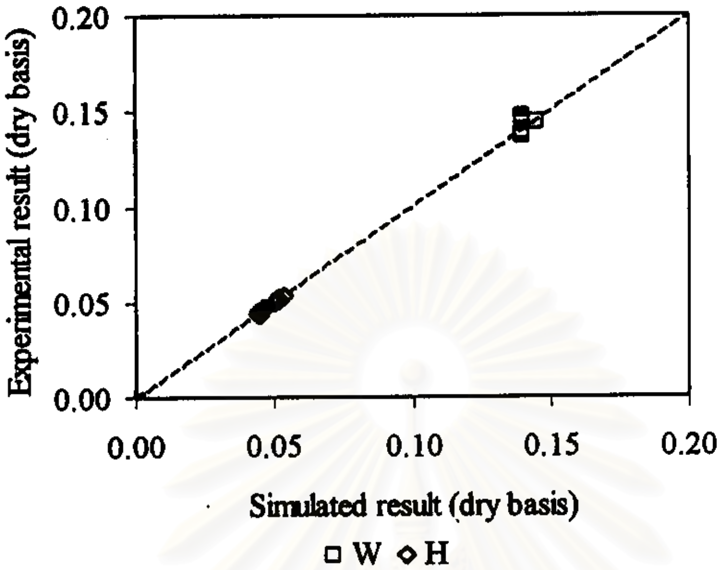

Figure 5.19 Comparison of outlet moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.14 kg/kg dry flour

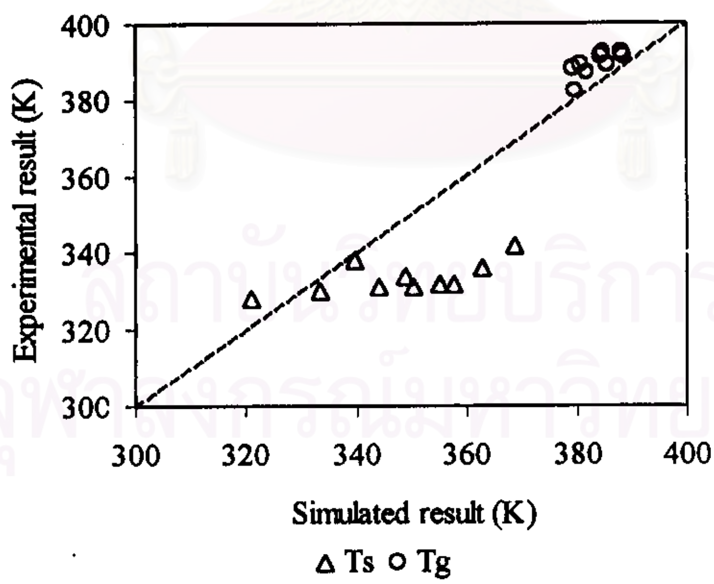

Figure 5.20 Comparison of outlet flour and air temperatures between experimental and simulated results when $W_{eq,0}$ = 0.14 kg/kg dry flour

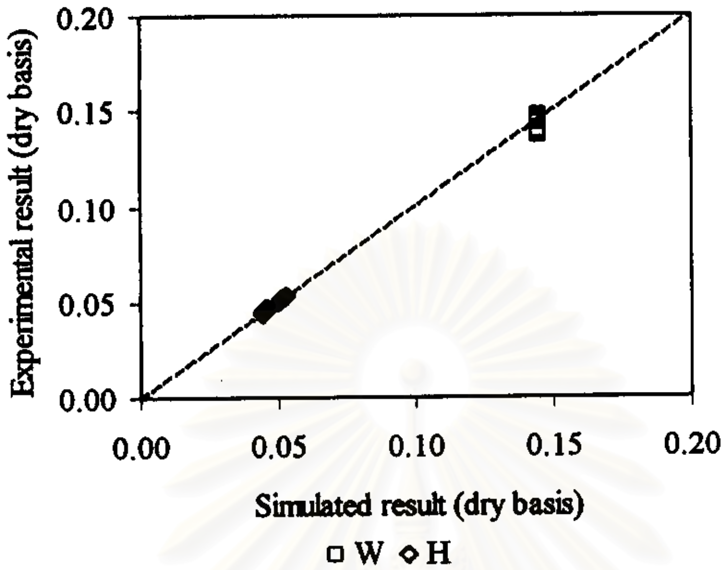

Figure 5.21 Comparison of moisture content and humidity between experimental and simulated results when $W_{eq,0}$ = 0.145 kg/kg dry flour

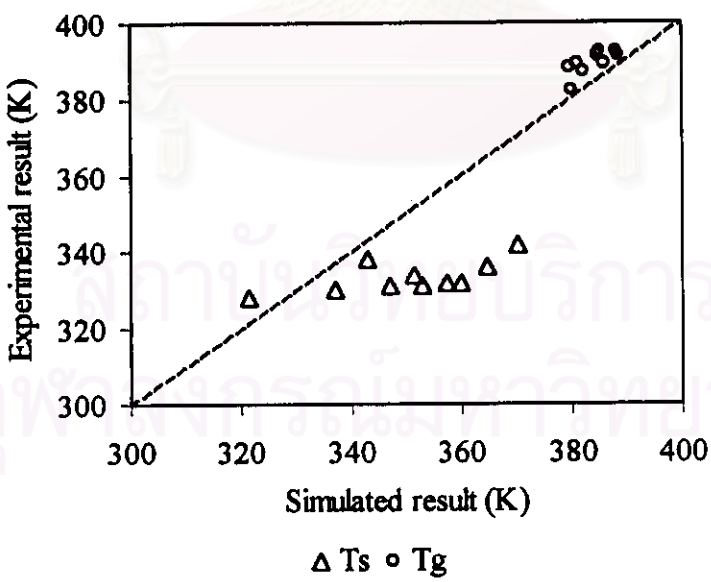

Figure 5.22 Comparison of outlet flour and air temperatures between experimental and simulated results when $W_{eq,0}$ = 0.145 kg/kg dry flour

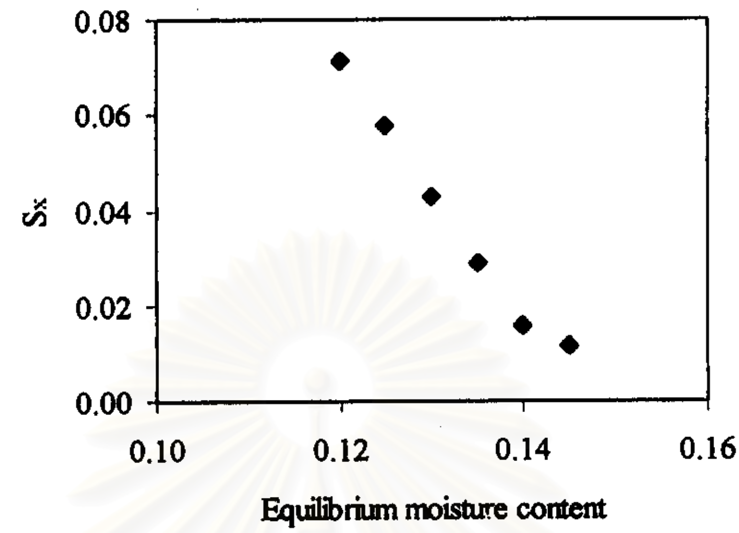

Figure 5.23 Effect of equilibrium moisture content on S_x of outlet moisture content

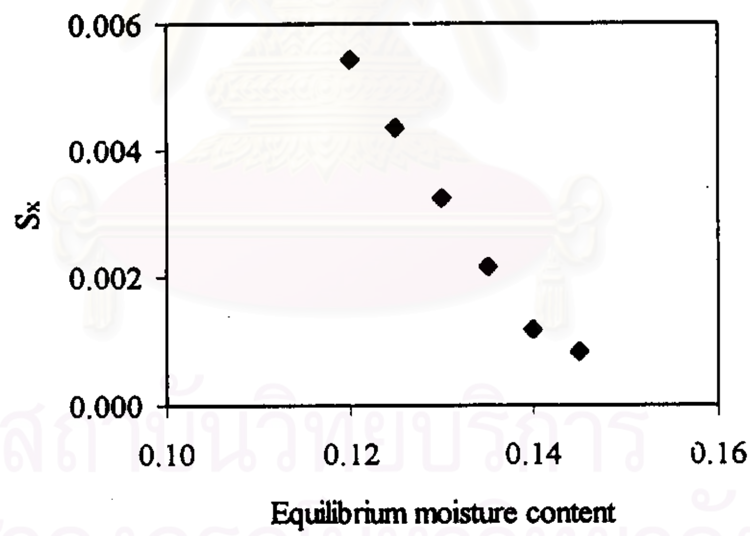

Figure 5.24 Effect of equilibrium moisture content on S_x of outlet humidity

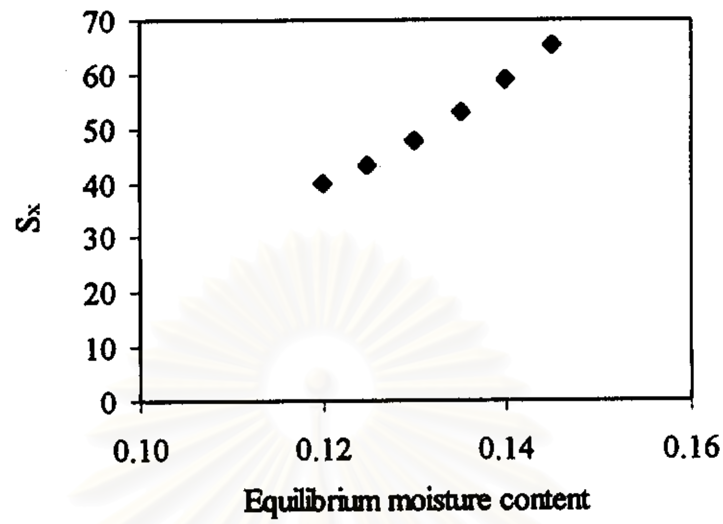

Figure 5.25 Effect of equilibrium moisture content on S_x of outlet flour temperature

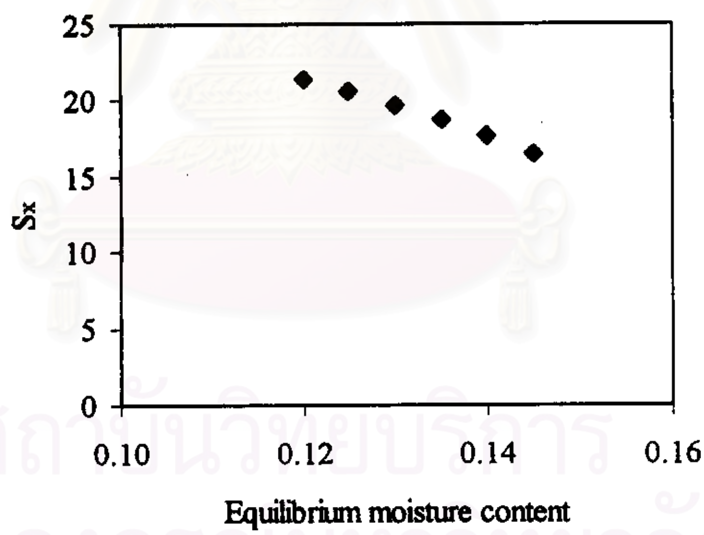

Figure 5.26 Effect of equilibrium moisture content on S_x of outlet air temperature

the experimental results while the simulated flour temperature diverges from the experimental result. By compromising the results of all flour four variables, it is concluded that a value of 13 % dry basis is the most suitable for the initial equilibrium moisture content in flour drying.

5.4 Comparison between simulation and experimental results

The present simulated results for the case $W_{eq,0}$ = 13 % are compared to both the experimental results and the results obtained from the previous model. For case of comparison, the results as well as the data and parameters used in the two models are summarized in Table 5.3. In the previous model, an effective flour size has been introduced and varied to account for the agglomeration of particle during drying. Its suitable value is shown to be 0.45 mm, and the critical and equilibrium moisture content are assumed to remain constant throughout the dryer. In contrast, the dry flour mean diameter, in the present model which equals 0.12 mm, can directly used in place of the effective size and the critical moisture content is determined naturally during the model simulation, as the moisture content at which the diffusion controlled rate becomes dominant, i.e. where the model switching occurs. Of course, the two models use the same dryer configuration and inlet conditions.

Graphical comparisons of the two models' results with the experimental results are shown in Figures 5.27 and 5.28. Obviously, the outlet moisture contents predicted by the present model agree more closely with the experimental values than the previous predictions. Similarly, comparison of the outlet air humidity and temperature reveals that the present predictions are also more accurate than the previous. As for the outlet

Table 5.3 Operating condition, dryer configuration, flour properties and parameters used in flour simulation and comparing with experimental results

Conditions/Configuration/ Properties/Parameters	Present model	Previous model	Experiment
Dryer configuration			
Dryer diameter (m)	1		
Dryer length (m)	57		
Flour properties			
Density (kg/m^3)	1540		N.A.
Specific heat (kcal/kg K)	0.44		N.A.
Inlet conditions (See detials in Table 5.1)			
Air temperature (K)	453 - 481		
Air humidity (kg/kg dry air)	0.014 - 0.018		
Mass flow rate of air (kg/hr)	73000 - 80000		
Flour temperature (K)	304 - 307		
Flour moisture content (% dry basis)	52.7 - 61.8		
Mass flow rate of flour (kg/hr)	5000 - 6200		
Model parameters			
Internal moisture diffusivity (m^2/s)	$1*10^{-9}$	(not used)	N.A.
Equilibrium moisture content (% dry basis)	13	10	N.A.
Slope of equilibrium moisture content	0.4	(not used)	N.A.
Critical moisture content (% dry basis)	(13.02) *	17	N.A.
Effective particle size (mm)	(0.12) *	0.45	N.A.
Outlet conditions			
Air temperature (K)	379-388	375-385	382-392
Air humidity (kg/kg dry air)	0.045-0.054	0.045-0.056	0.044-0.053
Flour temperature (K)	321-365	318-321	328-342
Flour moisture content (% dry basis)	13-14.5	8.8-16.6	13.9-14.7

N.A. Not Applicable or Not Available

* Determined naturally during model simulations (not a model parameter)

** Mean particle size of dried product (not a model parameter)

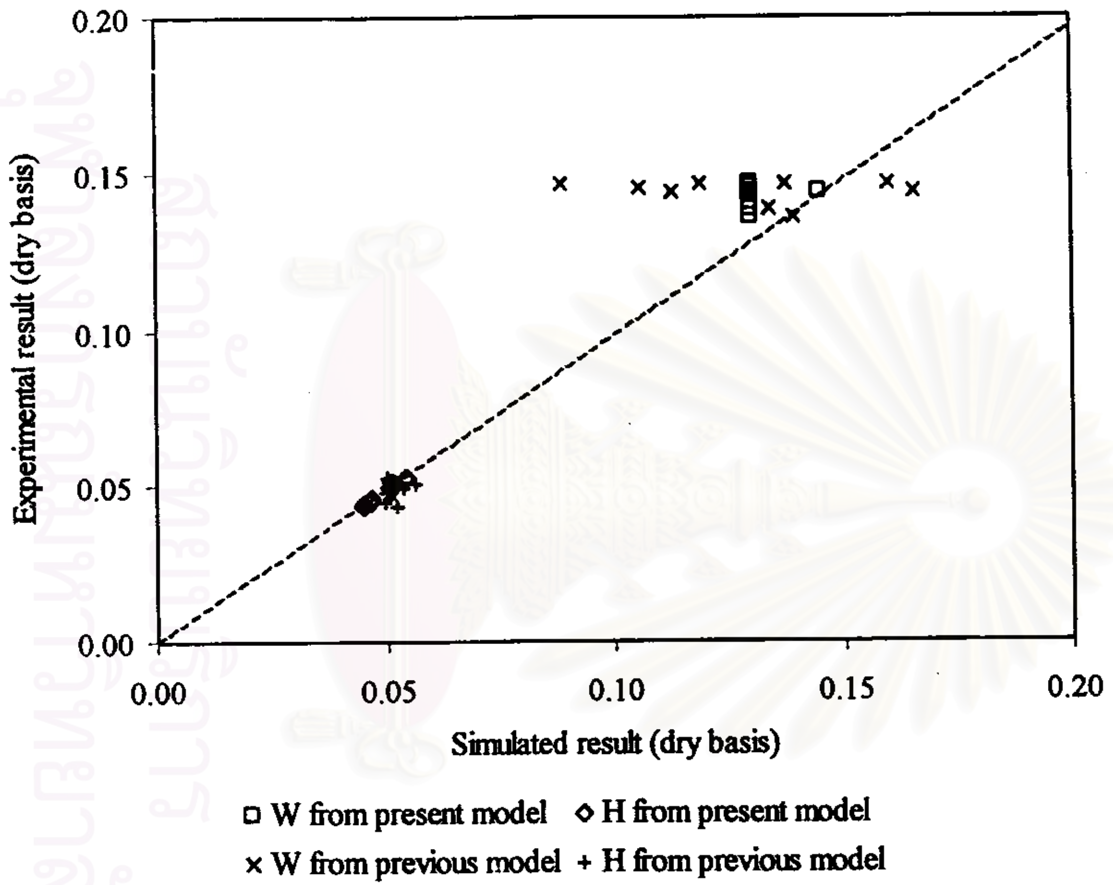

Figure 5.27 Comparison of outlet moisture content and humidity between experimental and simulated results from present and previous model

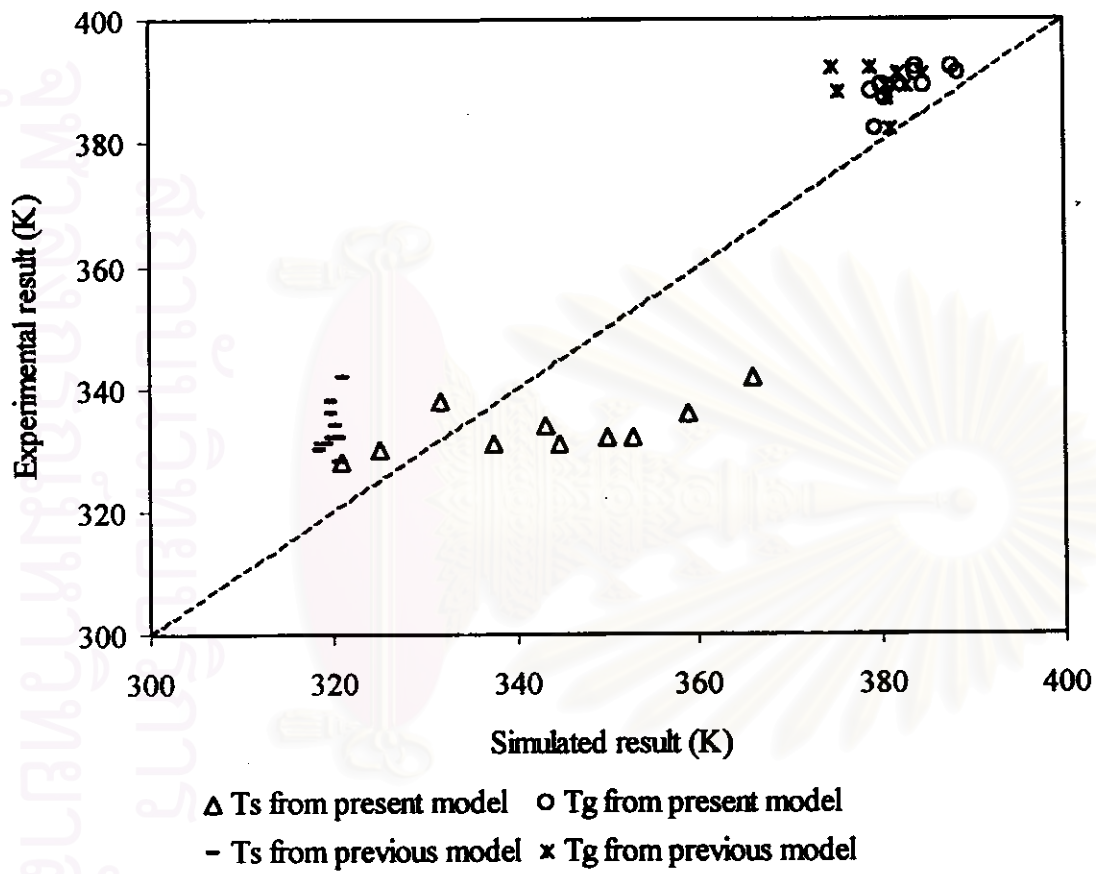

Figure 5.28 Comparison of outlet flour and air temperatures between experimental and simulated results from present and previous model.

flour temperature, the predictions by the present model, which rise above the wet-bulb temperature due to the falling of drying rate in the internal moisture diffusion controlled period are slightly higher than the experimental values, though the relative errors are less than 7 %. Nevertheless, these predictions are apparently more reasonable than the previous prediction. Consequently, it can be concluded that the present model is not only more general than the previous model but also give better predictions pneumatic conveying drying of cassava flour.

5.5 Example of changes occurring within dryer

A typical example of the simulated changes in the drying variables along the dryer length for the fourth case of Table 5.1 is illustrated in Figure 5.29. The dryer configuration, flour properties and parameters are summarized in Table 5.3. In this case the simulation switches from the surface evaporation model to the internal moisture diffusion controlled model at 54.9 m of dryer length where the "critical moisture content" is 13.02 % dry basis. Before the model switching, the rate of decrease in the moisture content is nearly constant and the flour temperature is nearly stable at the wet-bulb temperature while air temperature and humidity continuously change. After the critical point, the drying rate falls rapidly while the flour temperature rises steadily.

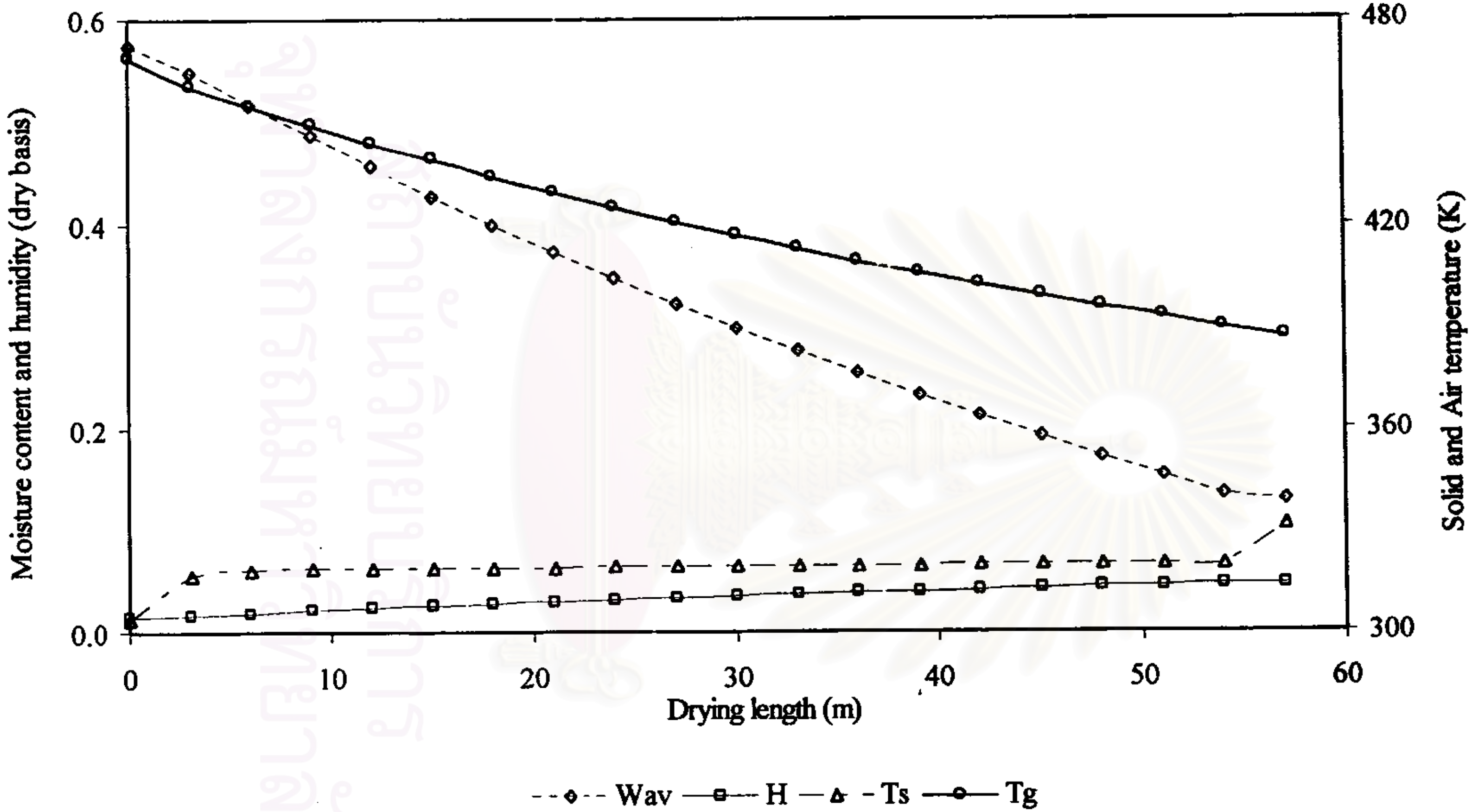

Figure 5.29 Simulated distributions of moisture content, humidity and solid and air temperatures along the dryer length in case (the fourth case in Table 5.1)