CHAPTER VIII

QUALITY VARIATION MANAGEMENT IN DRYING PROCESS WITHIN FALLING DRYING RATE PHASE

From Chapter 7, the heated raw materials are dried within the second phase of the drying process. After drying within the second phase, they are dried again within the third phase which is used to dry the raw materials with falling drying rate. Therefore, quality variation management in the drying process within falling rate phase is studied in this chapter as Figure 8.1. The results of this chapter are the optimal temperature levels for drying the raw materials to the target and the mathematical models for representing the behavior of the moisture content within the drying with falling rate phase.

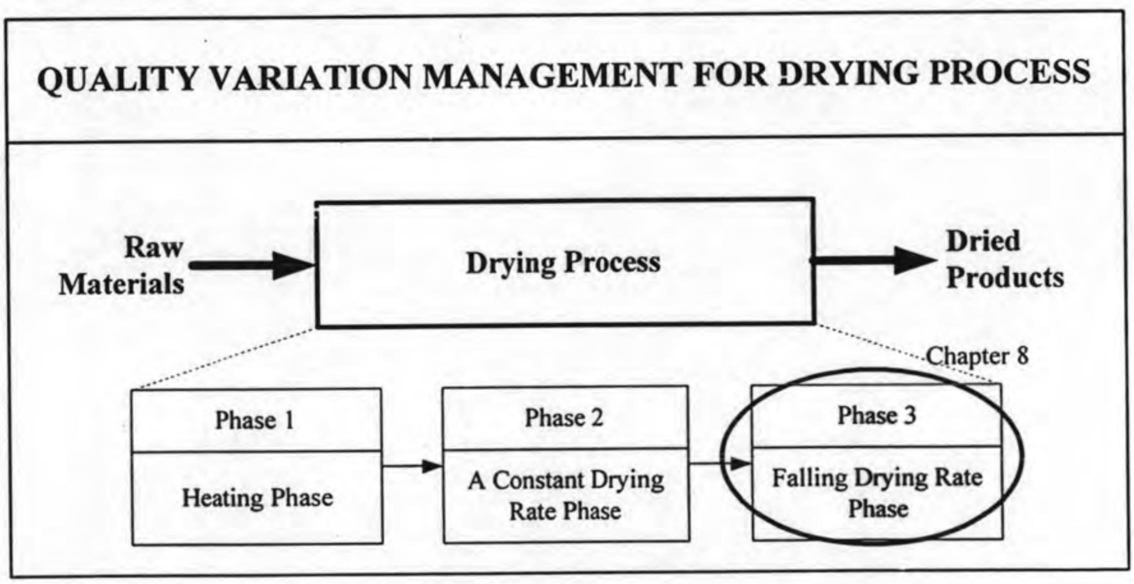

Figure 8.1 Scope of quality variation management in drying process within falling drying rate phase

The outline of this chapter is organized into five sections. In Section 8.1 to 8.4, experimental results of paddy rice, cassava chip, tobacco, and longan are explained and discussed respectively. Experimental results for each dried product type can be divided into two sections. The first section is the experimental results of the drying process within falling drying rate phase. The second section is the experimental results of the drying process within the adjustment period time. This adjustment period time is added and proposed into the drying process by this dissertation. Finally, after all results are presented, they are concluded and summarized into Section 8.5.

8.1 Experimental Results of Paddy Rice

In this phase, paddy rice is dried within 12 hours by varying levels of drying temperature. The target of the moisture content after drying is desired to 14.0% w.b. Experimental results are shown as below.

8.1.1 Falling Drying Rate Phase

Paddy rice with the initial moisture content at 19.0% w.b. from the second phase is dried with varying levels of the drying temperature at 55, 60, and 65°C. The experimental results are explained as below.

(1) Drying Temperature Level at 55°C

From Figure 8.2, the moisture content from 19.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 14.3% w.b. It is very near to its target. However, *MSD* is equaled to 0.117 (% w.b.)^2.

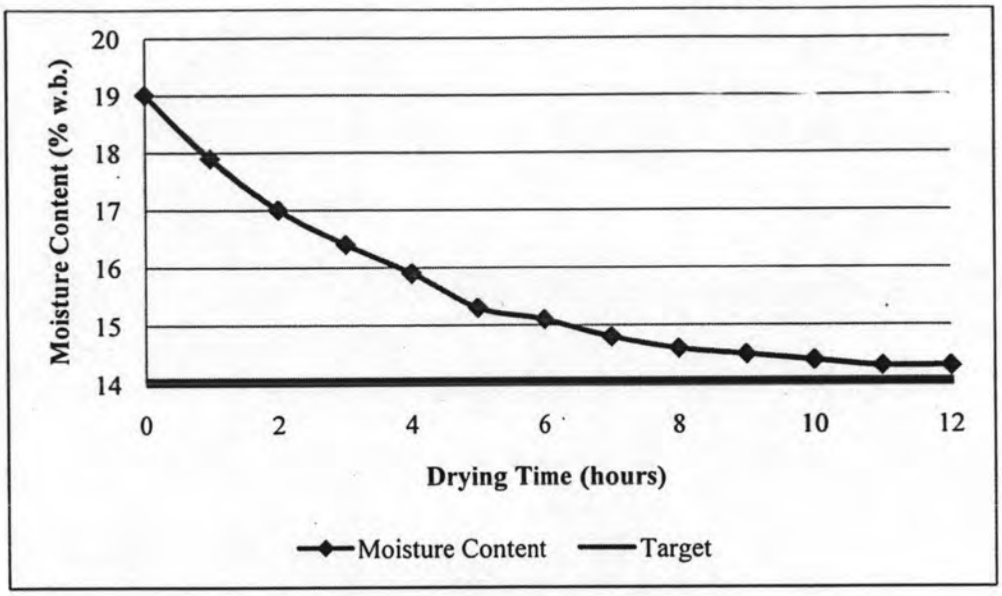

Figure 8.2 Drying results of paddy rice at 55°C

(2) Drying Temperature Level at 60°C

From Figure 8.3, the moisture content from 19.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 14.2% w.b. It is very near to its target. However, *MSD* is equaled to 0.135 (% w.b.)^2.

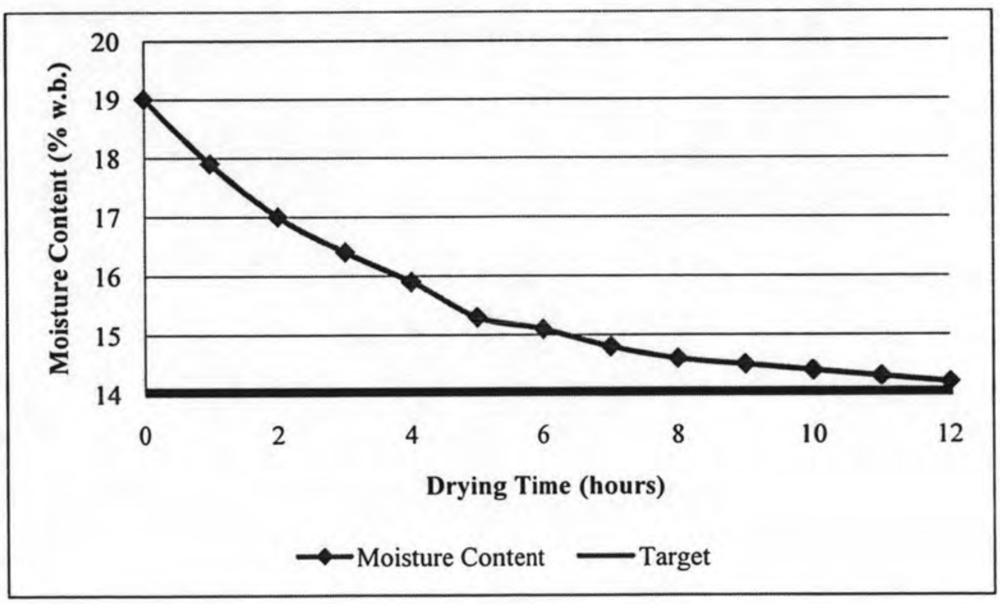

Figure 8.3 Drying result of paddy rice at 60°C

(3) Drying Temperature Level at 65°C

From Figure 8.4, the moisture content from 19.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 13.5% w.b. It is less than its target. However, *MSD* is equaled to 0.495 (% w.b.)^2.

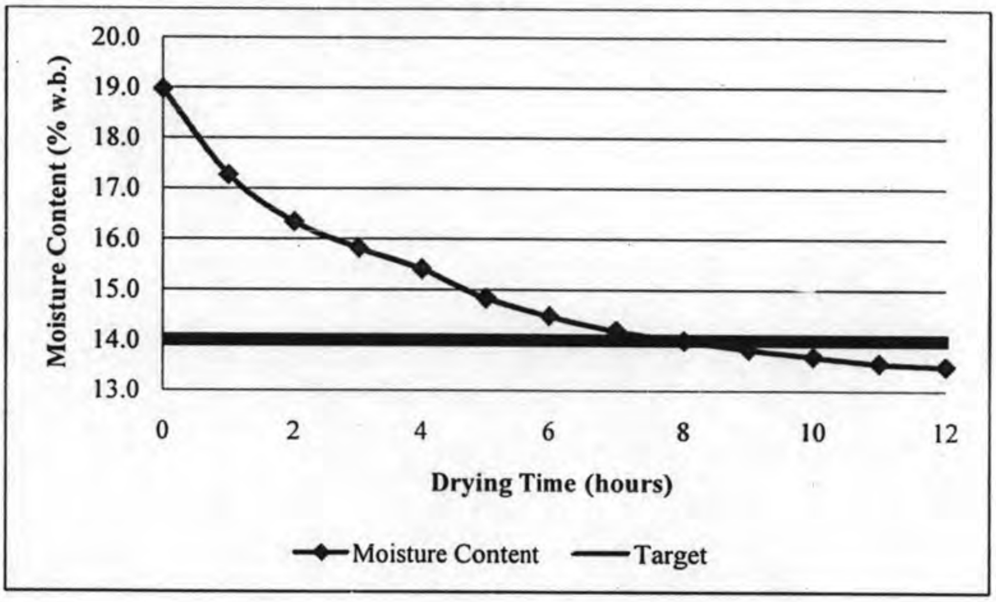

Figure 8.4 Drying result of paddy rice at 65°C

(4) Selecting Optimal Drying Temperature Level

Minimum *MSD* is a criterion to select the optimal drying temperature level. From all experimental results, their *MSD*s are plotted in Figure 8.5. It shows that minimum *MSD* is from drying temperature level at 60°C. Therefore, the optimal temperature level for drying paddy rice is at 60°C.

(5) Constructing Mathematical Model

After selecting the optimal drying temperature level, the mathematical model for drying paddy rice is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.1).

$$M(t)_3 = 14.2 + 4.9e^{(-t/3.8)}, \qquad 0 \le t \le 12 \qquad (8.1)$$

where

$M(t)_3$ = the moisture content during falling drying rate phase at time t

t = drying time in hours

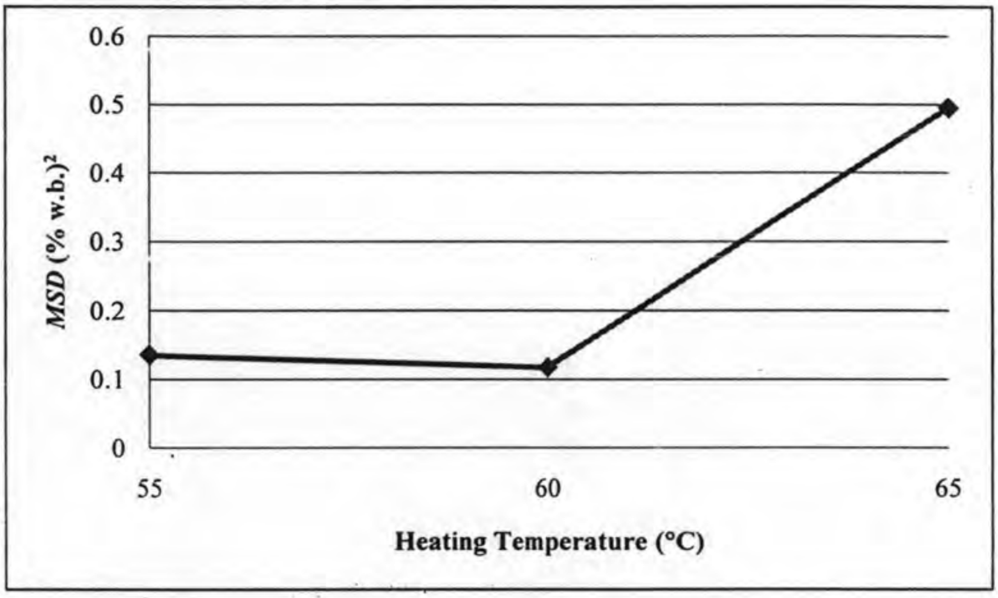

Figure 8.5 *MSD* from drying paddy rice within falling drying rate

8.1.2 Adjustment Drying Temperature Period

Although the optimal temperature level for drying within falling rate phase of paddy rice is found, the moisture content after drying cannot be achieved the target at 14.0% w.b. With the mathematical model from the Equation (8.1), the moisture content after drying within 12 hours is equaled to 14.4% w.b. Therefore, adjusting the level of the drying temperature is required in order to reduce the moisture content to the target.

From Figure 8.6, drying rate at 60°C is illustrated. During drying time between 7^{th} and 12^{th} hours, the drying rate is equaled to zero. It means that the moisture content cannot be reduced by the optimal drying temperature level at 60°C. Therefore, during this period, the adjustment period should be replaced in order to reduce the moisture content to the target. Each drying temperature level in this period is conducted with five replications.

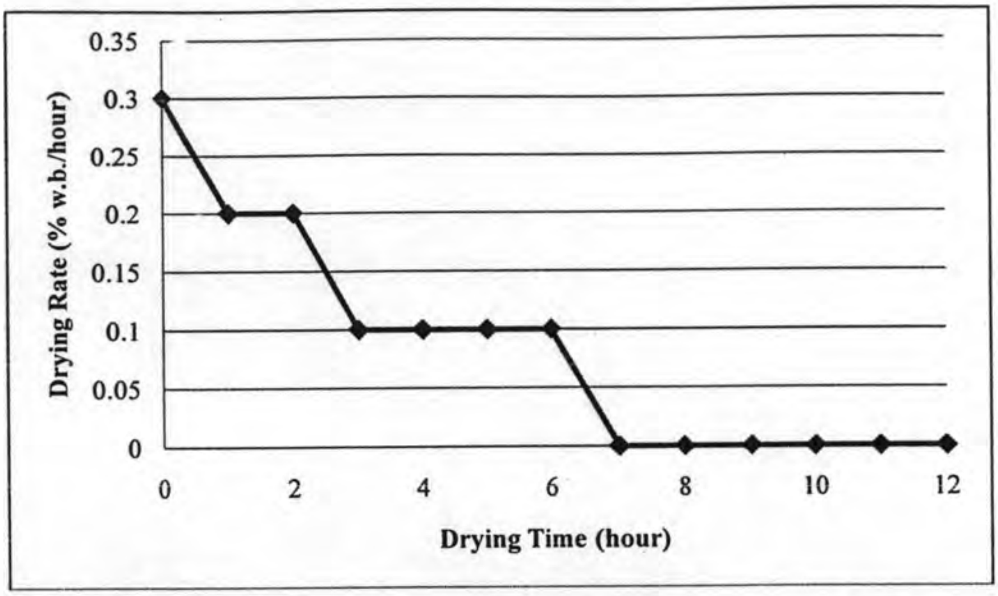

Figure 8.6 Drying rate within falling rate phase of paddy rice

In the adjustment period, the initial moisture content is 15.0% w.b. from the Equation (8.1). The drying temperature level in this period is varied at 61, 65, and 70°C. From Figure 8.7, the drying temperature level at 65°C can be used to reduce the moisture content from 15.0% w.b. to 14.0% w.b. as its target. Meanwhile, the raw materials which are dried with temperature levels at 61 and 70°C cannot be achieved the target. Moreover, *MSD* from the drying temperature level at 65°C is the minimum value (Figure 8.8). Therefore, the temperature at 65°C is the optimal temperature level for drying within the adjustment period.

After selecting the optimal drying temperature level, the mathematical model for drying paddy rice within the adjustment period is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.2).

$$M(t)_4 = 15.0 - 0.189t, \qquad 0 \le t \le 5$$

(8.2)

where

$M(t)_4$ = the moisture content in the drying within adjustment drying temperature period at time t

t = drying time in hours

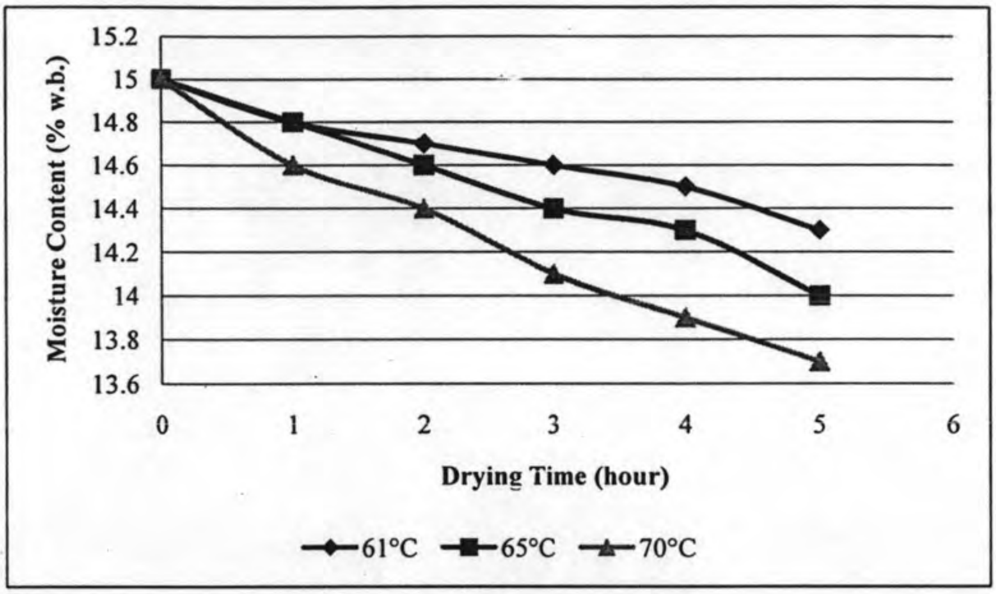

Figure 8.7 Drying result of paddy rice with varying levels of drying temperature within adjustment drying temperature period

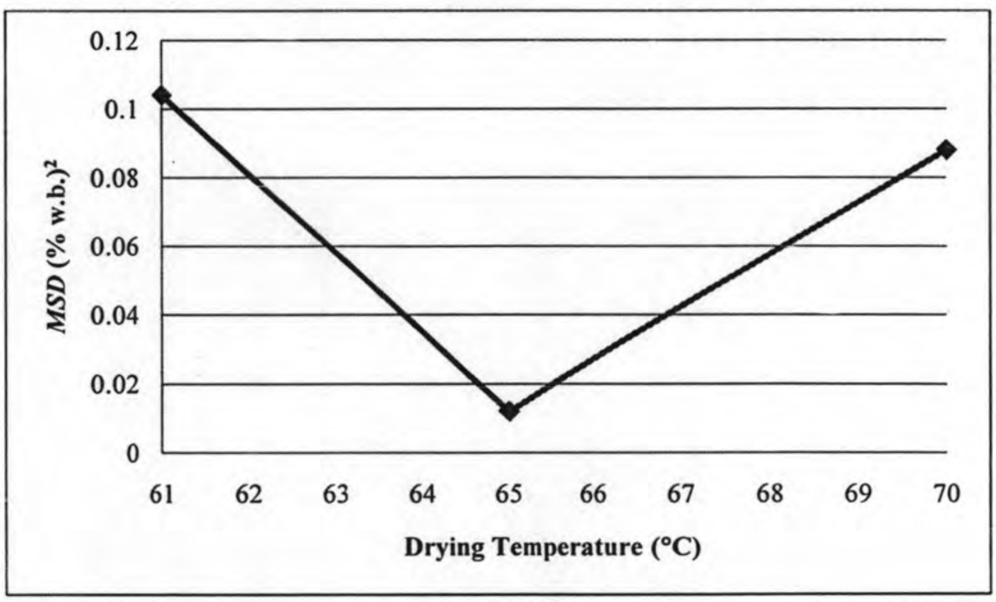

Figure 8.8 *MSD* from drying paddy rice within adjustment drying temperature period

8.2 Experimental Results of Cassava Chip

In this phase, cassava chips are dried within 15 minutes by varying levels of drying temperature. The target of the moisture content after drying is desired to 14.0% w.b. Experimental results are shown as below.

8.2.1 Falling Drying Rate Phase

Cassava chip with the initial moisture content at 30.0% w.b. from the second phase is dried with varying levels of the drying temperature at 95, 100, and 105°C. The experimental results are explained as below.

(1) Drying Temperature Level at 95°C

From Figure 8.9, the moisture content from 30.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 14.4% w.b. It is greater than its target at 14.0% w.b. Moreover, *MSD* is equaled to 0.154 $(\% \text{ w.b.})^2$.

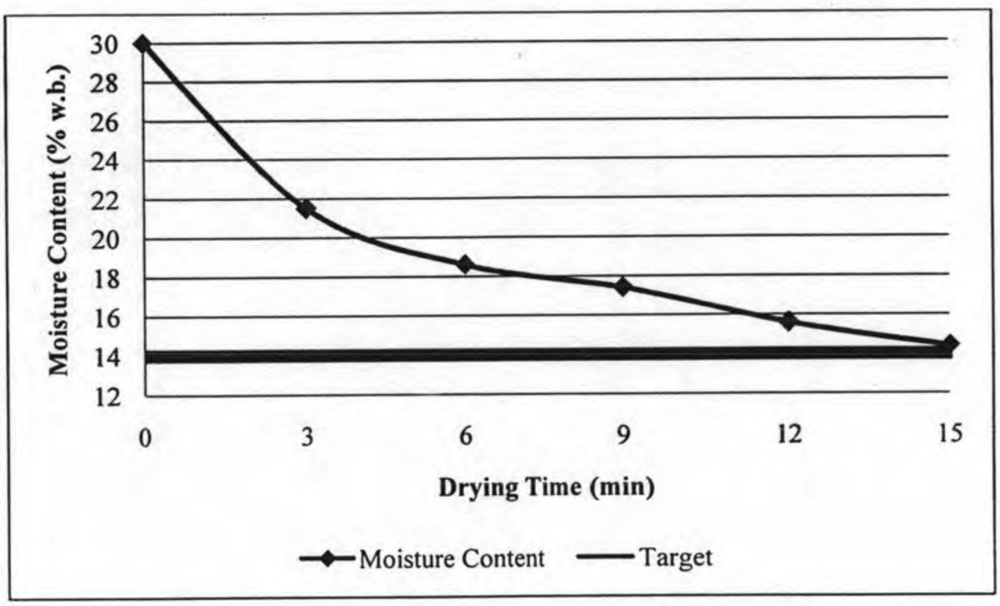

Figure 8.9 Drying results of cassava chip at 95°C

(2) Drying Temperature Level at 100°C

From Figure 8.10, the moisture content from 30.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 14.3% w.b. It is still greater than its target at 14.0% w.b. Moreover, *MSD* is equaled to 0.074 (% w.b.)^2.

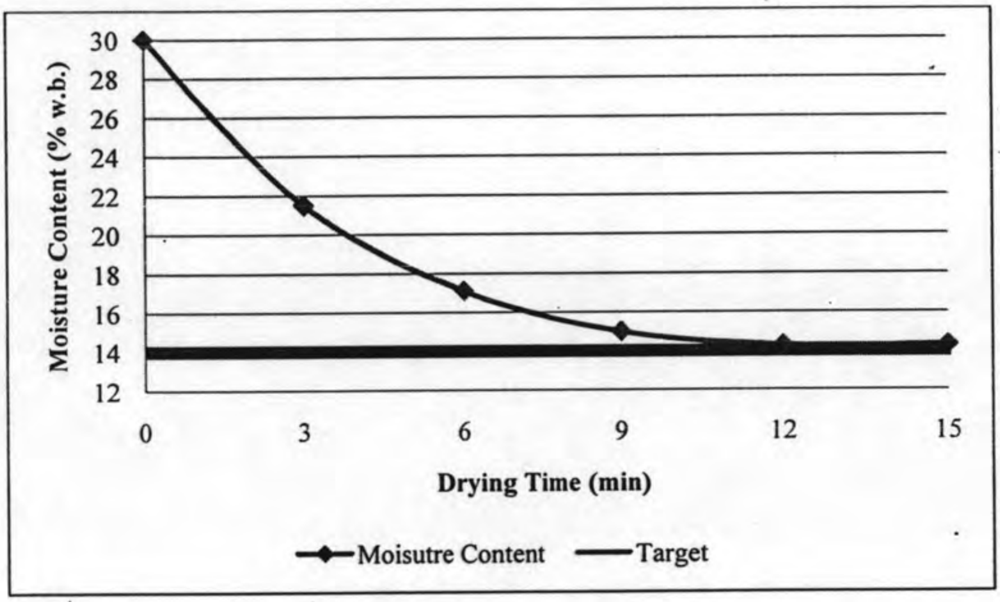

Figure 8.10 Drying result of cassava chip at 100°C

(3) Drying Temperature Level at 105°C

From Figure 8.11, the moisture content from 30.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 13.3% w.b. It is less than its target. Moreover, *MSD* is equaled to 0.780 (% w.b.)^2.

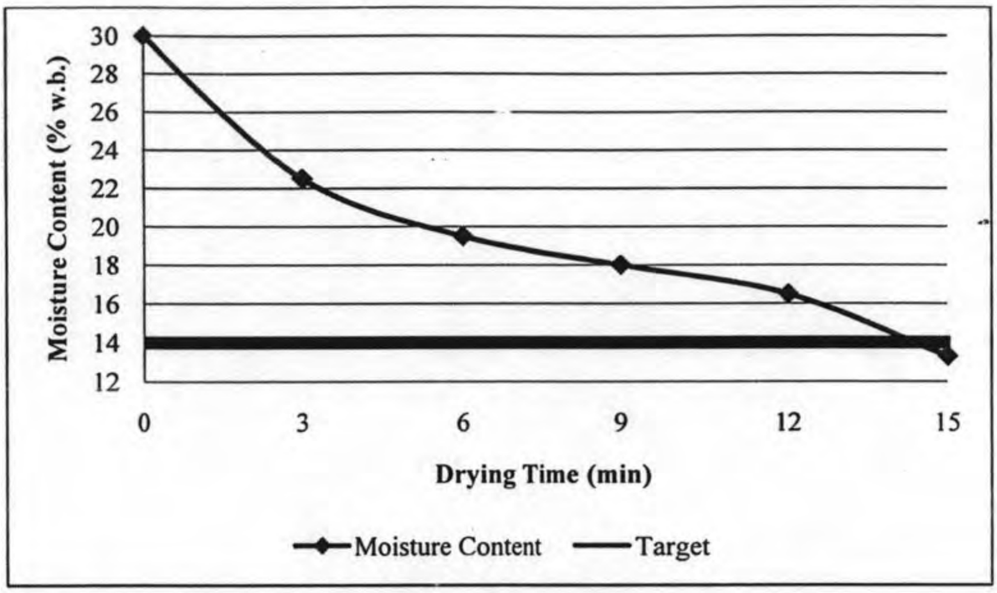

Figure 8.11 Drying result of cassava chip at 105°C

(4) Selecting Optimal Drying Temperature Level

Minimum *MSD* is a criterion to select the optimal drying temperature level. From all experimental results, their *MSD*s are plotted in Figure 8.12. It shows that minimum *MSD* is from drying temperature level at 100°C. Therefore, the optimal temperature level for drying cassava chip is at 100°C.

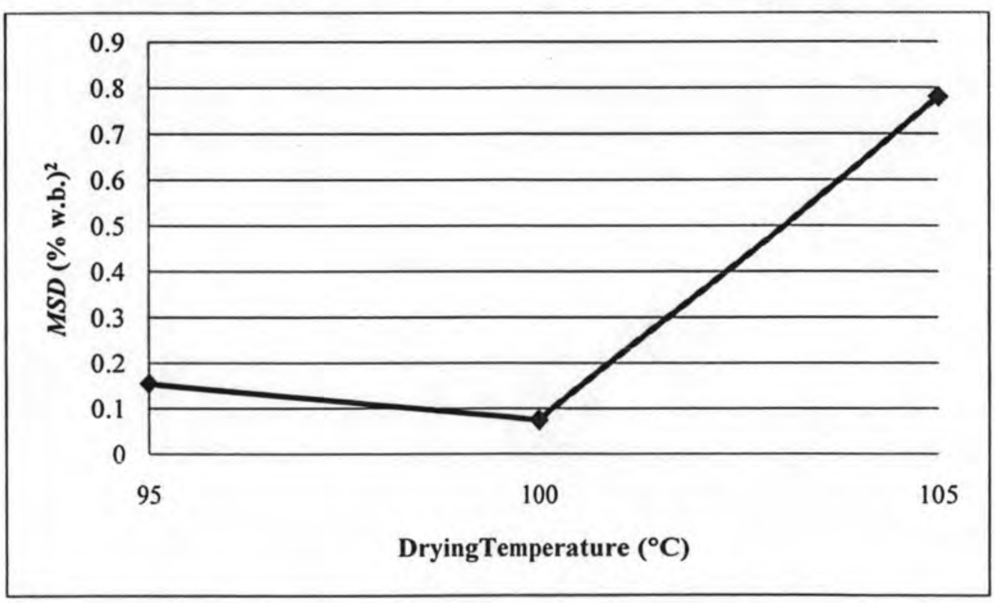

Figure 8.12 *MSD* from drying cassava chip within falling drying rate

(5) Constructing Mathematical Model

After selecting the optimal drying temperature level, the mathematical model for drying cassava chip is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.3).

$$M(t)_3 = 14.2 + 15.8e^{(-t/3.93)}, \quad 0 \le t \le 15 \tag{8.3}$$

where

$M(t)_3$ = the moisture content during falling drying rate phase at time t

t = drying time in minutes

8.2.2 Adjustment Drying Temperature Period

Although the optimal temperature level for drying within falling rate phase of cassava chip is found, the moisture content after drying cannot be achieved the target at 14.0% w.b. With the mathematical model from the Equation (8.3), the moisture content after drying within 15 minutes is equaled to 14.5% w.b. Therefore, adjusting the level of the drying temperature is required in order to reduce the moisture content to the target.

From Figure 8.13, drying rate at 100°C is illustrated. During drying time between 12th and 15th minutes, the drying rate is equaled to zero. It means that the moisture content cannot be reduced by the optimal drying temperature level at 100°C. Therefore, during this period, the adjustment period should be replaced in order to reduce the moisture content to the target. Each drying temperature level in this period is conducted with five replications.

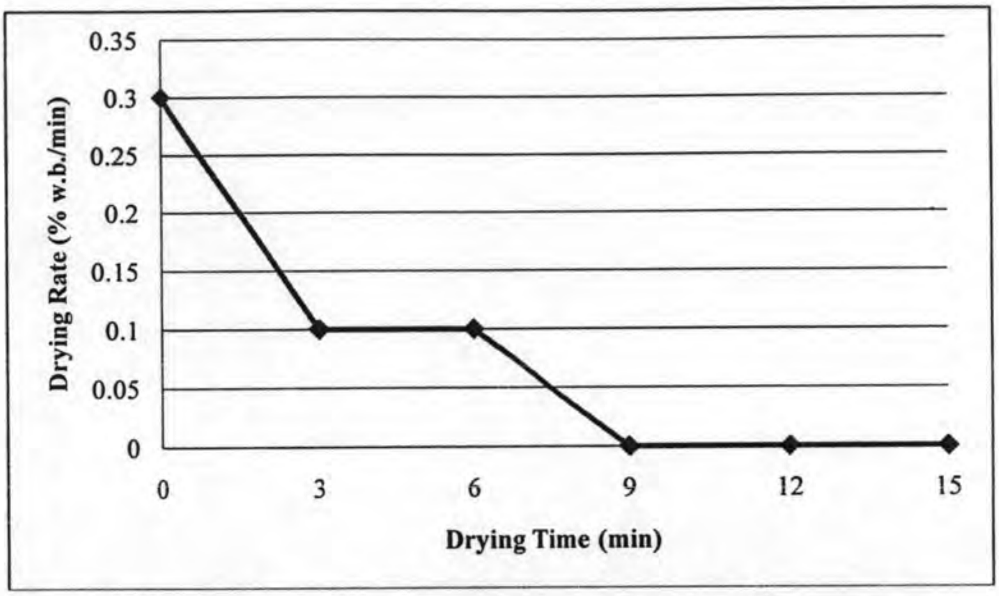

Figure 8.13 Drying rate within falling rate phase of cassava chip

In the adjustment period, the initial moisture content is 14.3% w.b. from the Equation (8.3). The drying temperature level in this period is varied at 105, 110, and 115°C. From Figure 8.14, the drying temperature level at 110°C can be used to reduce the moisture content from 14.3% w.b. to 14.0% w.b. as its target. Meanwhile, the raw materials which are dried with temperature levels at 105 and 115°C cannot be achieved the target. Moreover, *MSD* from the drying temperature level at 110°C is the minimum value (Figure 8.15). Therefore, the temperature at 110°C is the optimal temperature level for drying within the adjustment period.

After selecting the optimal drying temperature level, the mathematical model for drying cassava chip within the adjustment period is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.4).

$$M(t)_4 = 14.3 - 0.12t, \qquad 0 \le t \le 3 \qquad (8.4)$$

where

$M(t)_4$ = the moisture content in the drying within adjustment drying temperature period at time t

t = drying time in minutes

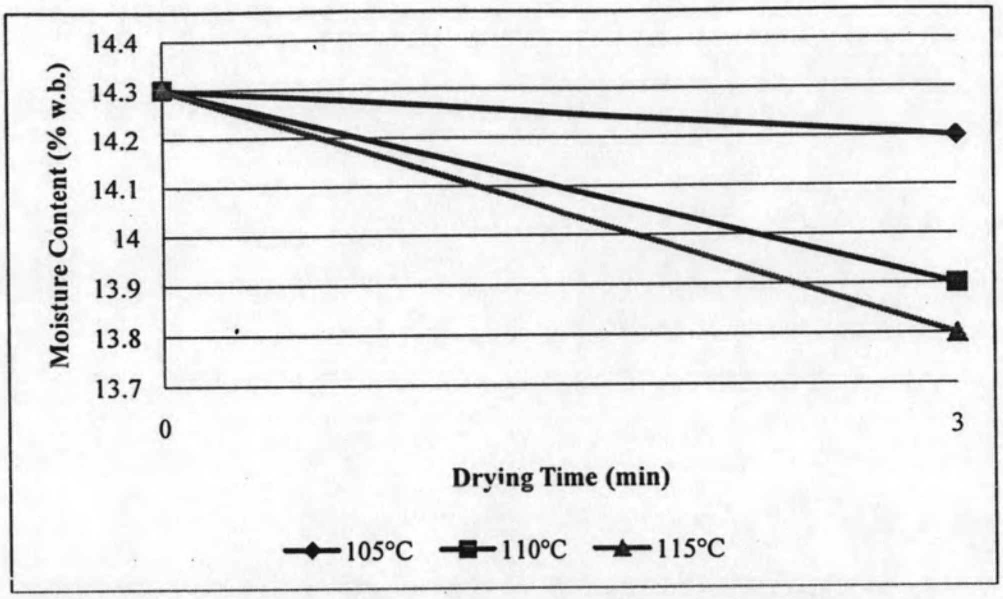

Figure 8.14 Drying result of cassava chip with varying levels of drying temperature within adjustment drying temperature period

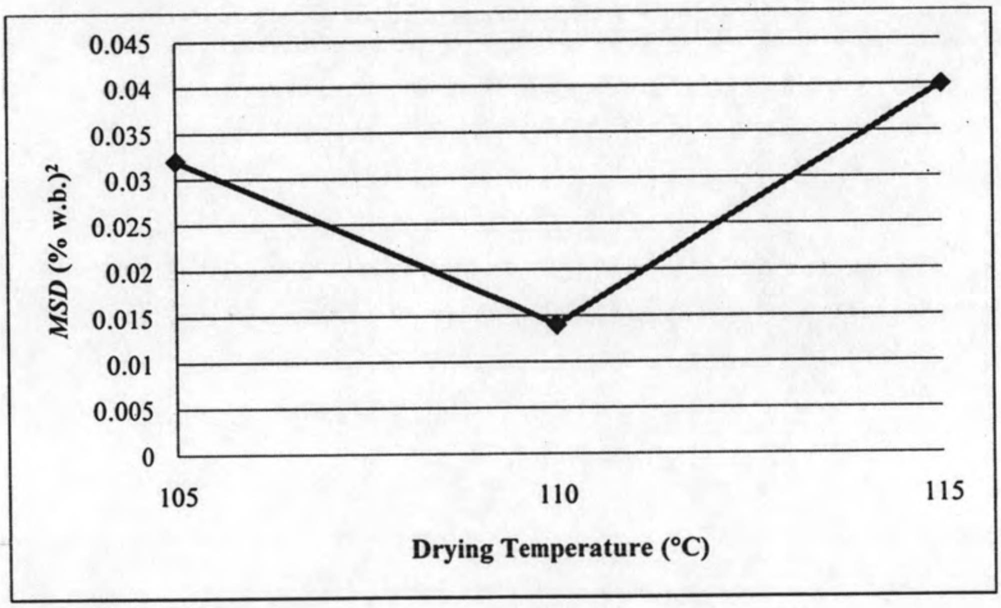

Figure 8.15 *MSD* from drying cassava chip within adjustment drying temperature period

8.3 Experimental Results of Tobacco

In this phase, tobacco is dried within five minutes by varying levels of drying temperature. The target of the moisture content after drying is desired to 12.5% w.b. Experimental results are shown as below.

8.3.1 Falling Drying Rate Phase

Tobacco with the initial moisture content at 14.0% w.b. from the second phase is dried with varying levels of the drying temperature at 45, 50, and 55°C. The experimental results are explained as below.

(1) Drying Temperature Level at 45°C

From Figure 8.16, the moisture content from 30.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 12.9% w.b. It is greater than its target at 12.5% w.b. Moreover, *MSD* is equaled to 0.145 $(\% \text{ w.b.})^2$.

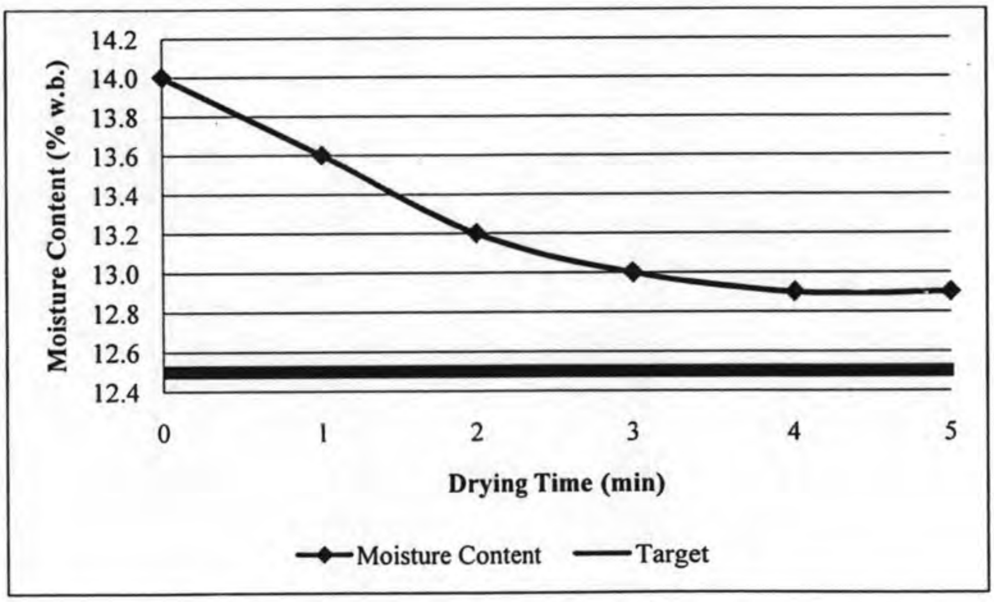

Figure 8.16 Drying results of tobacco at 45°C

(2) Drying Temperature Level at 50°C

From Figure 8.17, the moisture content from 14.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 12.5% w.b. equaled to the target at 12.5% w.b. Moreover, *MSD* is equaled to 0.007 (% w.b.)^2.

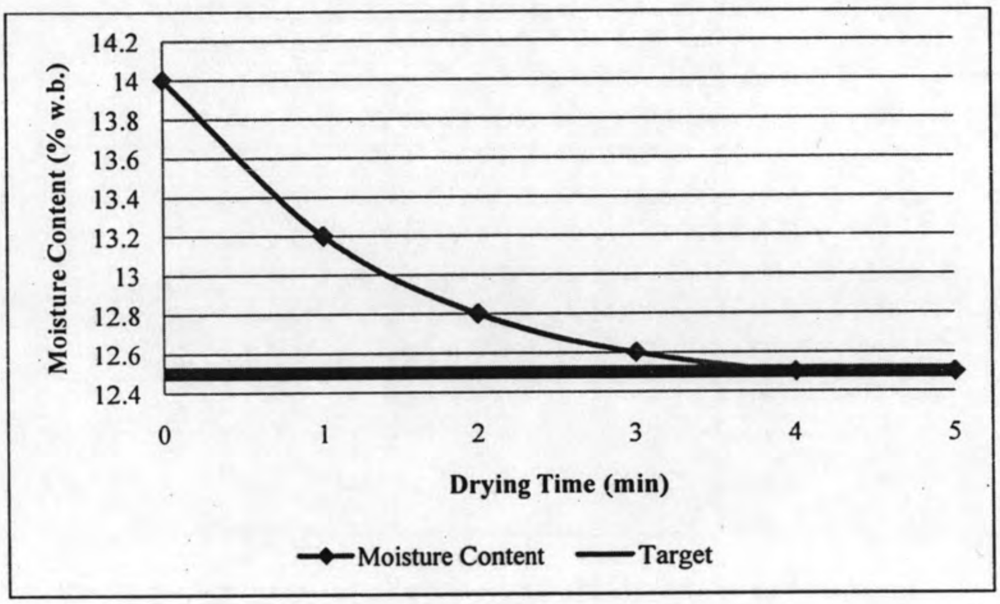

Figure 8.17 Drying result of tobacco at 50°C

(3) Drying Temperature Level at 55°C

From Figure 8.18, the moisture content from 14.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 12.0% w.b. It is less than its target. Moreover, *MSD* is equaled to 0.244 (% w.b.)^2.

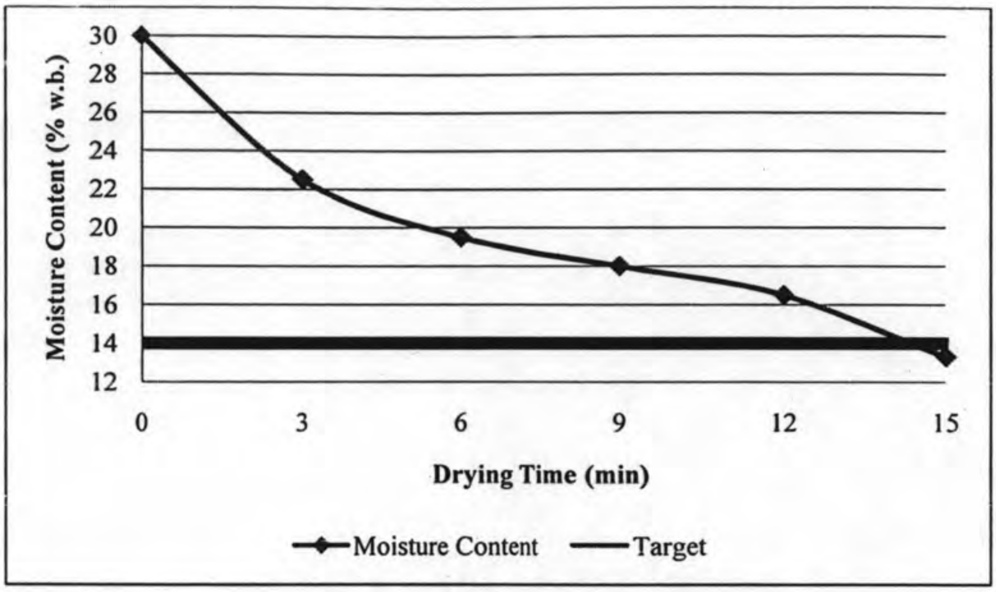

Figure 8.18 Drying result of tobacco at 55°C

(4) Selecting Optimal Drying Temperature Level

Minimum *MSD* is a criterion to select the optimal drying temperature level. From all experimental results, their *MSD*s are plotted in Figure 8.19. It shows that minimum *MSD* is from drying temperature level at 50°C. Therefore, the optimal temperature level for drying tobacco is at 50°C.

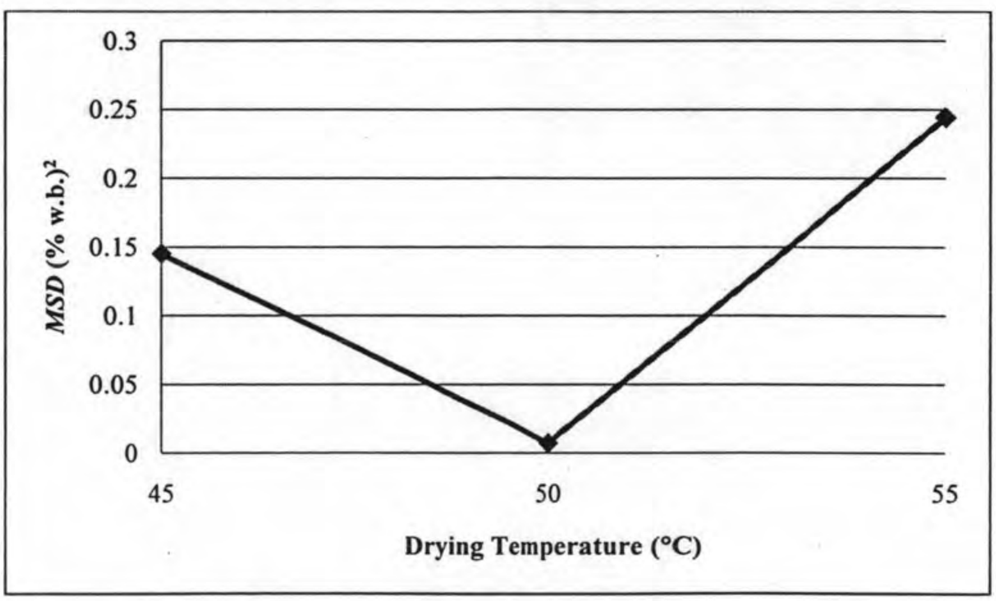

Figure 8.19 *MSD* from drying tobacco within falling drying rate

(5) Constructing Mathematical Model

After selecting the optimal drying temperature level, the mathematical model for drying tobacco is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.5).

$$M(t)_3 = 12.5 + 1.5e^{(-t/1.35)}, \qquad 0 \le t \le 5 \qquad (8.5)$$

where

$M(t)_3$ = the moisture content during falling drying rate phase at time t

t = drying time in minutes

8.3.2 Adjustment Drying Temperature Period

In the drying process within falling drying rate phase of tobacco, the optimal drying temperature can be used to reduce the moisture content of tobacco to the target at 12.5% w.b. Therefore, the adjustment drying temperature period is not required for the tobacco drying process. The reason why the adjustment period is not required for the tobacco drying process may be that this drying process is operated within the closed system, while other drying processes are operated within the open system. In addition to the closed system, the tobacco is dried with the continuous dryer, while other products are dried with the batch dryers.

8.4 Experimental Results of Longan

In this phase, longan is dried within 10 hours by varying levels of drying temperature. The target of the moisture content after drying is desired to 18.0% w.b. Experimental results are shown as below.

8.4.1 Falling Drying Rate Phase

Longan with the initial moisture content at 73.0% w.b. from the second phase is dried with varying levels of the drying temperature at 80, 85, and 90°C. The experimental results are explained as below.

(1) Drying Temperature Level at 80°C

From Figure 8.20, the moisture content from 73.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 20.0% w.b. It is greater than its target at 18.0% w.b. Moreover, *MSD* is equaled to 3.922 (% w.b.)^2.

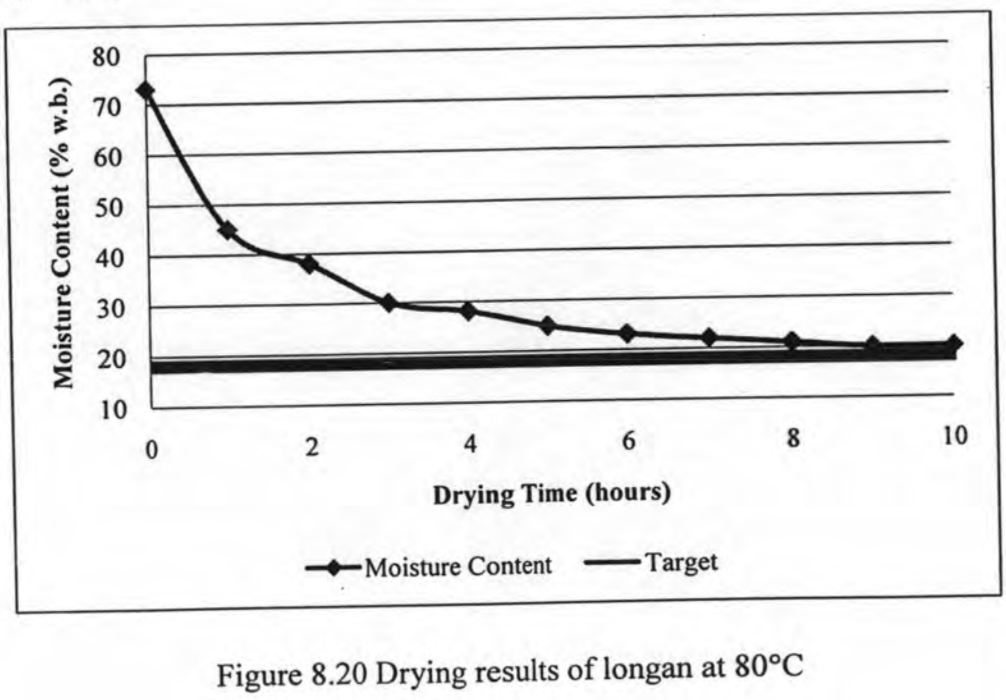

Figure 8.20 Drying results of longan at 80°C

(2) Drying Temperature Level at 85°C

From Figure 8.21, the moisture content from 73.0% w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 19.0% w.b. It is still greater than its target at 18.0% w.b. Moreover, *MSD* is equaled to 1.004 (% w.b.)^2.

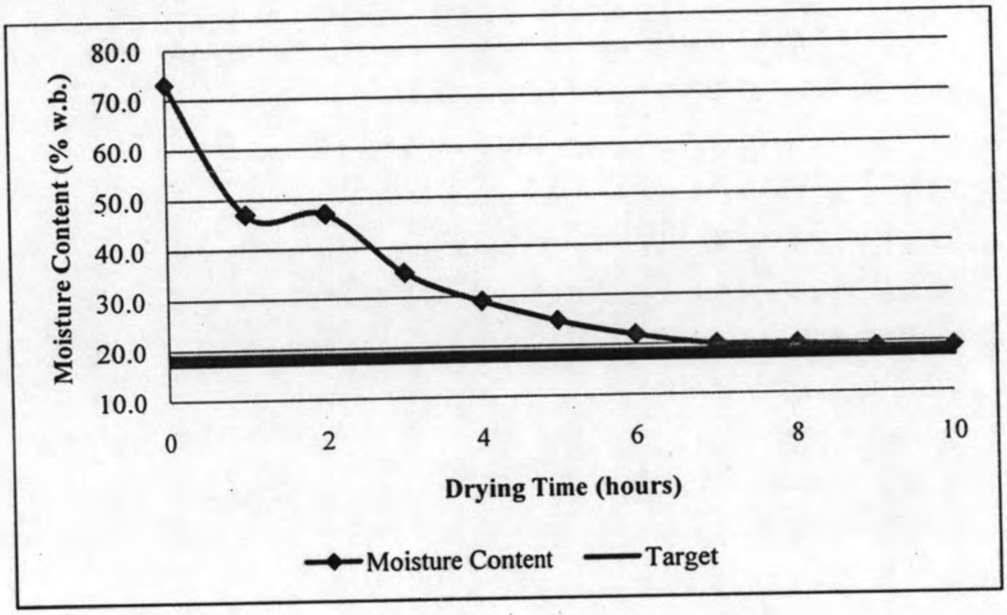

Figure 8.21 Drying result of longan at 85°C

(3) Drying Temperature Level at 90°C

From Figure 8.22, the moisture content from 73.0%w.b. is reduced continuously with falling drying rate. After drying, the moisture content is 16.8% w.b. It is less than its target. Moreover, *MSD* is equaled to 1.368 (% w.b.)^2.

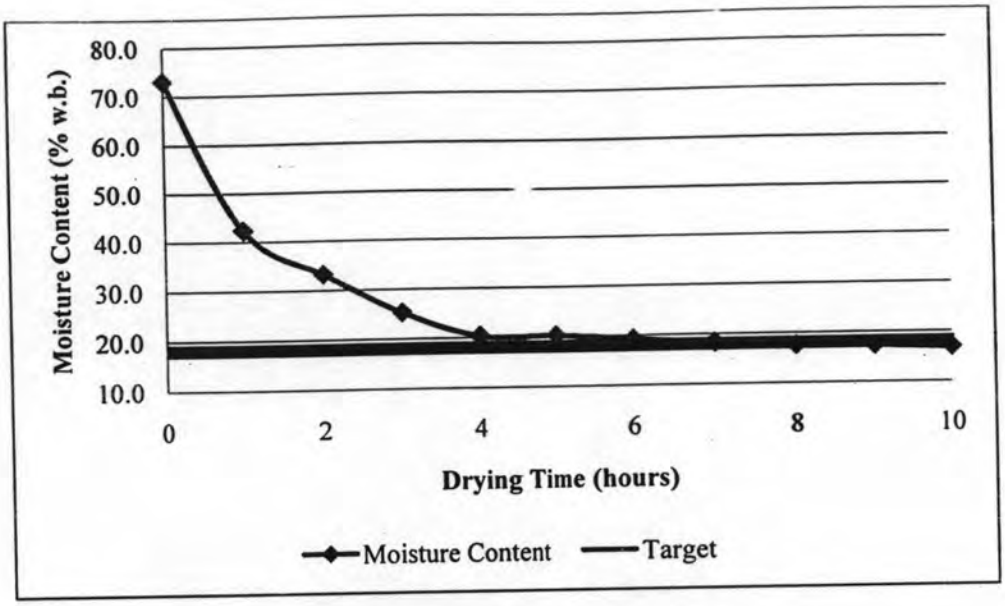

Figure 8.22 Drying result of longan at 90°C

(4) Selecting Optimal Drying Temperature Level

Minimum *MSD* is a criterion to select the optimal drying temperature level. From all experimental results, their *MSD*s are plotted in Figure 8.23. It shows that minimum *MSD* is from drying temperature level at 85°C. Therefore, the optimal temperature level for drying longan is at 85°C.

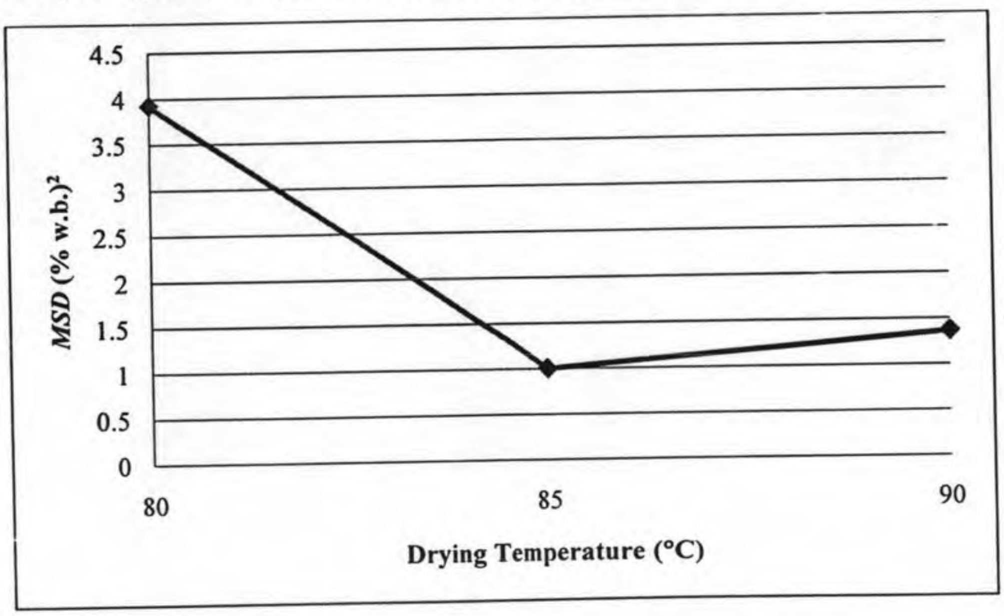

Figure 8.23 *MSD* from drying longan within falling drying rate

(5) Constructing Mathematical Model

After selecting the optimal drying temperature level, the mathematical model for drying cassava chip is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.6).

$$M(t)_3 = 19 + 54e^{(-0.45t)}, \qquad 0 \le t \le 10 \qquad (8.6)$$

where

$M(t)_3$ = the moisture content during falling drying rate phase at time t

t = drying time in hours

8.4.2 Adjustment Drying Temperature Period

Although the optimal temperature level for drying within falling rate phase of longan is found, the moisture content after drying cannot be achieved the target at 18.0% w.b. With the mathematical model from the Equation (8.6), the moisture content after drying within 10 hours is equaled to 19.6% w.b. Therefore, adjusting the level of the drying temperature is required in order to reduce the moisture content to the target.

From Figure 8.24, drying rate at 85°C is illustrated. During drying time between 7th and 10th hours, the drying rate is equaled to zero. It means that the moisture content cannot be reduced by the optimal drying temperature level at 85°C. Therefore, during this period, the adjustment period should be replaced in order to reduce the moisture content to the target. Each drying temperature level in this period is conducted with five replications.

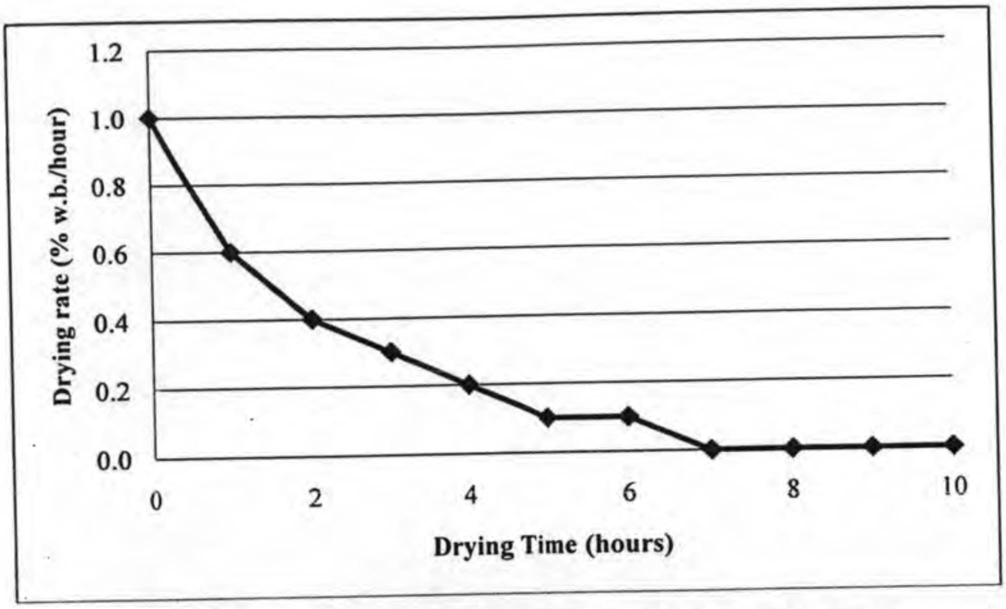

Figure 8.24 Drying rate within falling rate phase of longan

In the adjustment period, the initial moisture content is 22.6% w.b. from the Equation (8.6). The drying temperature level in this period is varied at 87, 88, and 89°C. From Figure 8.25, the drying temperature level at 88°C can be used to reduce the moisture content from 22.6% w.b. to 18.0% w.b. as its target. Meanwhile, the raw materials which are dried with temperature levels at 87 and 89°C cannot be achieved the target. Moreover, *MSD* from the drying temperature level at 88°C is the minimum value (Figure 8.26). Therefore, the temperature at 88°C is the optimal temperature level for drying within the adjustment period.

After selecting the optimal drying temperature level, the mathematical model for drying longan within the adjustment period is constructed by Matlab program with function *polyfit*. As a result, the mathematical model is shown as Equation (8.7).

$$M(t)_4 = 22.1 - 1.08t, \qquad 0 \le t \le 4 \qquad (8.7)$$

where

$M(t)_4$ = the moisture content in the drying within adjustment drying temperature period at time t

t = drying time in hours

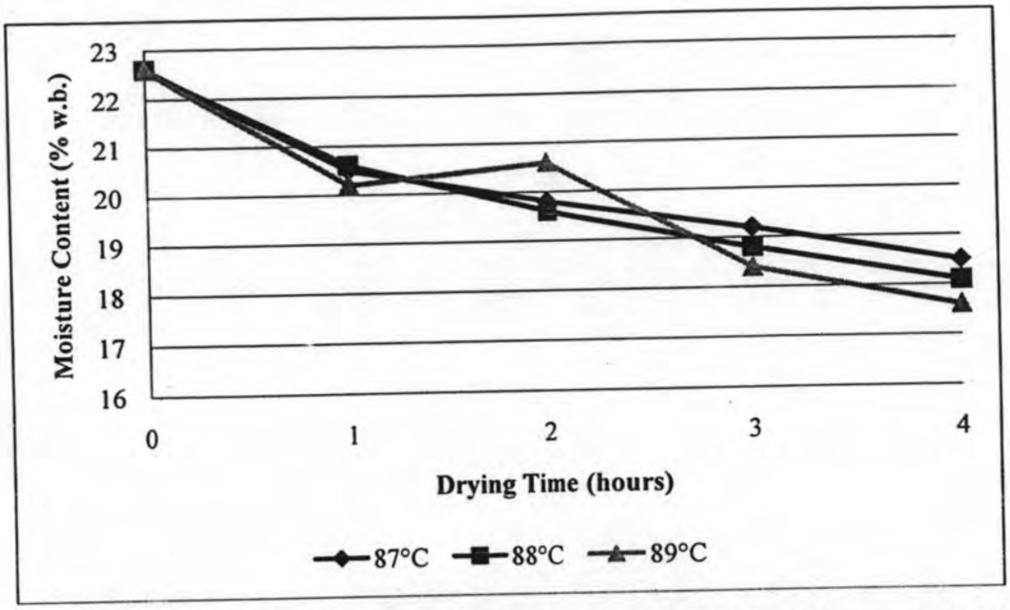

Figure 8.25 Drying result of longan with varying levels of drying temperature within adjustment drying temperature period

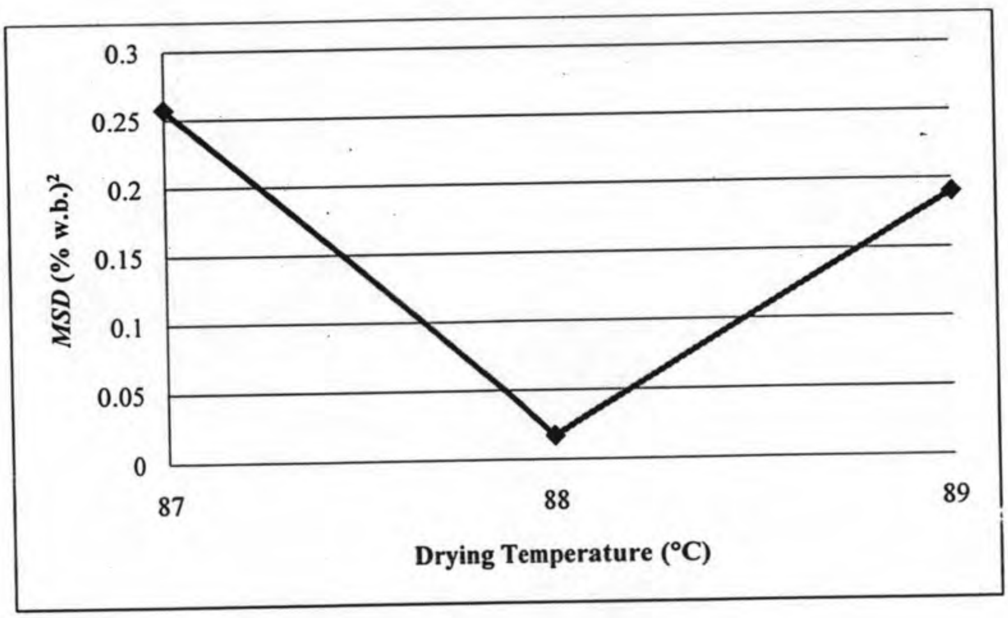

Figure 8.26 *MSD* from drying longan within adjustment drying temperature period

8.5 Conclusion

The aims of this chapter are to find the optimal temperature level for drying the raw materials from the second phase and to construct the mathematical models in order to represent the behavior of the moisture content during drying period time with falling drying rate. Experiments are conducted by varying levels of drying temperature. The drying temperature level which can minimize *MSD* is selected to be the optimal temperature level for drying the raw materials within the third phase. After selecting the optimal drying temperature level, the mathematical models are constructed by Matlab with function *polyfit*. All mathematical models are in uniform distribution. However, all experimental results of this chapter can be summarized in Table 8.1.

Table 8.1 Summary results of drying process within falling drying rate phase

Product	**Drying Time**	**Optimal Temperature Level (°C)**	**Mathematical model**
Paddy rice	6 hours	60	$M(t)_3 = 14.2 + 4.9e^{(-t/3.8)}$
Cassava chip	12 minutes	100	$M(t)_3 = 14.2 + 15.8e^{(-t/3.93)}$
Tobacco	5 minutes	50	$M(t)_3 = 12.5 + 1.5e^{(-t/1.35)}$
Longan	6 hours	85	$M(t)_3 = 19 + 54e^{(-0.45t)}$

Although the optimal drying temperature levels can be found in the third phase, they cannot be used to dry the products their targets. These products are paddy rice, cassava chip, and longan. In order to achieve their targets of the moisture content, the adjustment drying temperature period is added and proposed by this dissertation. It can be summarized in Table 8.2.

Table 8.2 Summary results of drying process within adjustment drying temperature period

Product	Drying Time	Optimal Temperature Level (°C)	Mathematical model
Paddy rice	6 hours	65	$M(t)_4 = 15.0 - 0.189t$
Cassava chip	3 minutes	120	$M(t)_4 = 14.3 - 0.12t$
Longan	4 hours	88	$M(t)_4 = 22.1 - 1.08t$