CHAPTER IV

RESULTS and DISCUSSION

Equilibrium Moisture Content and Sorption Isotherm of Chillies

The equilibrium moisture content (EMC) at 32.2°C, 48.9°C and 68.3°C with relative humidity between 11.1% - 96.5% were determined and used to estimate the parameters in the expressions of the moisture desorption isotherm models by using the non-linear regression procedure solving with STATISTICA 6.0 in order to investigate the relation between EMC, temperature and relative humidity. The regression analysis was repeated several times with different initial values above and below those calculated to confirm the validity of the regression parameters. The coefficients of the Halsey, Modified Henderson, Modified Halsey, Modified Oswin, Modified BET, and Modified Smith with their static mean relative error (MRE) and standard error of estimate (SEE) are presented in Table 5. The observed and predicted desorption isotherms using six models are shown in Figure 25 to Figure 30. The results indicate EMC increases when temperature decreases with constant ERH. At constant temperature, the EMC increases with increasing ERH. For a wide range of temperature and relative humidity, the six models can be accepted as the values of R^2 are more than 0.8. The Modified Oswin model can be accepted for high temperature range. Its MRE, R^2 and SEE values were 26.76 %, 0.98 and 4.94 respectively. It can be seen that the EMC data were best fitted by Modified Halsey model, with MRE of 26.54 %, R^2 of 0.98 and SEE of 4.88. The residual plot distributions for Modified Halsey model showing data points not far scattered from zero as shows in Figure 31. This indicates that the Modified Halsey model was appropriate to describe EMC of chillies as the following equation.

$$M = \left[\frac{-\exp(4.153975 - 0.005358T)}{\ln(RH)} \right]^{1/1.61421} \qquad (20)$$

Table 5 Predicted Parameters and Comparison Criteria for EMC Models of Chillies.

EMC models	Parameters and criteria						
	A	B	C	D	MRE,%	SEE	R^2
Halsey	2607.797	1.65036	-	-	40.01	10.83	0.96
Modified Henderson	0.00056	101.0631	0.8235	-	30.08	8.37	0.94
Modified Halsey	4.15398	-0.00536	1.61421	-	26.54	4.88	0.98
Modified Oswin	15.45423	-0.04166	0.56241	-	26.76	4.94	0.98
Modified BET	4.94087	-0.02589	554740.8	-	32.29	8.48	0.95
Modified Smith	-12.8084	0.2198	29.1178	-0.1274	29.22	7.34	0.96

From the preliminary study, it can be seen from Figure 25 to Figure 30 that the equilibrium moisture content, EMC of chillies decreased with increased air temperature owing to the container temperature was increased that caused the moisture rapid escaped from the chillies. The EMC of chillies also increased with the increase of the ERH. From the preliminary study results as explained above, the desorption isotherm of chillies can be predicted by using the Modified Halsey Model from equation (20) for drying temperature of 50, 60 and 70 ^{o}C which is shown in Figure 32. It indicated that at constant ERH, the EMC decreased with increasing surrounding air temperature. These isotherms will be useful to the prediction and control for chillies drying process in the next part.

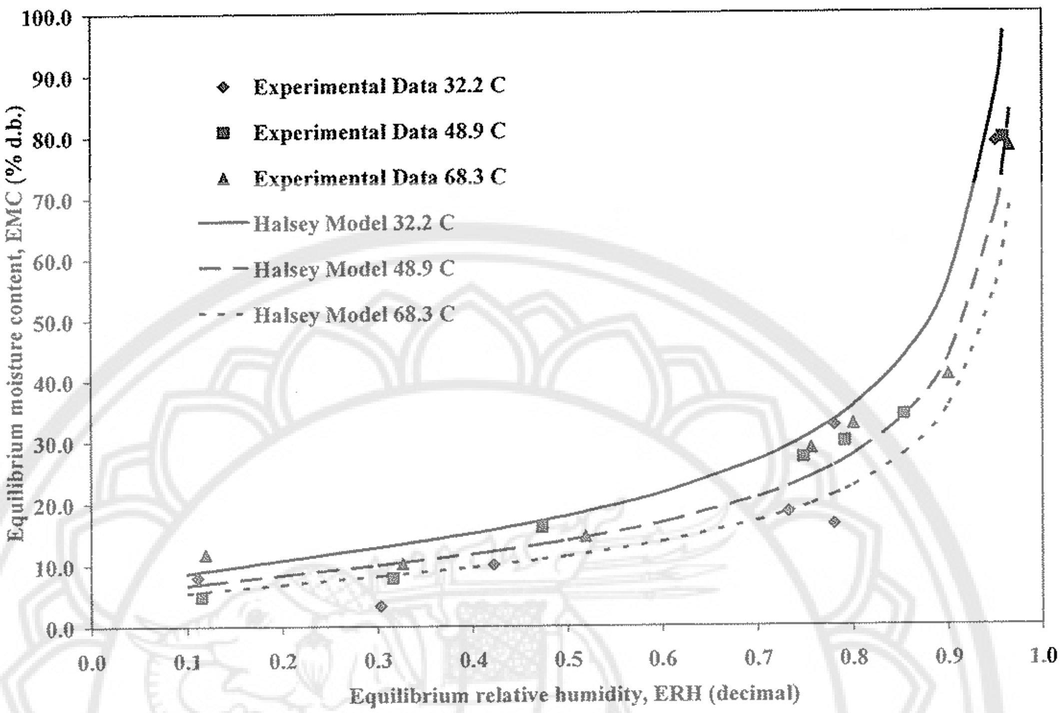

Figure 25 EMC of Chillies at Various Temperatures by Halsey Model.

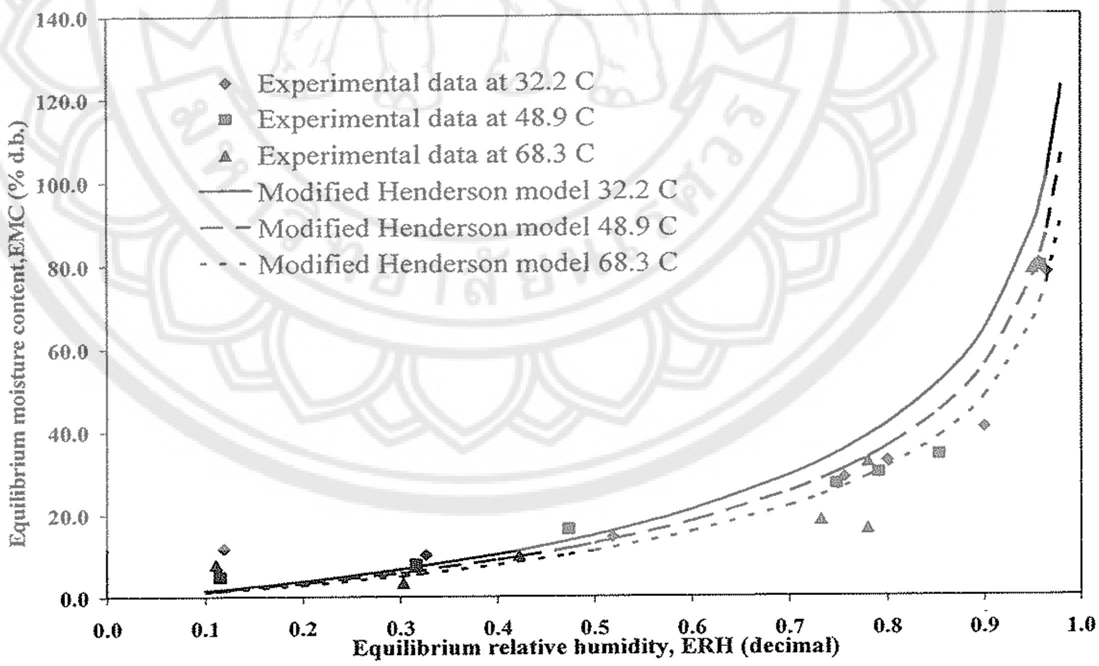

Figure 26 EMC of Chillies at Various Temperatures by Modified Henderson Model.

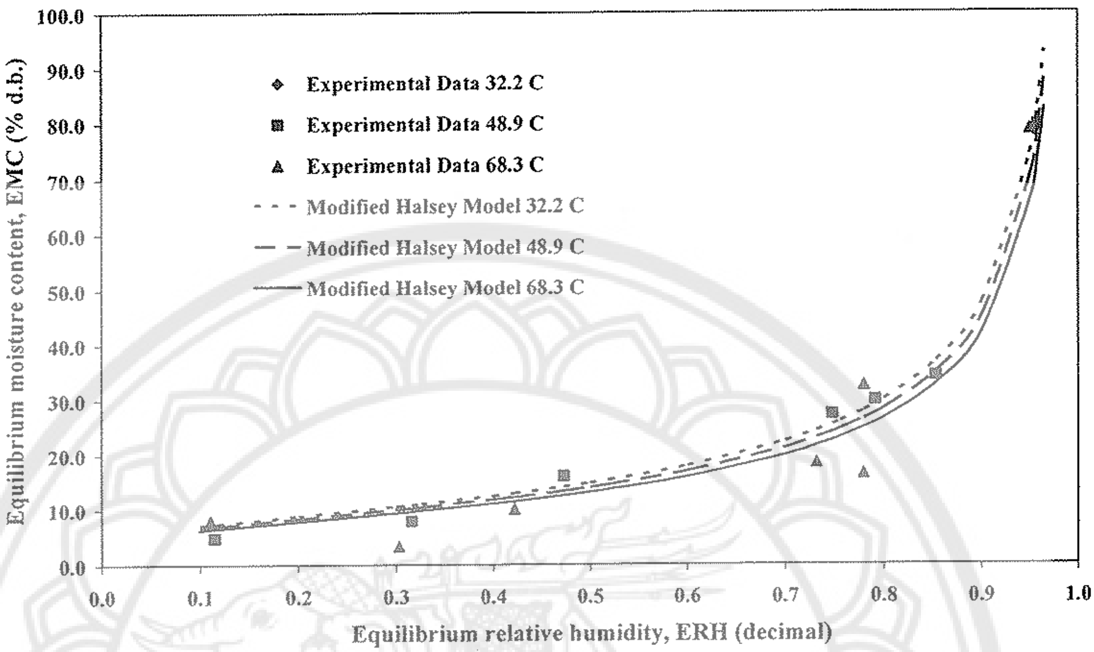

Figure 27 EMC of Chillies at Various Temperatures by Modified Halsey Model.

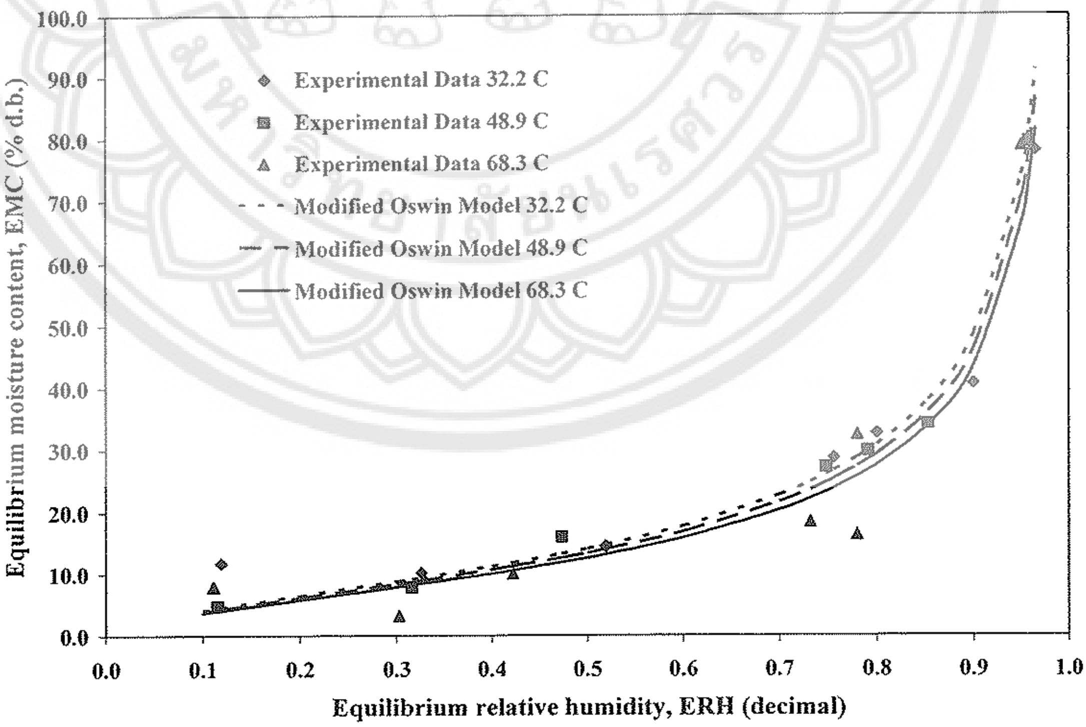

Figure 28 EMC of Chillies at Various Temperatures by Modified Oswin Model.

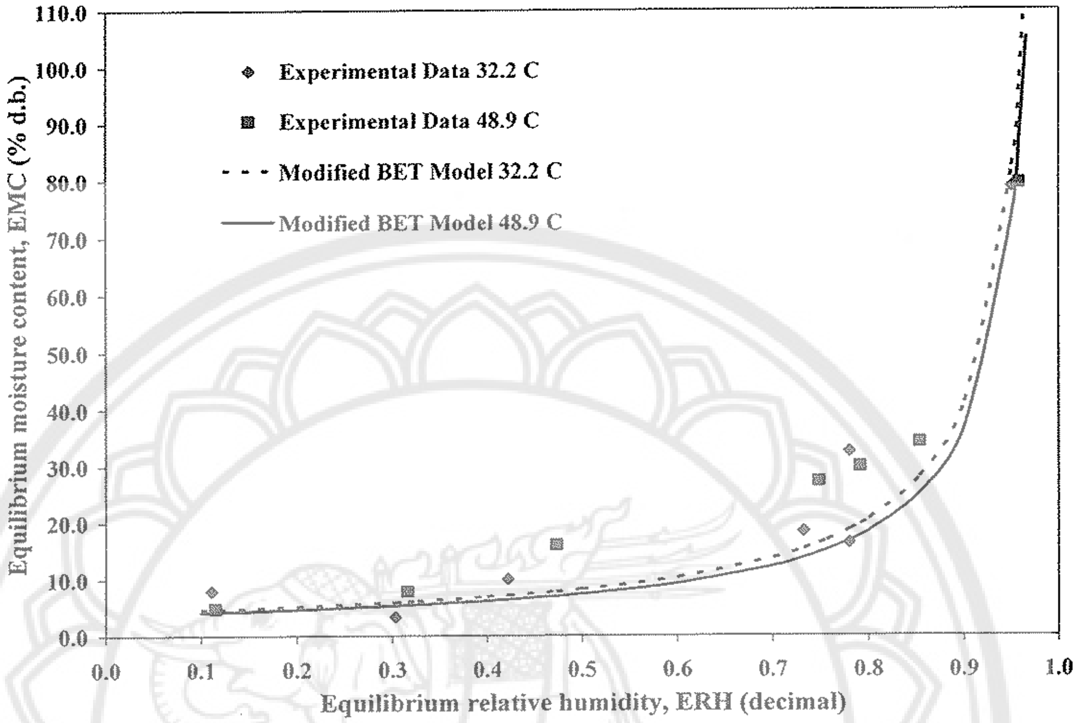

Figure 29 EMC of Chillies at Various Temperatures by Modified BET Model.

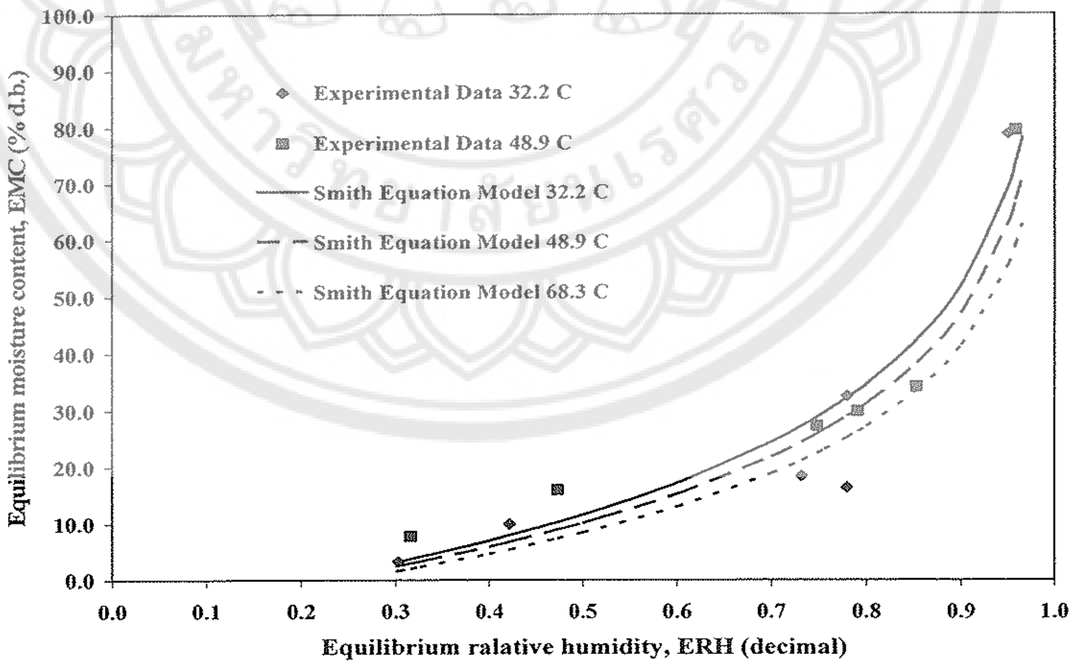

Figure 30 EMC of Chillies at Various Temperatures by Smith Equation Model.

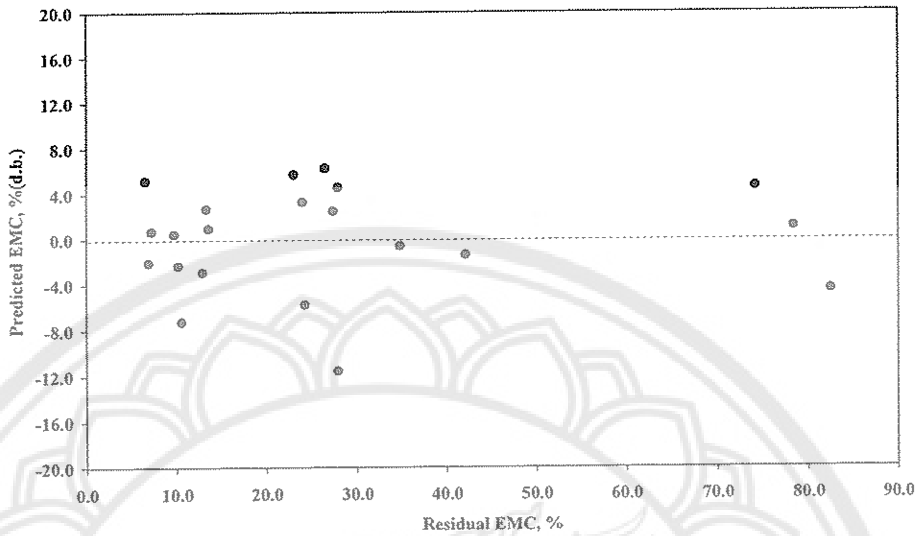

Figure 31 Plots of residual EMC by Modified Halsey Model vs Predicted EMC for Chillies.

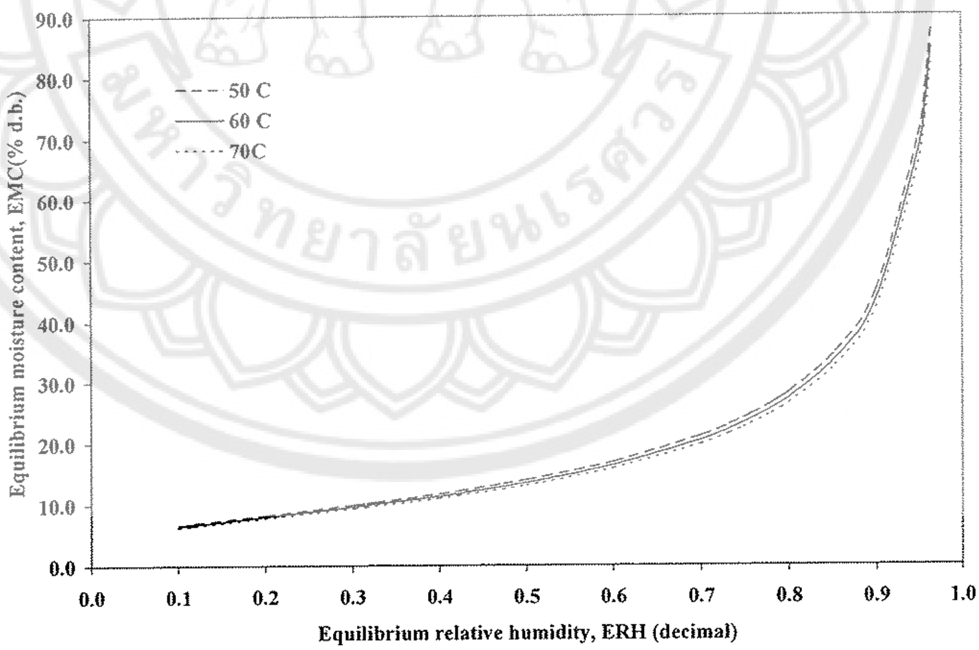

Figure 32 Predicted Sorption Isotherms of Chillies Using Modified Halsey Model at Drying Air Temperature of 50, 60 and 70 °C

Analysis of Experimental Results

The analysis of experimental results in this research can be explained into 5 items ; specific heat of chilies, producer gas generation, outlet air temperature from the solar collector, thermal efficiency of the solar dryer system and color of dried chillies.

1. Specific heat of chillies

The experimental results showed that the specific heat of chillies increased linearly when the moisture content increased (Figure 33). From the regression analysis, it was found that both parameters related with coefficient of determination of 0.81 can be expressed as:

$$c_p = 0.3536 + 0.0009\,MC \qquad (21)$$

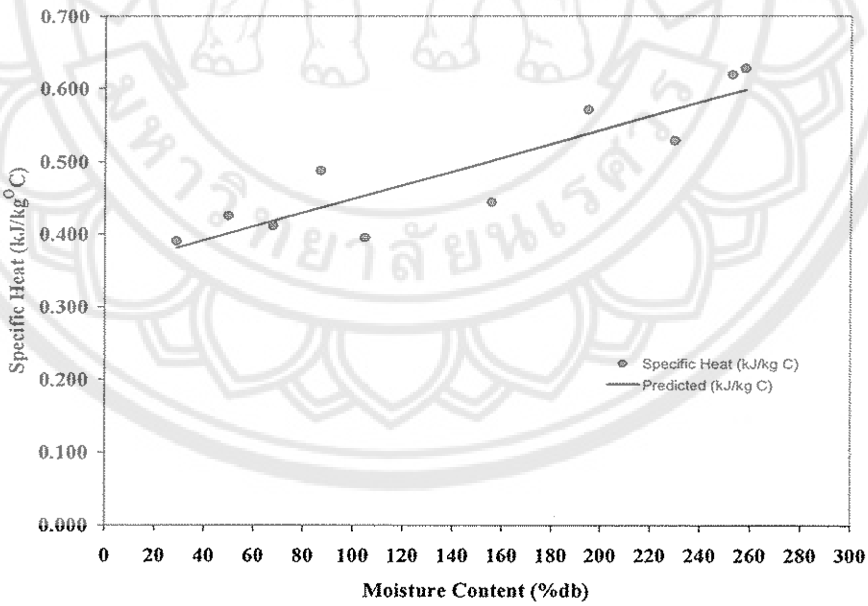

Figure 33 Relationship of Moisture Content and Specific Heat of Chillies

2. Producer gas generation

Producer gas from the experiments was the main production which was generated from downdraft reactor by using corn cob as fuel. The corn cob in this research was investigated for chemical compositions by The Department of Science Service and the results are shown in Table 7 (Appendix A). Carbon monoxide (CO) was considered in order to achieve an appropriate condition to generate the maximum amount of CO. From the results, it was found that the flow rate of inlet air effected to the gas productions.

At started, the butterfly valve was controlled in order to get the suitable air flow rate to generate the producer gas. After burn the producer gas, it could be seen that the flame could not be maintained continuously. Then it was improved by the butterfly valve adjustment to about 20 m/s of air velocity to let enough air flow into the combustion zone in order that fuel could be burned well, next adjusted the butterfly valve again to reduce the air flow rate to be 4 m/s which was suitable to maintain the gas production rate. It was found that the appropriate flow rate of air inlet to the reactor was 5.44×10^{-3} kg/s.

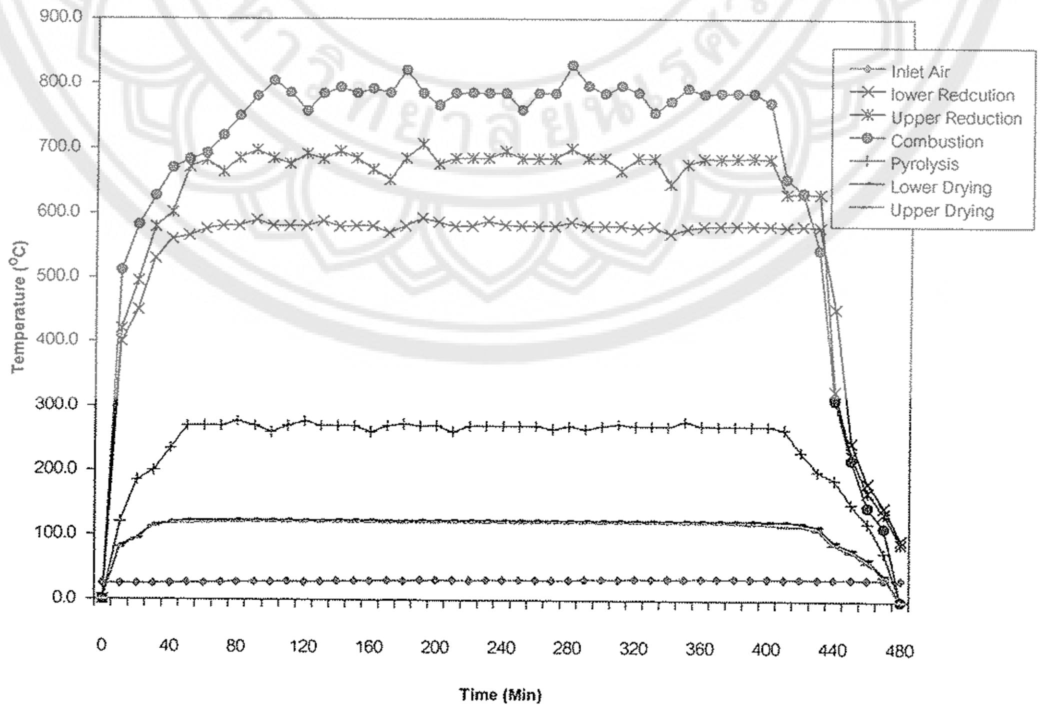

Figure 34 Temperatures of Inlet Air and Various Zones in the Reactor

From the test as shows in Figure 34 while approximate inlet air was 30.1 ^{O}C, the average temperature in upper drying zone, lower drying zone, pyrolysis zone, combustion zone, upper reduction zone, lower reduction zone were 120 ^{O}C, 123 ^{O}C, 270 ^{O}C, 785 ^{O}C, 680 ^{O}C and 580 ^{O}C respectively. For further study, the insulation at the reactor should be improved to rise up the temperature at upper reduction zone.

From the experiment, it was found that the downdraft reactor of 0.374 m^3 can produce 39.25 MJ/hr from 60 kg of corn cob for 8 hours of working time. By using the equilibrium model to conduct the composition of producer gas, the following shows the result from computing by the computer program.

By varying the moisture content of corn cob from 10 % to 35% whereas the temperature of the gasifier was 680^{O}C. As can be seen from the Figure 36, the quantity of carbon monoxide and hydrogen are decreased with the increasing moisture content. On the contrary, the carbon dioxide was increased with higher value of moisture content. From the experiment, the producer gas comprised CO of 19.3%, H_2 of 7.4%, CO_2 of 18.5% and O_2 of 1.5% in average. And its high heating value was 3.14 MJ/m^3. The Figure 37 shows the model predictions comparing with the experiment data. The experimental data are for air flow rate of 5.44 x 10^{-3} kg/s, corn cob feed rate of 7.5 kg/h, and corn cob moisture content of 12.1 %. It shows that almost components are in good agreement with experimental data except hydrogen which is more than the experimental data.

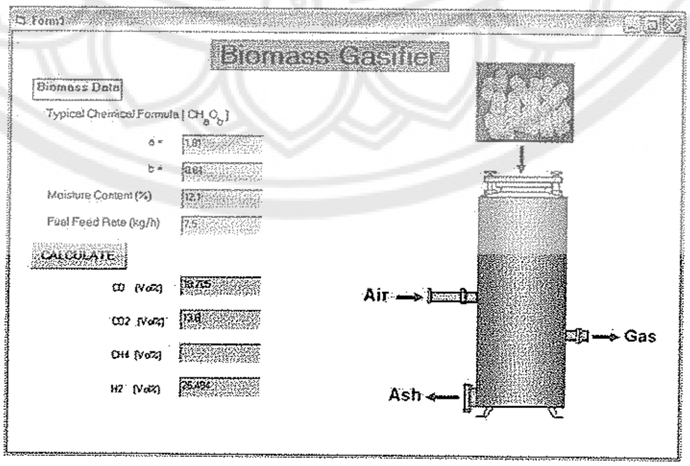

Figure 35 Results from Using the Equilibrium Model to Predict the Composition of the Producer Gas.

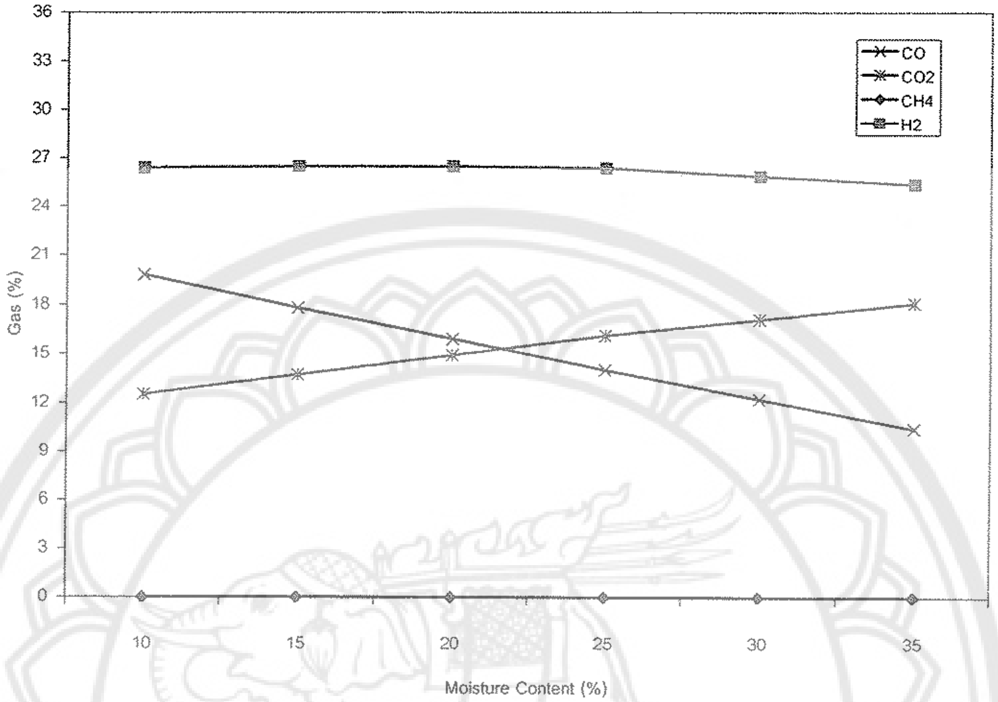

Figure 36 Effect of Moisture Content on the Quantity of Product Constituents.

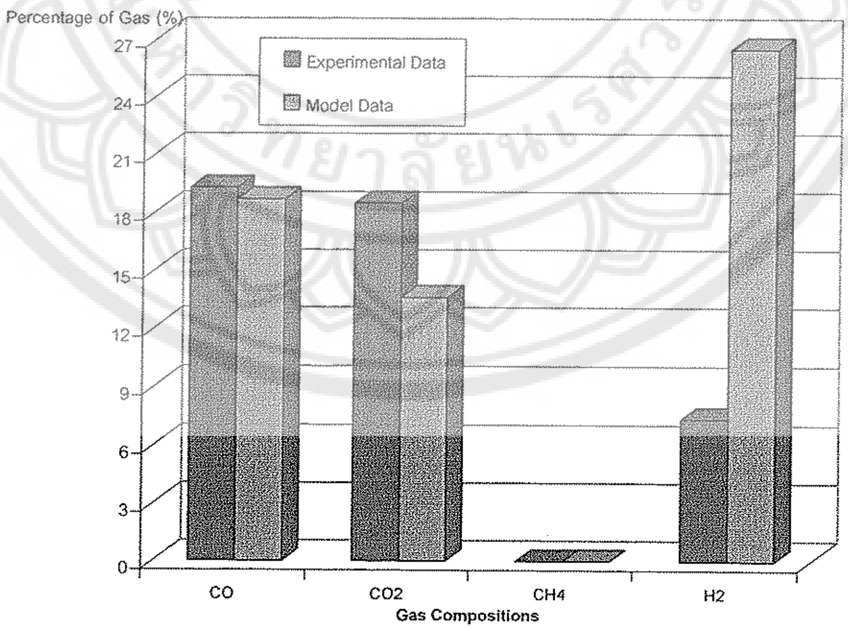

Figure 37 Model Comparisons with Experimental Data

The results showed that the average thermal efficiency of biomass reactor was 34.7 %. (Detail of calculation shows in Appendix E)

3. Outlet Air Temperature from the Solar Collector

The thermal efficiency of the solar collector can be calculated from the equation as follows:

$$\eta_C = \frac{mc_p(T_{f,o} - T_{f,i})}{A_C G_T} \tag{22}$$

Equation 22 can be written in

$$T_{f,o} - T_{f,i} = \frac{\eta_C A_C G_T}{m_a C_a} \tag{23}$$

Then, the outlet air temperature from the collector can be expressed by

$$T_{f.o} = \frac{\eta_C A_C G_T}{m_a c_a} + T_{f,i} \tag{24}$$

By substitution each parameters into equation 24, it was found that the outlet air temperature varied by global solar radiation and inlet air temperature as the following.

$$T_{f,o} = 0.03983 G_T + T_{f,i} \tag{25}$$

Figure 38 shows the relationship between outlet air temperature from the solar collector and global solar radiation which incidences on solar collector panel from the experiments and mathematical model. It showed that the outlet air temperature from the solar collector by mathematical model closed to the results from the experiments for high range of global solar radiation. Furthermore, it was found that the average outlet air temperature from the solar collector was 61.7 ^{o}C. From the model, the outlet air temperature can be calculated from equation (25) which will be used for drying temperature control at the requirement. If the air temperature is too high the cool air outside the drying chamber can be mixed with the drying air. On the other hand, drying air temperature can be increased by using auxiliary heat source.

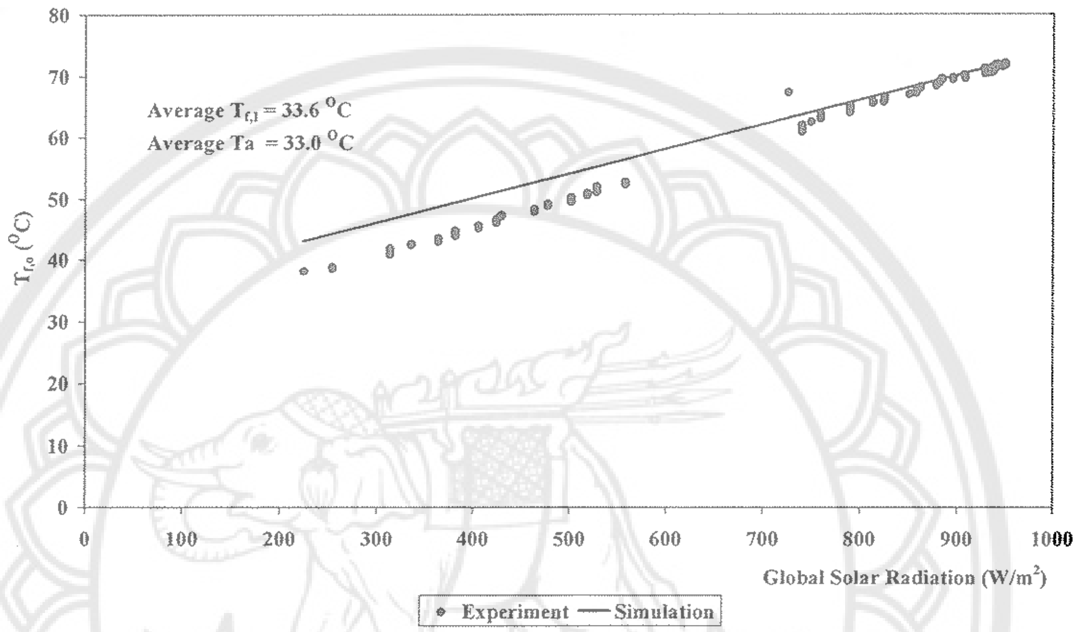

Figure 38 Evolution of Air Outlet Temperature from Collector Compare to the Solar Incident.

4. Thermal Efficiency of the Solar Dryer System

4.1 Chillies drying by using only solar energy

Fresh chillies approximately of 19.2 kg were dried in a solar dryer for each batch. The experimental results showed that the average drying rate was 2.8 kg water evaporated/day or 0.7 kg water evaporated/h. The Figure 39 shows the relationship between the moisture content of the chillies and time for 5 batches. It was found that the first falling rate period was between 2-15 hours. The solar dryer could reduce the average moisture content of chillies from 312.3 %db to 8.0 %db with 25 hours at the average temperature of drying air of 54.7 °C.

The first law efficiency of the drying system can be calculated as follows:

Experiment date: 8 May 2005.

Initial weight of chillies	= 20.0	kg
Final Weight of chillies	= 16.4	kg
Weight of evaporated water	= 20.0 – 16.4 = 3.6	kg
Solar irradiation which incident on the solar collector plane and cabinet roof	= 23.70	MJ
Electricity which was consumed by air blower	= 0.54	MJ
Total energy consumption in drying system	= 24.24	MJ
Latent heat for water evaporation	= 2.4	MJ/kg

The first law efficiency of the drying system = (3.6 x 2.4)/24.24 x 100 = 35.6 %

Specific energy consumption = 24.24/3.6 = 6.7 MJ/kg water evaporated

Specific Electricity consumption = 0.54/3.6 = 0.2 MJ/kg water evaporated

From the testing results, it was found that the average first law efficiency of the drying system was 32.5 % by using only solar energy.

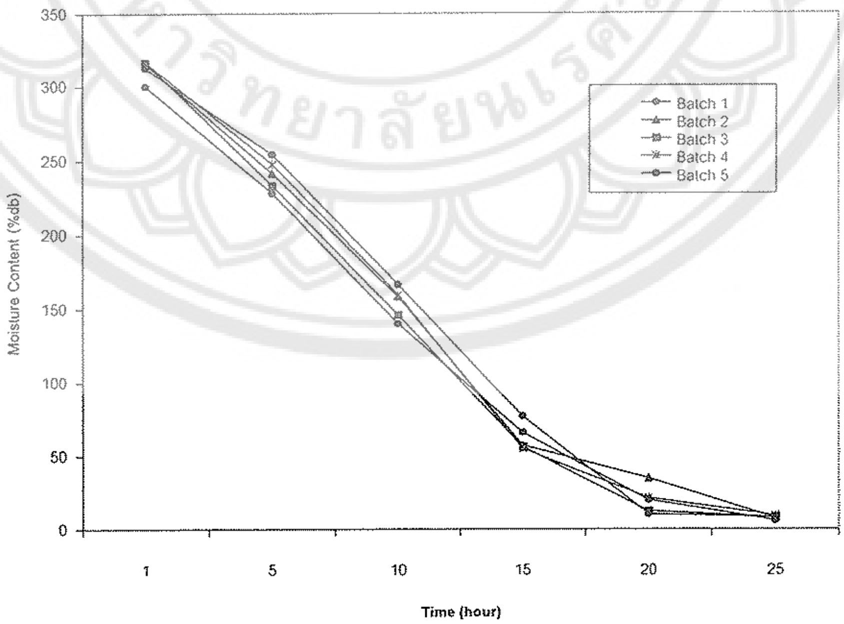

Figure 39 Relationship of Moisture Content of Chillies and Drying Time Compared for 5 Batches.

Figure 40 Chillies on the Trays in the Drying Chamber

4.2 Chillies Drying by Using Solar and Biomass Energy

Fresh chillies approximately of 20 kg were dried in a solar dryer for each batch. The experimental results showed that the average drying rate was 3.42 kg water evaporated/day or 0.76 kg water evaporated/h. The dryer which use both solar and biomass energy could reduce the average moisture content of chillies from 300.0 %db to 8.0 %db with 18 hours at the average temperature of drying air of 60.0 ^{O}C.

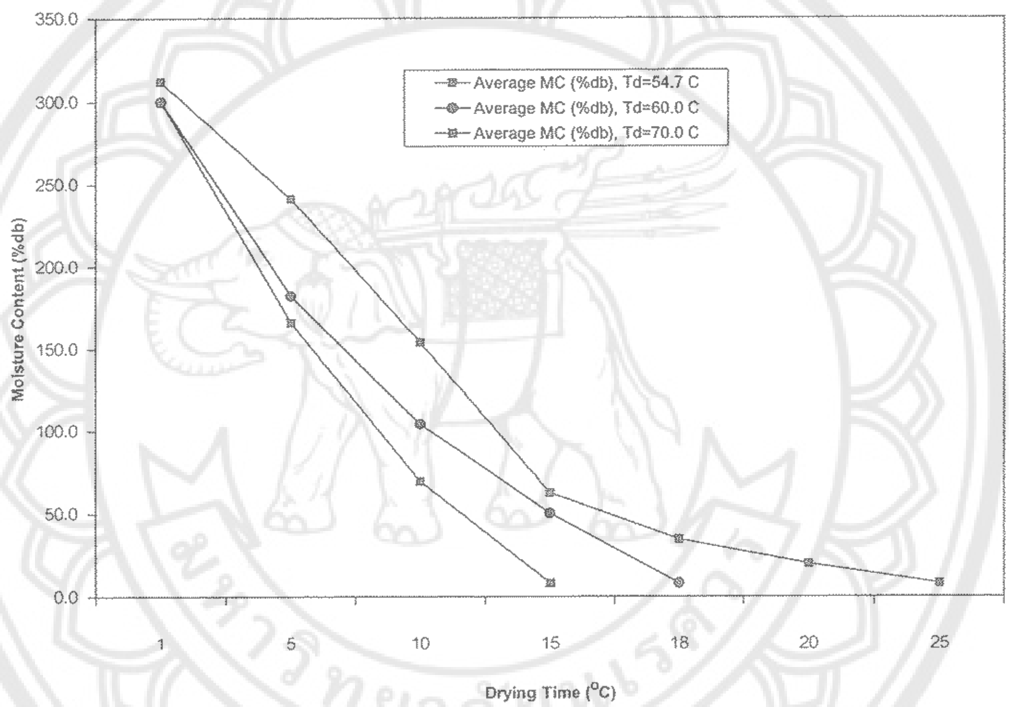

Figure 41 Comparison of Moisture Content by Time at Various Drying Air Temperature

Figure 40 shows the relationship between the moisture content of chillies and time from using drying air temperature of 54.7, 60 and 70 ^{O}C. It was found that at drying air temperature of 70 ^{O}C, the drying time was shortest at 15 hours while at 60 and 54.7 ^{O}C, the drying time were 18 and 25 hours respectively. From the testing results, it was found that the average first law efficiency of the drying system was 19.9 % by using both solar and biomass energy. The efficiency from hybrid system was lower than using only solar energy because the flow rate of the producer gas could not be controlled properly and the movement of the upper part of the gas tank could not move well. They need to be developed in the further study.

5. **Color of Dried Chillies**

Color of fresh and dried chillies were investigate with the Hunter Lab and convert the results to be CIE Lab (L* a* b*). The results were shown in Table 4 which indicates that the CIE Lab color value, L*a* b* of fresh chillies from the local market were 26.62, 41.36 and 20.15 respectively. It was found that the blanching and drying temperature influenced the final color of dried chillies. The color of dried chillies from open sun dry method which the chillies received sunlight directly, obtained dark red as CIE Lab, L*a* b* were 25.41, 8.41 and 13.75. The color of chillies from the solar dryer is lighter. In addition, the color of dried chillies which were blanched and dried in biomass/solar dryer was lightest in red with CIE Lab, 26.61, 41.36 and 20.15. It was close by the color of fresh chillies in comparison (Figure 39). This color is required by the chillies market.

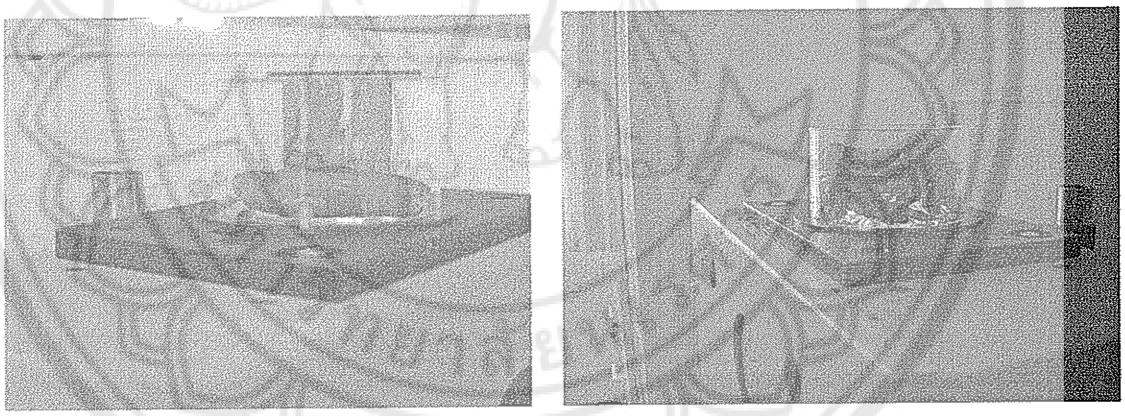

Figure 42 Hunter Lab Testing for Chillies Color

Figure 43 Fresh and Dried Chillies

Table 6 Color Parameters of Fresh and Dried Chillies

Samples	Color Parameters						Color
	Hunter Lab			CIE Lab			
	L	a	B	L*	a*	b*	
Chillies (Fresh)	22.27	30.51	10.09	26.62	41.36	20.15	
Traditional Drying (Open sun drying)	21.33	19.04	7.68	25.41	28.41	13.75	
Solar Drying	22.28	30.51	10.10	26.61	41.36	20.15	
Biomass/Solar Drying (No blanching)	25.28	32.83	11.66	30.38	43.13	22.56	
Biomass/Solar Drying (blanching)	28.27	35.66	15.12	33.97	45.39	31.46	

6. Energy Consumption

The energy consumption indicates in the following:

6.1 Chillies drying by using only solar energy

The average total energy consumption for drying 19.2 kg of chillies was 12.78 MJ/kg-water evaporated, of which 12.4 MJ/kg-water evaporated from solar energy and 0.38 MJ/kg-water evaporated from electricity

6.2 Chillies Drying by Using Solar and Biomass Energy

The average total energy consumption for drying 20 kg of chillies was 12.60 MJ/kg-water evaporated, of which 5.04 MJ/kg-water evaporated from solar energy, 7.32 MJ/kg-water evaporated from producer gas and 0.14 MJ/kg-water evaporated from electricity.

7. Drying Model

From the experimental result, the empirical drying model which was determined to be suitable model for chillies drying based on Page drying model which R^2 of 0.99:

$$MR = \exp(-xt^{y}) \tag{26}$$

Whereas

$x = 0.387075$

$y = -0.655268 + 0.038546\,T - 0.399721\,M_{in}$

This drying model is useful for drying rate and drying time prediction for chillies drying.

From the analysis it indicates that the dryer system using biomass and solar energy can be use efficiently to dry chillies in order to get the required moisture content and color. This dryer type is useful in term of using agricultural wastes as the supplementary heat source whereas the solar energy is the main energy source. It is environmental friendly application. In addition, it can make the product which will be value added.