CHAPTER VI

TESTING OF PRESENT MODEL ON OTHER DRYING MATERIALS

In the previous chapter, the present model has been validated using the experimental results of industrial-scaled flour drying. The comparison shows that the present model is superior to the previous model and suitable for predicting pneumatic conveying drying of flour, because it is composed of two transport phenomena models, namely, surface evaporation model and internal moisture diffusion controlled rate model, which cover the entire general drying behavior. Thus, the model should be applicable to the pneumatic conveying drying of a varieties of materials. In this chapter, the general applicability of the present model will be tested by comparing the simulated results with the reported results on 5 other materials.

6.1 Reported results on other drying materials

The results used to confirm the generality of the present model are reported industrial-scale pneumatic conveying drying of ilmenite ($FeTiO_3$), Glauber's salt ($NaSO_4 \cdot 10HO_2$), carbon, ammonium sulfate ($(NH_4)_2SO_4$) and polyvinylchloride (PVC) resins. These results are reported in a book by R. Toei (1986). Table 6.1 summarizes the operating conditions of the industrial dryers. Since air humidity is not reported, the inlet air humidity is assumed to be 0.015 kg/kg dry air and the outlet value is back calculated from an overall mass balance on H_2O. The wet solid is assumed to be fed at room temperature (298 K). Then an overall energy balance is used to double - check the

Table 6.1 Reported operating conditions of industrial pneumatic conveying dryers

Material	Ilmenite	Glauber's salt	Ammonium sulfate	Carbon	PVC
Dryer configuration					
Dryer diameter (m)	0.38	0.40	0.36	0.54	0.65
Dryer length (m)	15	10	8	22	25
Inlet conditions					
Air temperature (K)	473	473	423	523	413
Air humidity (kg/kg dry air)	0.015	0.015	0.015	0.015	0.015
Mass flow rate of air (kg dry air/hr)	3620	2630	2940	8740	15050
Mean particle size (mm)	0.25	0.30	0.25	0.20	0.13
Solid temperature (K)	298	298	298	298	298
Moisture content (% dry basis)	6.4	3.0	3.1	11.1	20
Mass flow rate of solid (kg dry solid/hr)	4000	3000	2000	4000	2000
Outlet conditions					
Air temperature (K)	353	368	343	378	343
Air humidity (kg/kg dry air)	0.085	0.044	0.035	0.042	0.040
Solid temperature (K)	343	348	338	358	323
Moisture content (% dry basis)	0.1	0.5	0.2	5.3	1.5
Overall energy balance of dryer					
Energy balance error (%)	-5.70	-4.80	4.20	-16.00	-3.80

reasonableness of the assumptions. A minus sign of the relative error means that the total outlet energy is lower than the total inlet energy. Table 6.1 shows that the overall energy balance has a relative error between –16 % to +4%. The drying capacity of these dryers ranges between 60-370 kg/hr. The diameter of the drying materials falls in the range of 0.1-0.3 mm.

6.2 Estimation of unknown model parameters

As mentioned in section 5.2, the present model typically contains three unknown parameters, that is, intrinsic equilibrium moisture content (at 0% relative humidity), slope of the equilibrium moisture content curve with respect to relative humidity change and internal moisture diffusion coefficient. However, the equilibrium data of the above materials are not reported and can not be found elsewhere. Only the internal moisture diffusivity is reported in the case of carbon (Mujumdar, 1995) and PVC(J. Brandrup and E.H. Immergut, 1989). Therefore, it is necessary to estimate these parameters for the above materials.

According to section 5.3, it has been shown that the slope of the equilibrium moisture content curve within the range of 0.1-5 has little effect on the simulated results. In other words, this means that at constant temperature, the results are insensitive to the slope of the equilibrium moisture content. As shown in Table 6.1, the inlet air temperature is generally high enough that the slope of the equilibrium curve may be taken to be less than 5. Thus, its value is simply set as 0.4 for all the above materials as in the case of flour drying.

The internal moisture diffusion coefficients of carbon and PVC have been reported as $1*10^{-8}$ m^2/s and $2.7*10^{-8}$ m^2/s, respectively (Mujumdar, 1995). Though the coefficients depend significantly on the moisture content, their reported values have been adopted here. Thus in the cases of carbon and PVC, only the intrinsic equilibrium moisture content is the unknown parameter to be estimated. On the other hand, in the cases of ilmenite, Glauber's salt and ammonium sulfate, both the intrinsic equilibrium moisture content and the internal moisture diffusivity are unknown and need to be estimated. Since their product moisture contents are close to zero, their equilibrium moisture contents may be approximated as zero and only the values of the internal moisture diffusion coefficient have to be estimated.

Figures 6.1 to 6.5 illustrate the effect of the parameter of interest on the product moisture content and temperature, and outlet air temperature for each material. With respect to the internal moisture diffusivity parameter, an increase in this parameter causes the product moisture content to increase as shown in Figures 6.1 to 6.3. Whereas in the case of the intrinsic equilibrium moisture content, the product moisture content also increases along with the parameter, as shown in Figures 6.4 and 6.5. The estimated values of the unknown parameter for each material are listed in Table 6.2. They are the sets of parametric values that provide the best fit with the reported product moisture contents.

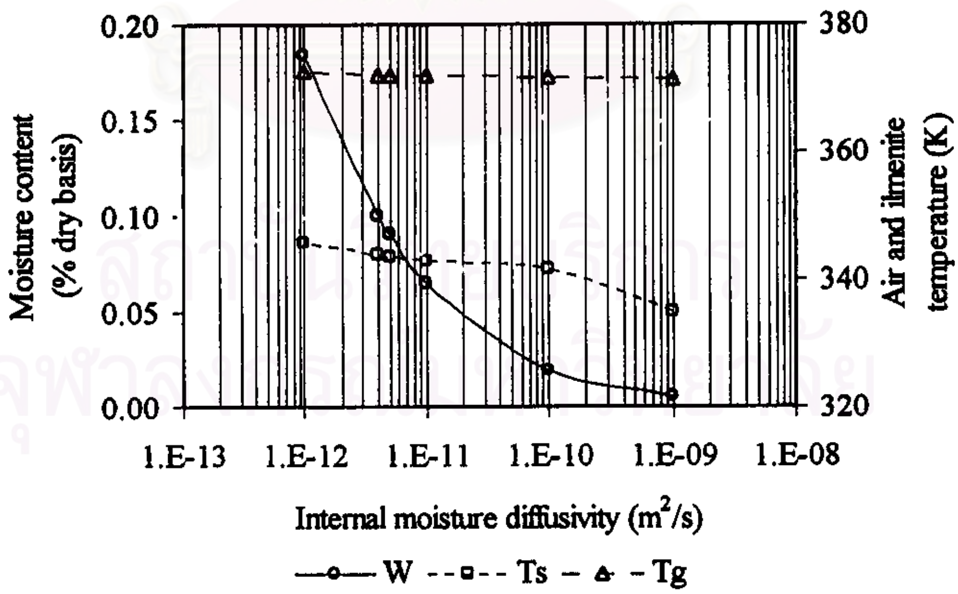

Figure 6.1 Effect of internal moisture diffusivity on product moisture content and temperature and outlet air temperature in the case of ilmenite

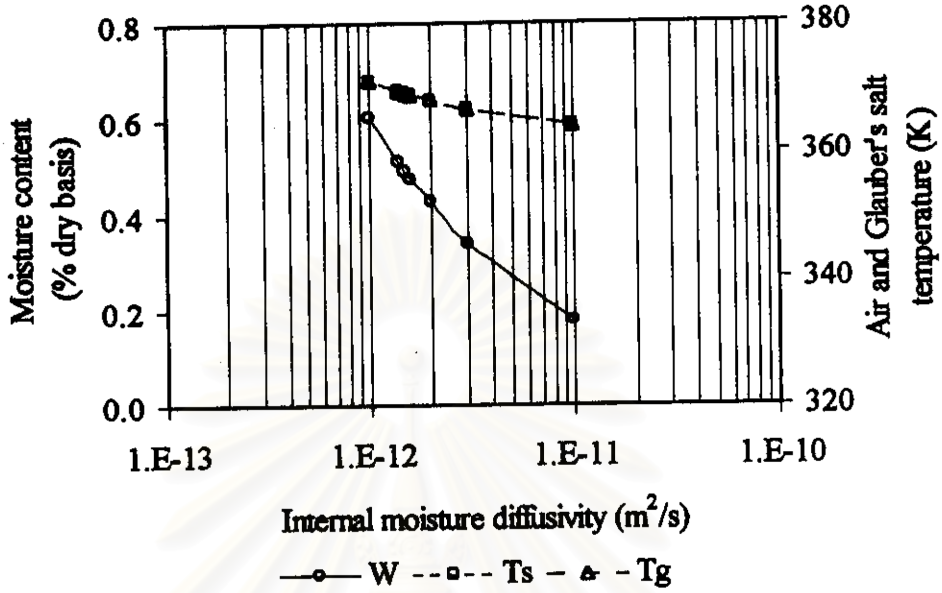

Figure 6.2 Effect of internal moisture diffusivity on product moisture content and temperature and outlet air temperature in the case of Glauber's salt

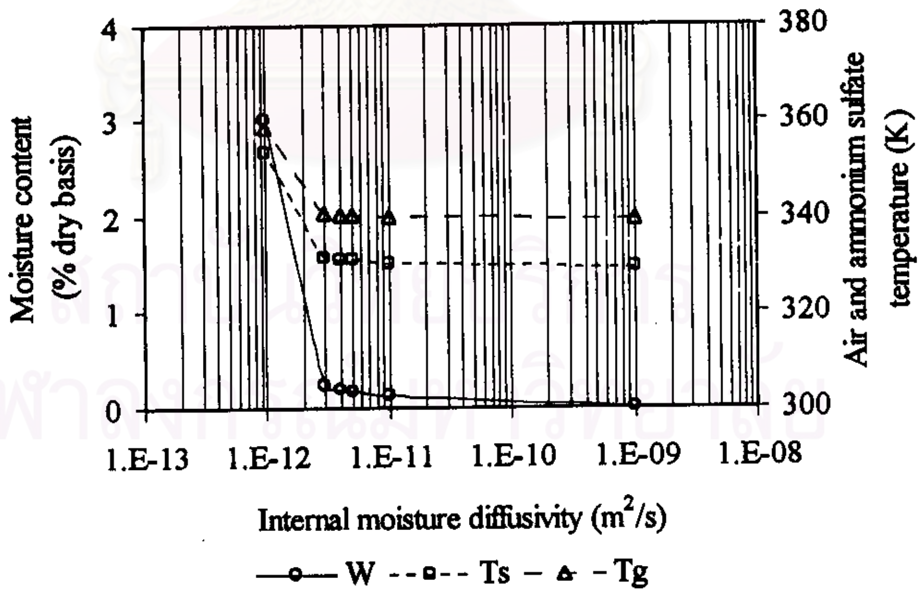

Figure 6.3 Effect of internal moisture diffusivity on product moisture content and temperature and outlet air temperature in the case of ammonium sulfate

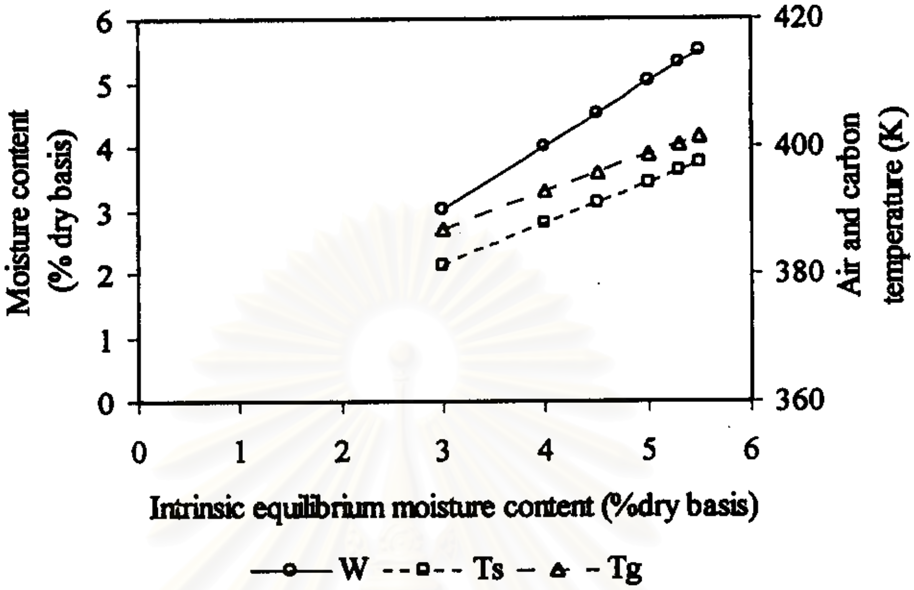

Figure 6.4 Effect of intrinsic equilibrium moisture content on product moisture content and temperature and outlet air temperature in the case of carbon

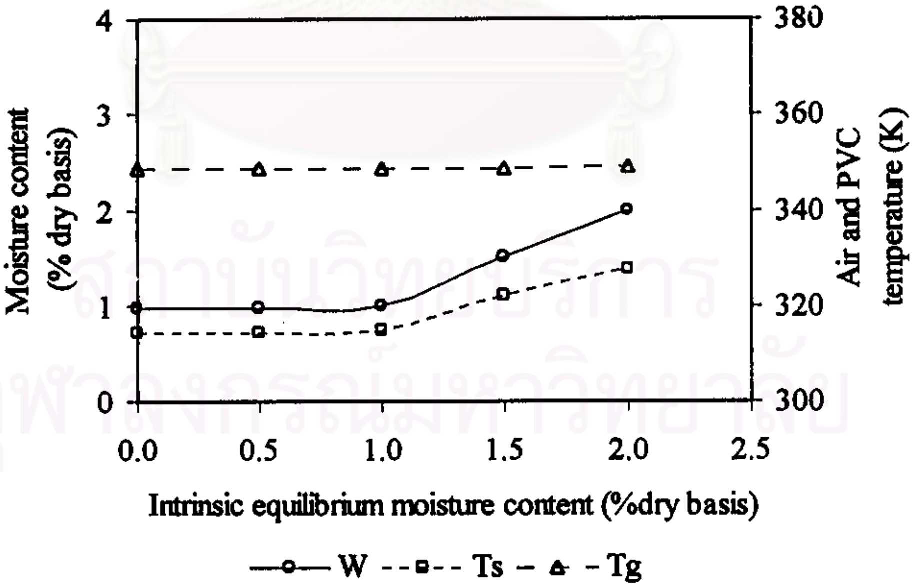

Figure 6.5 Effect of intrinsic equilibrium moisture content on product moisture content and temperature and outlet air temperature in the case of PVC

6.3 Comparison between simulation and actual results

The predicted moisture contents at the dryer outlet of all 5 materials are close to their reported values within ±2 % because it is the criterion used in the parameter estimation. In the case of ilmenite, the predicted product temperature of 344 K is very close to the reported value of 343 K but the outlet air temperature is overestimated by 19 K (372 K versus 353 K). On the other hand, Glauber's salt outlet temperature is overestimated (369 K versus 348 K) while its outlet air temperature is close to the reported value (369 K versus 368 K). Because the overall water balance is accurate in terms of the reported operating conditions for each material and because the predicted and reported product moisture contents agree very well, an error in the overall energy balance in terms of the operating conditions will unavoidably causes irreconcilable difference in the predicted and reported temperatures. This is because the model assumes negligible heat loss from the dryer, which in an industrial dryer could amount to 4 % or more of the total heat input, as seen from Table 6.1. In short, if the predicted outlet solid temperature is close, then the predicted outlet air temperature tends to be different, and vice versa. The higher the relative error in the overall energy balance, the bigger the discrepancy.

Anyway, the present model considerably overestimates both the product and outlet air temperature in the case of carbon drying because of the large negative error in the overall energy balance, which as high as -16 %. In the cases of ammonium sulfate and PVC, the present model predicts both the outlet solid and air temperature relatively

Table 6.2 Estimated parameters and the corresponding simulation results

Material	Ilmenite	Glauber's salt	Ammonium sulfate	Carbon	PVC
Parameters used in the simulation					
Internal moisture diffusivity (m^2/s)	4.00E-12	1.50E-12	4.00E-12	1.00E-08	2.70E-08
Slope of equilibrium moisture content curve	0.2	0.2	0.2	0.2	0.2
Equilibrium moisture content	0	0	0	5.3	1.5
Observed critical conditions					
Surface evaporation length of dryer (m)	12.63	1.72	4.04	6.29	23.90
Air temperature (K)	382.8	392.4	358.3	441.2	350.1
Air humidity (kg/kg dry air)	0.085	0.043	0.035	0.042	0.040
Solid temperature (K)	326.7	319.4	313.7	322.5	314.5
Moisture content (% dry basis)	0.103	0.513	0.208	5.306	1.502
Outlet conditions					
Air temperature (K)	372.2	369.2	340.4	400.4	348.7
Air humidity (kg/kg dry air)	0.085	0.044	0.035	0.042	0.040
Solid temperature (K)	343.7	369.1	330.9	396.3	321.8
Moisture content (% dry basis)	0.100	0.491	0.199	5.301	1.500

well, within ±2 %, because the temperature discrepancy is shared by both the air and solid.

At the predicted critical condition, the critical moisture content of each material is found to approach its equilibrium moisture content. This is primarily because the particle sizes are all relatively small. Generally, the internal moisture diffusion controlled rate period mainly serves to increase the solid temperature. In the cases of ilmenite and PVC, the switching between the two drying mechanisms occurs near the end of the dryer, whereas in the case of ammonium sulfate, the switching occurs at about half of the dryer's 8 m length. Thus, the product temperature of ammonium sulfate is moderately higher than the observed value. In the cases of Glauber's salt and carbon, switching from the surface evaporation model to the internal moisture diffusion controlled rate model occur quite early. Therefore, the solid temperature rises over a long dryer length. Thus, the outlet temperatures of Glauber's salt and carbon approach their outlet air temperatures.

In conclusion, only one unknown parameter (intrinsic moisture content or internal moisture diffusivity) has to be estimated in order to apply the present model to the above 5 different materials. On the overall, the model is capable of predicting the outlet conditions reasonably well. Because of the assumption of negligible heat loss, the predicted temperatures cannot avoid showing some discrepancy from the reported values as long as there is an error in the overall energy balance in terms of the reported operating conditions.