Maintaining Quality, Maximizing Throughput and Minimizing Energy Consumption in Fluidized Bed Paddy Drying

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ABSTRACT

The objective of this study was to conduct feasibility study of paddy drying by fluidization technique. Operating parameters affecting product quality, drying capacity and energy consumption were investigated. Experimental results showed that drying rate in a paddy kernel was controlled by diffusion. However, drying capacity increased with specific air flow rates and drying air temperatures. Energy consumption decreased when specific air flow rate decreased or fraction of air recycled increased. Maximum drying air temperature and final moisture content of paddy had to be limited at 115°C and 24-25% dry basis, respectively if product qualities in terms of head yield and colour were maintained. Simulated results obtained from a developed mathematical model indicated that the optimum operating parameters should be as follows : fraction of air recycled of 90%, air velocity of 4.4 m/s, bed thickness of 9.5 cm and specific air flow rate of 0.1 kg/s-kg dry matter. Economic analysis showed that total drying cost was about 0.08 US$/kg water evaporated.[1]

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INTRODUCTION

Paddy combined harvestors have been becoming popular in Thailand. Consequently, problem of high moisture grain is more serious as compared to the past. Rice mills who are responsible for the problem are looking for appropriate methods of drying. Recently, research work on fluidized bed paddy drying was published. The advantages of fluidized bed drying may be summarized as follows: (1) uniform product moisture content due to complete mixing and (2) high drying capacity due to high ratio of air mass to mass of product.

Research work on fluidized bed grain drying is still relatively limited. Satayaprasert and Vanishserwatana (1992) investigated on fluidized bed corn drying at temperature of 60-90°C, air velocity of 2.7-4.2 m/s and bed thickness of 3-12 cm. Experimental results showed that drying rate was controlled by moisture diffusion in grain kernel and could be explained by a logarithmic model. Giner and De Michelis (1988) investigated the effect of drying air temperature and fraction of air recycled on thermal efficiency of fluidized bed corn drying. Simulated results indicated that the efficiency increased with increasing temperature while drying time decreased. However, drying temperature had to be limited in order to maintain product quality, The efficiency also increased with increasing fraction of air recycled. It was found that about 0.70-0.86 of air recycled could be used for the bed thickness of 0.1-0.3 m.

Thorpe (1987) developed a mathematical model for continuous-flow fluidized bed grain disinfestor. Simulated results showed that it consumed electricity of 1.33 kW-h/ton and heat of 77 MJ/ton of grain, for the production capacity of 150 ton/h. The disinfestor could be modified to be a dryer by allowing longer resident time.

Sutherland and Ghaly (1990) investigated fluidized bed paddy drying. Experimental results showed that head yield was 58-61% when paddy was dried from 22% to 17% wet-basis but was 15-24% when the final moisture content was 16 % wet-basis. Drying air temperature was 40-90°C. For higher initial moisture content, 26% wet-basis, head yield was 55-58% when paddy was dried to 19% wet-basis. For the latter case, drying air temperature was 60-90°C. Tumambing and Driscoll (1991) found experimentally that drying rate was affected by drying air temperature and bed thickness. Drying conditions were as follows: drying air temperature of 40-100°C, bed thickness of 5-20 cm and air velocity of 1.5-2.5 m/s. Minimum fluidized bed velocities were 1.2 m/s for low moisture content and 2.0 m/s for moisture content of 23% wet-basis.

The objective of this study was to conduct feasibility study of paddy drying by fluidization technique. Operating parameters affecting product quality, drying capacity and energy consumption were investigated through experiment and mathematical simulation. Finally, drying cost was analyzed.

PROCEDURE

Development of Mathematical Model

It was assumed that thermal equilibrium between drying air and product existed. The model developed herein was somewhat similar in concept to that presented by Soponronnarit et al. (1992). Figure 1 shows control volumes (CV) for the derivation of energy and mass equations based on basic physical laws. Considering CV 1, it was assumed that paddy was completely mixed. Drying rate or change of moisture content during a time interval could be calculated by the equation developed by Prachayawarakorn (1992). It was written in the form of Page's (1949) equation as follows:

$$MR = [M(t) - M_{eq}]/[M_{in} - M_{eq}] = \exp(-xt^{y}) \tag{1}$$

where, $x = -0.73401 - 0.87872(m_{mix}/m_p) + 0.30876\ \ln(m_{mix}/m_p) + 0.0011160(T_{mix}) + 0.37784\ln(T_{mix}) - 0.76380(RH) + 0.042762\ln(RH)$

$y = 4.7106 + 0.82066(m_{mix}/m_p) - 0.31406\ln(m_{mix}/m_p) + 0.0093470(T_{mix}) - 1.2788\ln(T_{mix}) + 0.92350(RH) - 0.029890\ln(RH)$

Equilibrium moisture content of paddy could be calculated by using Henderson's equation.

$$1 - RH = \exp[-7.87 \times 10^{-6}(1.8T_{mix} + 491.7)(100\ M_{eq})^{2.088}] \tag{2}$$

To determine the change of moisture content of paddy during a small time interval, Equation (1) was differentiated with respect to time and substituted with finite differences.

From Figure 1, equations based on energy and mass conservation for each control volume could be written as follows:

$$T_{f1} = [Q_1/m_{mix}+C_aT_{mix}+W_{mix}(h_{fg}+C_vT_{mix})-W_{f1}h_{fg}-\Delta U_p-\Delta U_d]/(C_a+W_{f1}C_v) \tag{3}$$

$$T_{f2} = [Q_2/(RCm_{mix}) + C_aT_{f1} + W_{f1}(C_vT_{f1})]/(C_a + W_{f1}C_v) \tag{4}$$

$$W_{f1} = R(M_i - M_f) + W_{mix} \tag{5}$$

$$W_{mix} = (1-RC)W_i + RCW_{f1} \tag{6}$$

$$T_x = \{m_i C_a(T_i) + m_i W_i[h_{fg} + C_v(T_i)] + m_{rc} C_a T_{f2} + m_{rc} W_{f1}(h_{fg} + C_v T_{f2}) - m_{mix} W_{mix} h_{fg}\}/\{m_{mix}[C_a + W_{mix} C_v]\} \tag{7}$$

$$T_b = T_x + \Delta P/[(\rho_f e_f)(C_a + C_v W_{mix})] \tag{8}$$

$$Q_h = m_{mix}[C_a + (C_v W_{mix})](T_{mix} - T_b) - Q_3 \tag{9}$$

$$W_s = E/e_m \tag{10}$$

The equations were solved by iteration. Firstly, the value of exit humidity (W_{fi}) was assumed. The equations presented by Wilhelm (1976) were used to determine properties of moist air.

Method of Experiment

Figure 2 shows the fluidized bed dryer employed in this study. The reactor was made of stainless steel sheet. Its diameter and height were 20 cm and 140 cm, respectively. Exhaust air may be recirculated, mixed with fresh air and heated up to a desired temperature by four units of electrical heater (12 kW). A variable speed centrifugal fan (1.5 kW motor) was used to facilitate air movement.

Dry paddy was rewet and kept in a cold storage at the temperatures of 0-8°C for 5-7 days. During experiments, drying air temperature, air velocity, bed thickness, fraction of air recycled and drying time were varied. Moisture content of paddy was determined by air oven method at 103°C for 72 hours. The accuracy of a balance was 0.01 gram. Dry bulb and wet bulb temperatures were measured by thermocouple, type K, connected to a data logger with an accuracy of ± 1°C. Air velocity was measured by a hot wire anemometer which was calibrated with a pitot static tube.

Quality of paddy in terms of head yield and whiteness was investigated and compared to the reference samples (paddy dried by ambient air). The methods followed the guidelines of Rice Research Institute, Ministry of Agriculture and Agricultural Co-operative, Thailand.

RESULTS AND DISCUSSION

Drying Mechanism

From observation through a transparent reactor, it was found that minimum fluidized bed velocity was about 1.65 m/s. Moisture content of paddy was about 14% wet-basis. At the range of low velocity, 1.65 - 2.5 m/s, channelling occured. At higher velocity, air bubbles formed and moved upward and broke at the top of the bed. Experimental result showed that drying rate of a thin bed was controlled by moisture diffusion in grain kernels. Therefore, the effect of bubbles on the drying rate of a thick bed should not be significant.

Accuracy of the Mathematical Model

Figures 3 and 4 showed the comparison between results obtained from experiments and those obtained from mathematical simulation at the drying temperature of 100°C. It may be concluded that experimental and simulated moisture content of paddy and temperatures at the reactor exit were in good agreement. For other temperatures, similar trend was obtained.

Paddy Quality

Figures 5-7 showed the relationship between relative head yield and final moisture content for the initial moisture content of 45.3% dry-basis. Relative head yield was defined as the ratio of head yield to reference head yield which was explained in methods of experiment. For drying temperatures of 100 and 130°C (Figures 5 and 6), relative head yield dropped rapidly (below 80-90%) when moisture content, after drying, reached about 23-26% dry-basis, respectively. Due to the relatively fast drying rate, grain surface became hard rapidly and resulted in crackage of grain kernels if drying was further continued. For drying temperature of 150°C (Figure 7), relative head yield increased when final moisture content decreased. This was due to gelatinization effect. For the case of initial moisture content of 28.5 % dry-basis and drying temperature of 115°C, a similar result as Figures 5 and 6 was obtained as shown in Figure 8.

Figures 9-11 showed relationship between relative whiteness and final moisture content. The initial moisture content was 45.3% dry-basis. It could be concluded that relative whiteness was higher than 90% (still acceptable) for all final moisture content if drying air temperature was 100°C as shown in Figure 9. However, relative whiteness decreassed relatively fast with decreased final moisture content particularly for the case of 130 and 150°C as shown in Figures 10-11. For the case of initial moisture content of 28.5% dry-basis and drying air temperature of 115°C, it was found that relative whiteness was higher than 90% if final moisture content was not below 20% dry-basis as shown in Figure 12. It was believed that decreasing whiteness was due to caramelization.

Drying Strategy

Experimental results showed the trend of effect of specific air flow rate (mass flow rate of dry air divided by dry mass of paddy), fraction of air recycled and drying air temperature on energy consumption. However, conclusive results were not obtained. The developed mathematical model was therefore employed. The assumptions are as follows: diameter of reactor of 17 cm, initial moisture content of 38.5% dry - basis, final moisture content of 25% dry-basis, ambient temperature of 37°C, ambient relative humidity of 60%, drying air temperature of 115°C (This was the maximum temperature which yielded acceptable quality) and air velocity of 3.2 - 4.4 m/s. Simulated results were shown in Figures 13-16.

Figure 13 showed the effect of fraction of air recycled on specific energy consumption at different air velocities (or specific air flow rates). Bed thickness was fixed at 4.5 cm. It was found that total primary energy consumption decreased with increasing fraction of air recycled until 95 %. At low fraction of air recycled, exit air was still hot and dry but it was too humid at too high fraction of air recycled. Energy consumed was divided into heat for heating air and electricity for driving a fan. In this study, a factor of 2.6 was used to convert electricity into primary energy. Total primary energy consumption was then the sum of heat and the energy converted from electricity. It was also found that energy consumption decreased with decreasing specific air flow rate. Figure 14 showed the effect of fraction of air recycled on drying capacity at different air velocity (or specific air flow rate) for the same condition as in Figure 13. Drying capacity did not depend on fraction of air recycled until about 80 %. It decreased with decreasing specific air flow rate.

Figures 15 and 16 showed simulated results for the case of bed thickness of 9.5 cm. Similar results were obtained as compared to the case of bed thickness of 4.5 cm except that energy consumption decreased with increasing specific air flow rate as shown in Figure 15. At a thick bed depth, low specific air flow rate would result in long drying time and thus result in high energy consumption.

CONCLUSION

1. Minimum fluidized bed velocity was about 1.65 m/s. Drying rate of thin layer of paddy was diffusionally controlled. Drying air temperature should be limited to 115°C and paddy should not be dried below 24-25 % dry-basis if good quality of paddy was maintained.
2. A mathematical model developed was capable to predict the performance of fluidized bed paddy drying system.

3. According to simulated results, operating parameters should be as follows: 0.9 of fraction of air recycled, air velocity of 4.4 m/s and specific air flow rate of 0.13 kg/s-kg dry paddy (bed thickness of 9.5 cm). Drying air temperature was suggested in conclusion (1) above.

4. Economic analysis showed that total drying cost was about 0.08 US$/kg water evaporated (Prachayawarakorn, 1992).

SYMBOLS

C_a	-	specific heat of dry air
C_v	-	specific heat of vapor
E	-	power for driving a fan
e_f	-	efficiency of fan
e_m	-	efficiency of electrical motor
h_{fg}	-	latent heat of vaporization of water
m_p	-	dry mass of paddy
m_i	-	dry mass flow rate of fresh air
m_{mix}	-	dry mass flow rate of mixed air
m_{rc}	-	dry mass flow rate of recirculated air
M(t)	-	moisture content of paddy
M_{eq}	-	equilibrium moisture content
M_f	-	moisture content at the end of a time interval
M_i	-	moisture content at the beginning of a time interval
M_{in}	-	moisture content at the start of drying
Q_1,Q_2,Q_3	-	rate of heat lossses from control volumes to surroundings
Q_h	-	rate of heat supplied to the dryer
R	-	ratio of dry mass of paddy to dry mass of air
RC	-	fraction of air recycled

RH	-	relative humidity of air
t	-	drying time
T_b	-	air temperature at fan exit
T_{f1}	-	air temperature at reactor exit
T_{f2}	-	air temperature before mixing
T_i	-	fresh air temperature
T_{mix}	-	air temperature at reactor entrance
T_x	-	air temperature after mixing
W_{f1}	-	humidity ratio of air at reactor exit
W_i	-	humidity ratio of fresh air
W_{mix}	-	humidity ratio of air at reactor entrance
W_s	-	power for driving an electrical motor
ΔP	-	pressure drop
Δt	-	time interval for calculation
ΔU_p	-	change of internal energy of paddy per unit mass of dry air
ΔU_d	-	change of internal energy of reactor per unit mass of dry air
ρ_f	-	air density

REFERENCES

Giner, S.A. and De Michelis, A. 1988, Evaluation of Thermal Efficiency of Wheat Drying in Fluidized Beds, The British Society for Research in Agricultural Engineering Journal 41, 11 - 23.

Henderson, S.M. 1952, A Basic Concept of Equilibrium, Agri. Eng. 33, 29-31.

Page, G.E. 1949, Factors Influencing the Maximum Rate of Drying Shell Corn in Layers, Unpublished M.S. Thesis. Purdue University, West Lafayette, Indiana, USA.

Prachayawarakorn, S. 1992, Drying of High Moisture Paddy by Fluidization Technique, Master Thesis, King Mongkut's Institute of Technology Thonburi, Bangkok (in Thai).

Satayaprasert, C. and Vanishsriwatana, V. 1992, Drying Corn in Fluidized Bed, Thailand Engineering Journal 44(12), 76 - 79.

Soponronnarit, S., Achariyaviriya, S. and Tasaso, P. 1992, Optimum Strategies for Drying Papaya Glace', ASEAN Food Journal 7(1), 192 - 198.

Sutherland, J.W. and Ghaly, T.F. 1990, Rapid Fluid-Bed Drying of Paddy Rice in the Humid Tropics, Presented at the 13 th ASEAN Seminar on Grain Postharvest Technology, Brunei.

Thorpe, G.R. 1987, Thermodynamic Performance of Continuous - Flow Fluidized Bed Grain Disinfestor & Drier, J. AG. ENG. Research 37(1), 27 - 40.

Tumambing, J.A. and Driscoll, R.H. 1991, Modelling the Performance of Continuous Fluidized Bed Dryer for Pre - Drying of Paddy, Presented at the 14 th ASEAN Seminar on Grain Post-Harvest Technology, Philippines.

Wilhelm, L.R. 1976, Numerical Calculation on Psychrometric Properties in SI Units, Trans. ASAE. 19(2), 318-321, 325.

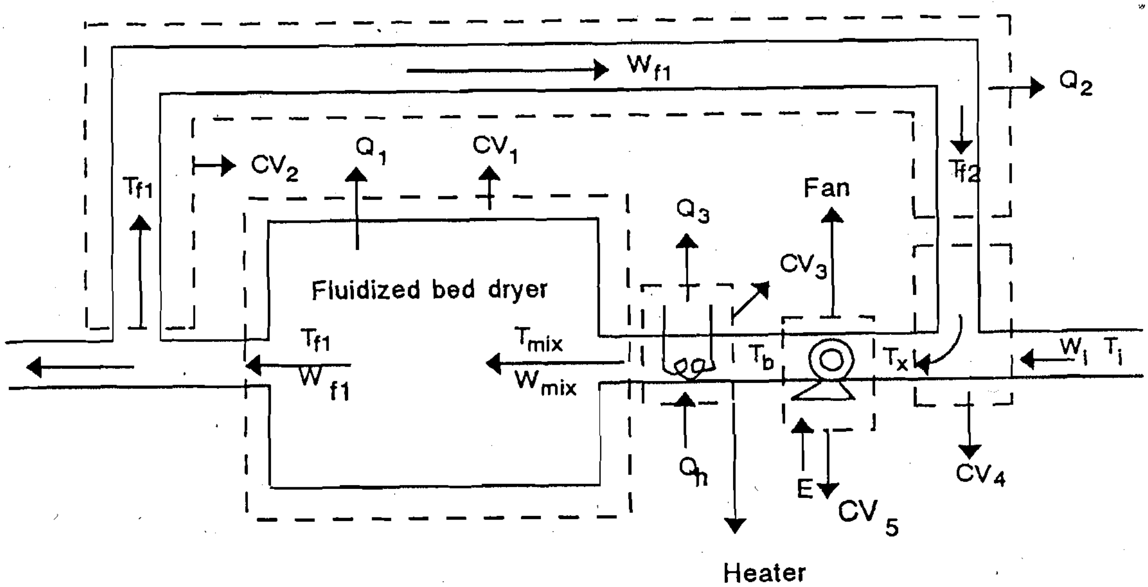

Figure 1. Control Volumes

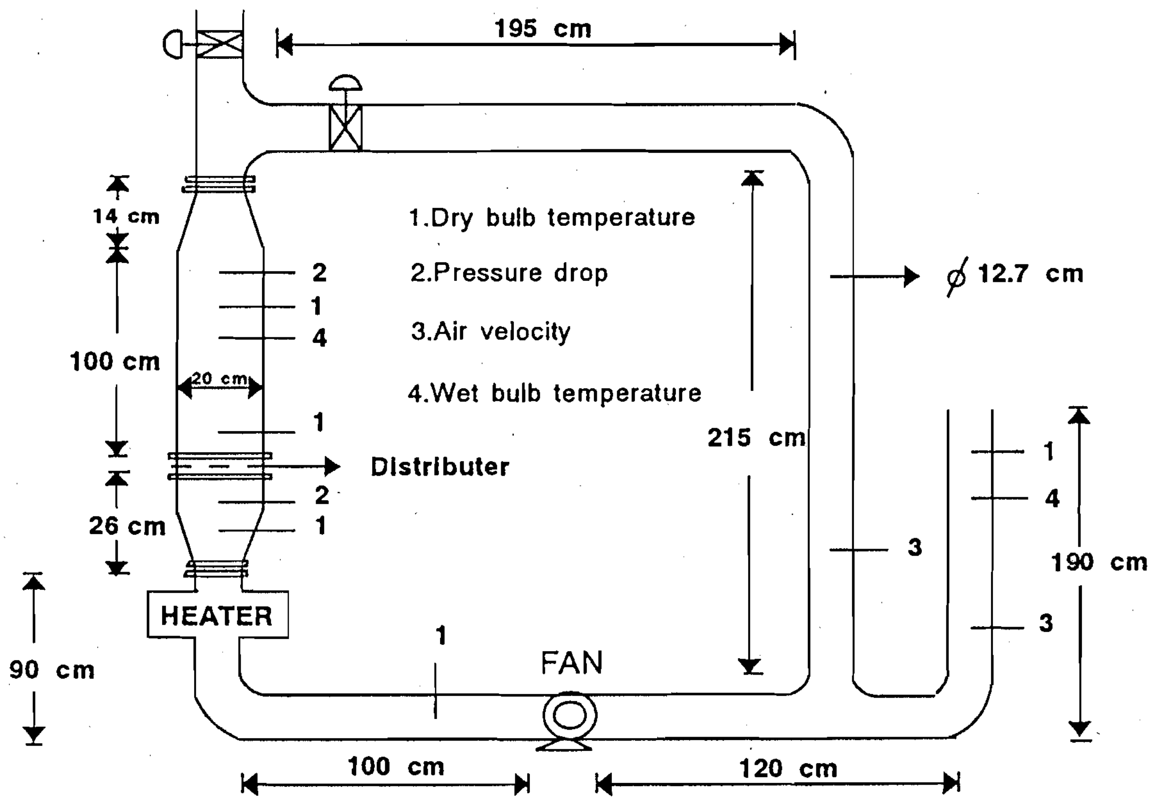

Figure 2. Experimental fluidized bed dryer

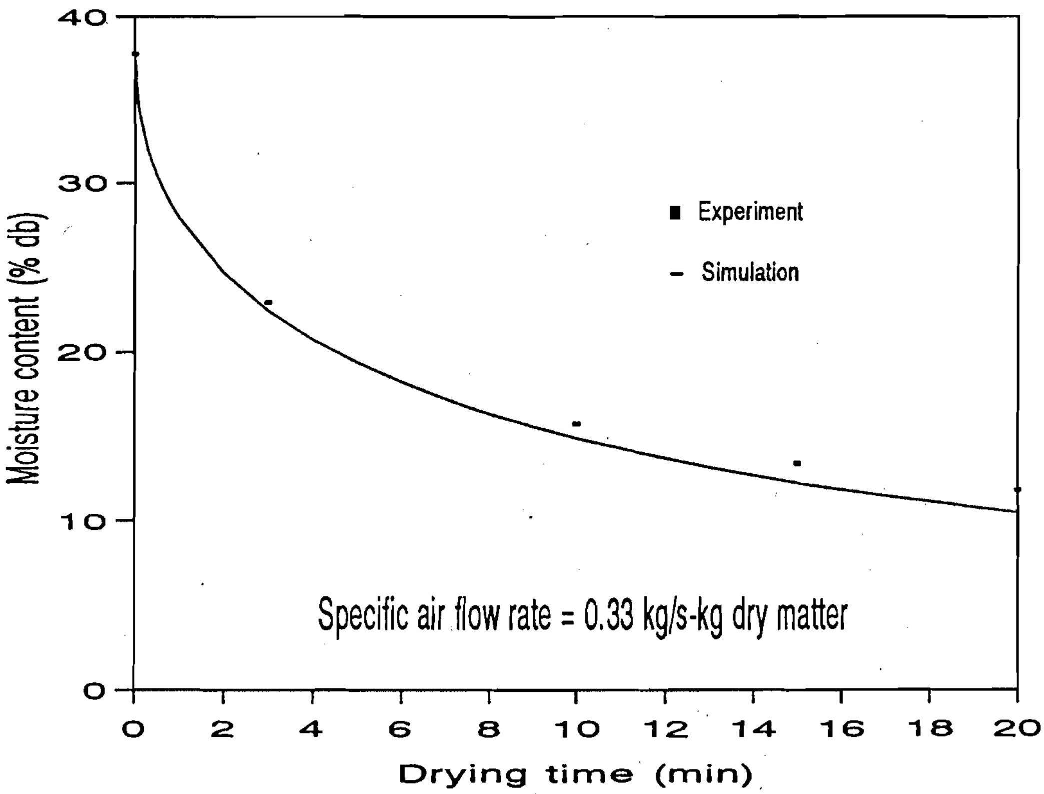

Figure 3 Evolution of simulated and experimental moisture content
[Fraction of air recycled = 50 %,Temperature = 100 C]
[Bed velocity = 4.4 m/s,Bed depth = 3.70 cm]

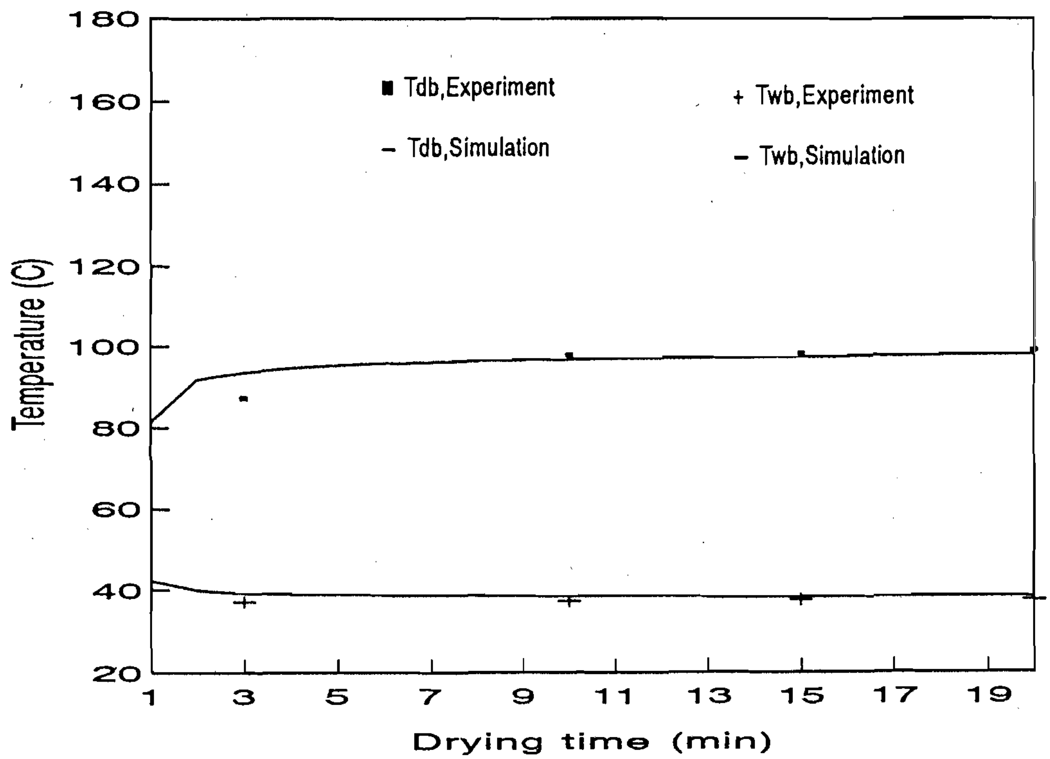

Figure 4. Evolution of outlet temperatures
[Fraction of air recycled = 50 %, Temperature = 100 C]
[Specific air flow rate = 0.33 kg/s-kg dry matter]

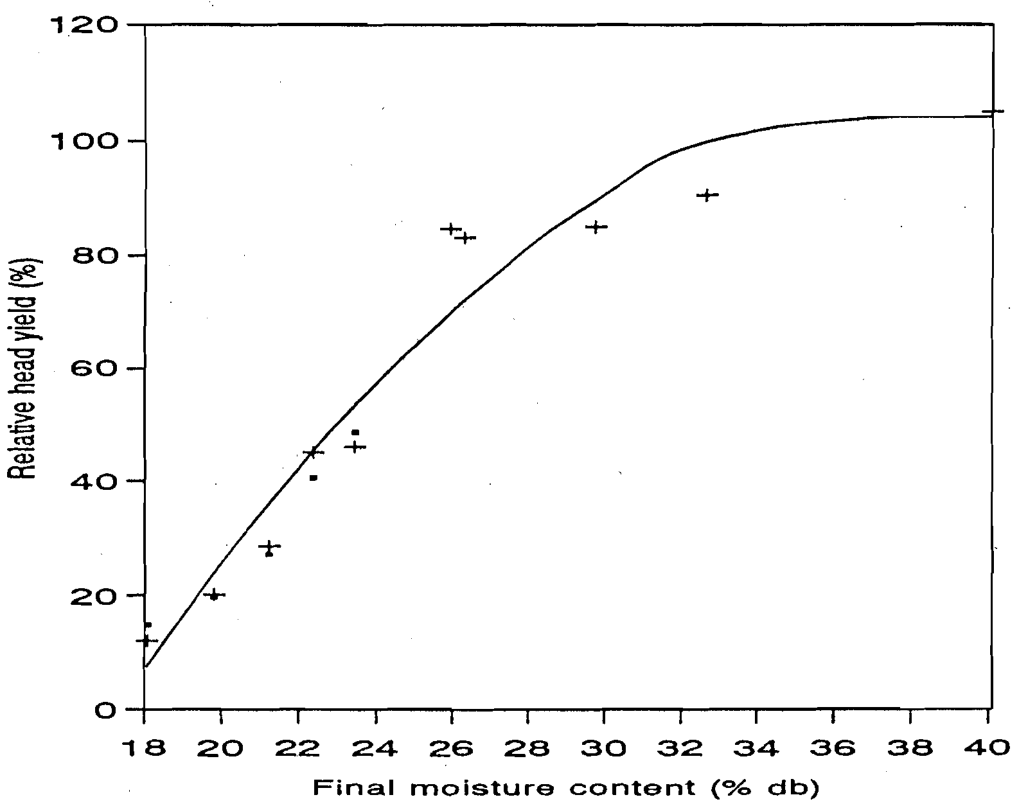

Figure 5. Relationship between relative head yield and final moisture content in fluidized bed drying. [Reference head yield = 30.7 %,Min = 45.30 % db] [Temperature = 100 C]

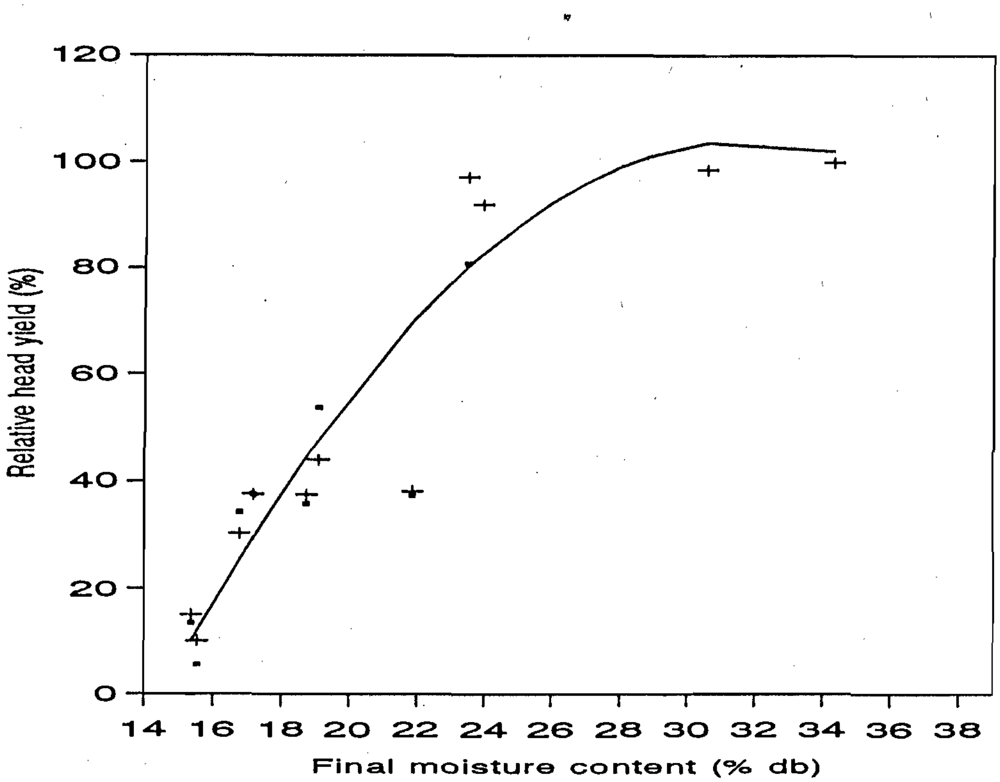

Figure 6. Relationship between relative head yield and final moisture content in fluidized bed drying.[Reference head yield = 30.7 %,Min = 45.30 % db]
[Temperature = 130 C]

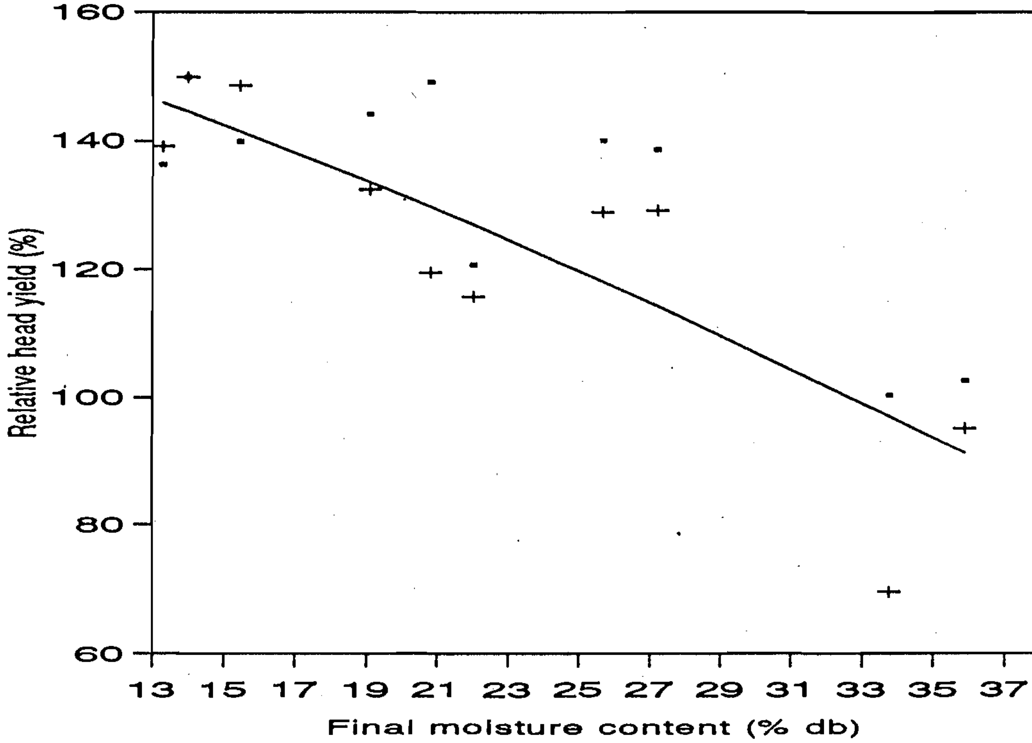

Figure 7. Relationship between relative head yield and final moisture content in fluidized bed drying. [Reference head yield = 30.7 %,Mi = 45.30 % db]
[Temperature = 150 C]

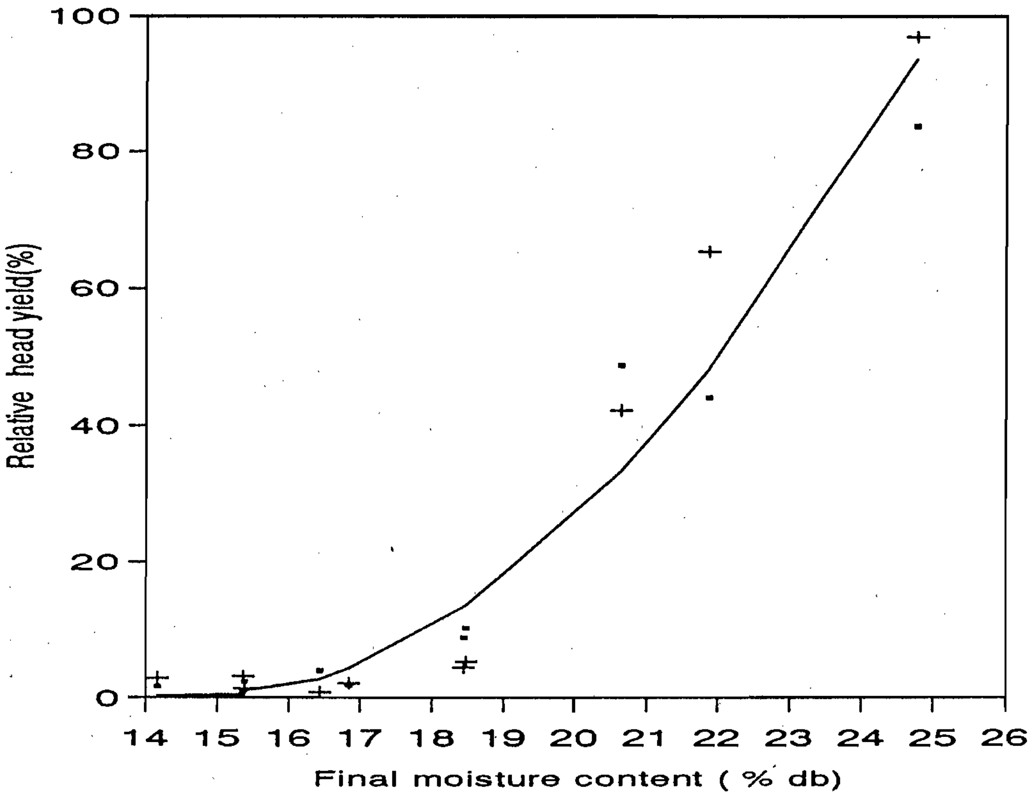

Figure 8. Relationship between relative head yield and final moisture content in fluidized bed drying. [Reference head yield = 30.64 %,Mi = 28.5 % db] [Temperature = 115 C]

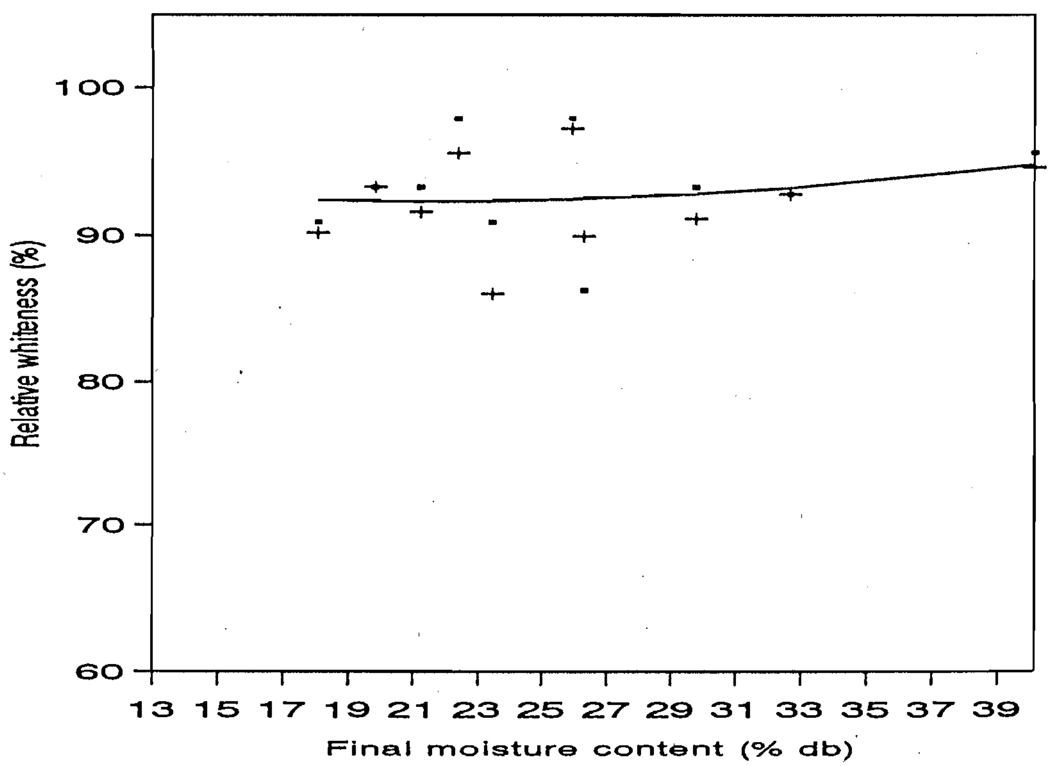

Figure 9. Relationship between relative whiteness and final moisture content in fluidized bed drying. [Reference whiteness = 42.9 ,Mi = 45.30 % db]
[Temperature = 100 C]

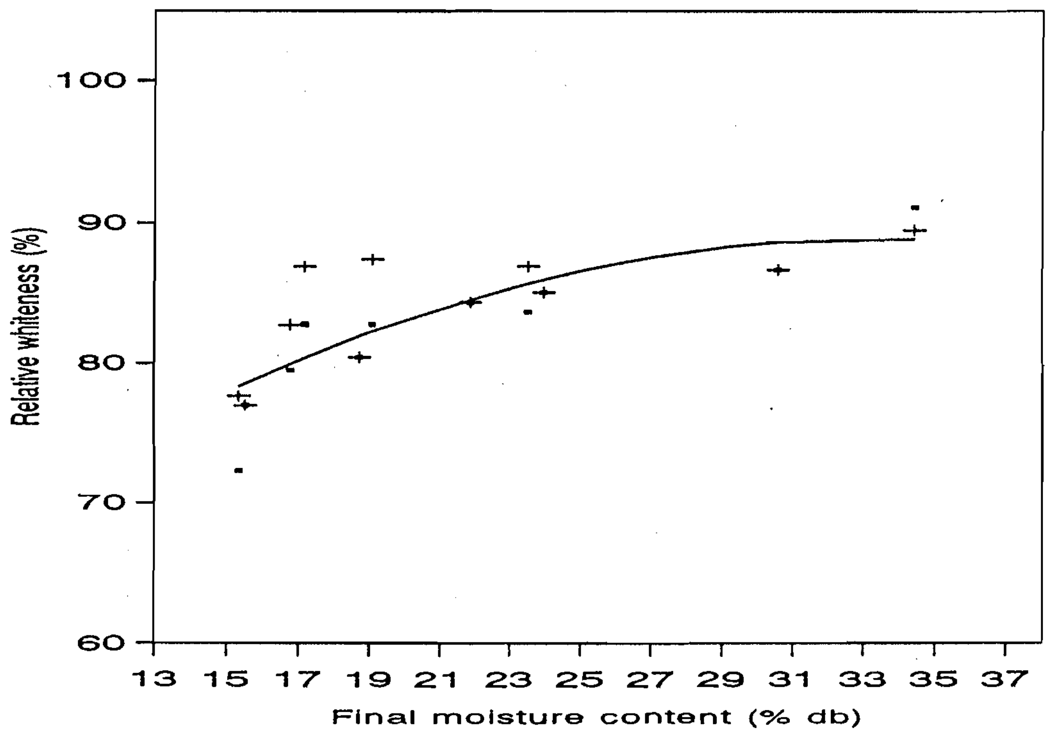

Figure 10. Relationship between relative whiteness and final moisture content in fluidized bed drying. [Reference whiteness = 42.9 ,Mi = 45.30 % db]
[Temperature = 130 C]

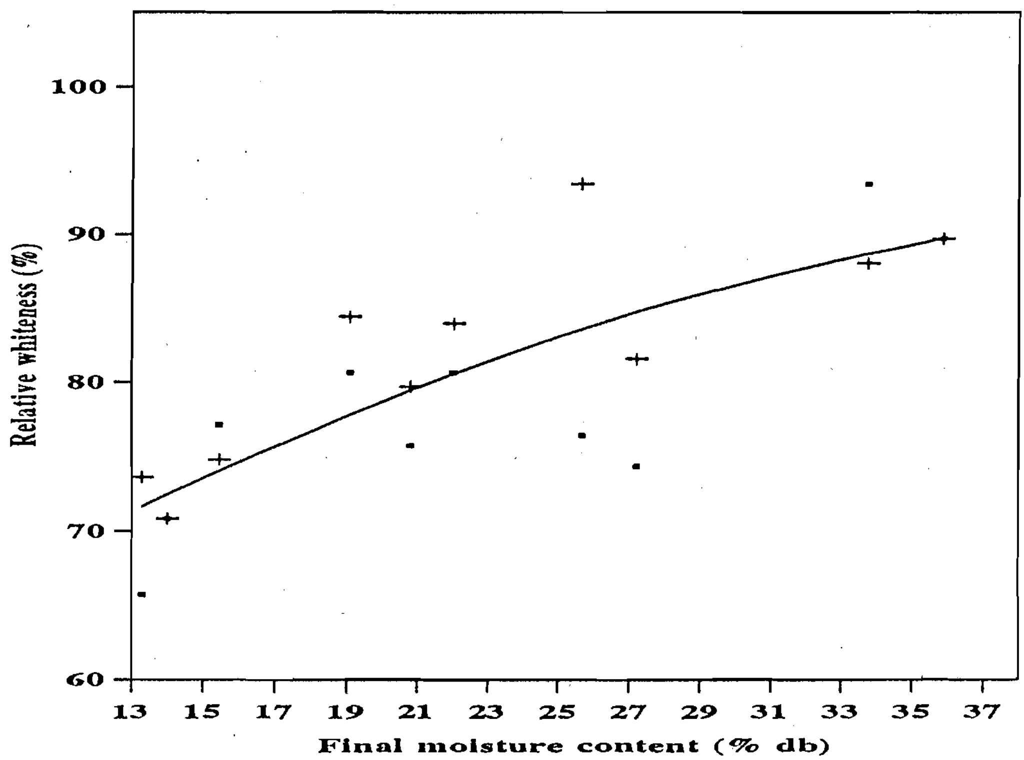

Figure 11. Relationship between relative whiteness and final moisture content in fluidized bed drying. [Reference whiteness = 42.9 ,Mi = 45.30 % db]
[Temperature = 150 C]

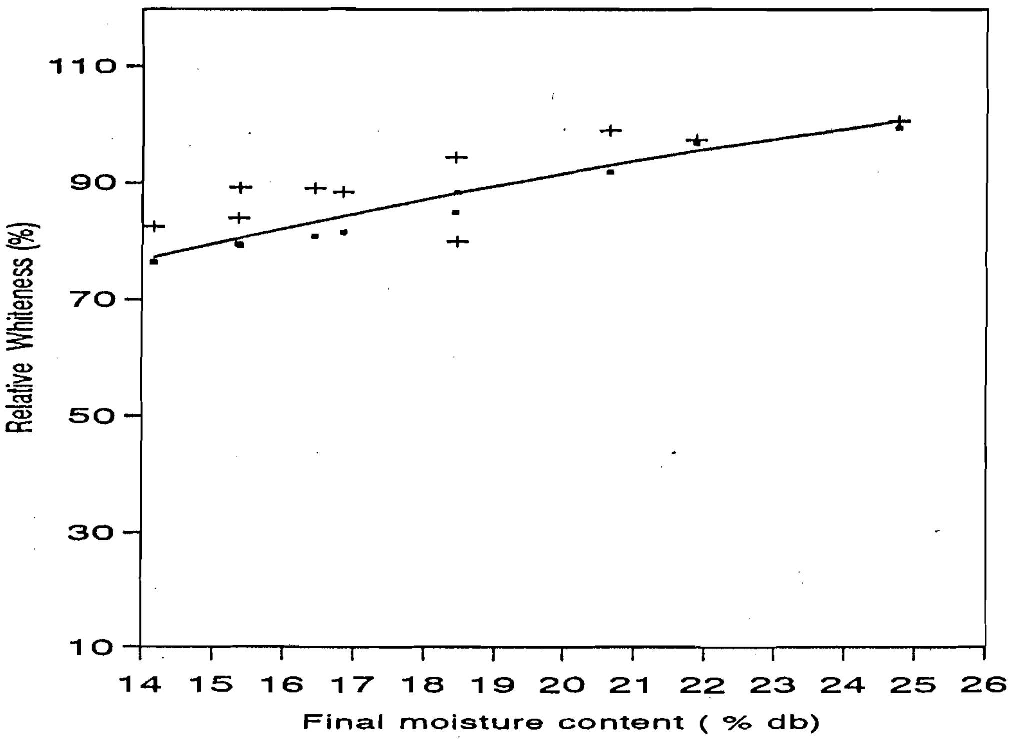

Figure 12 Relationship between final moisture content and relative whiteness in fluidized bed drying. [Reference whiteness = 43.50 Mi = 28.5 % db]
[Temperature = 115 C]

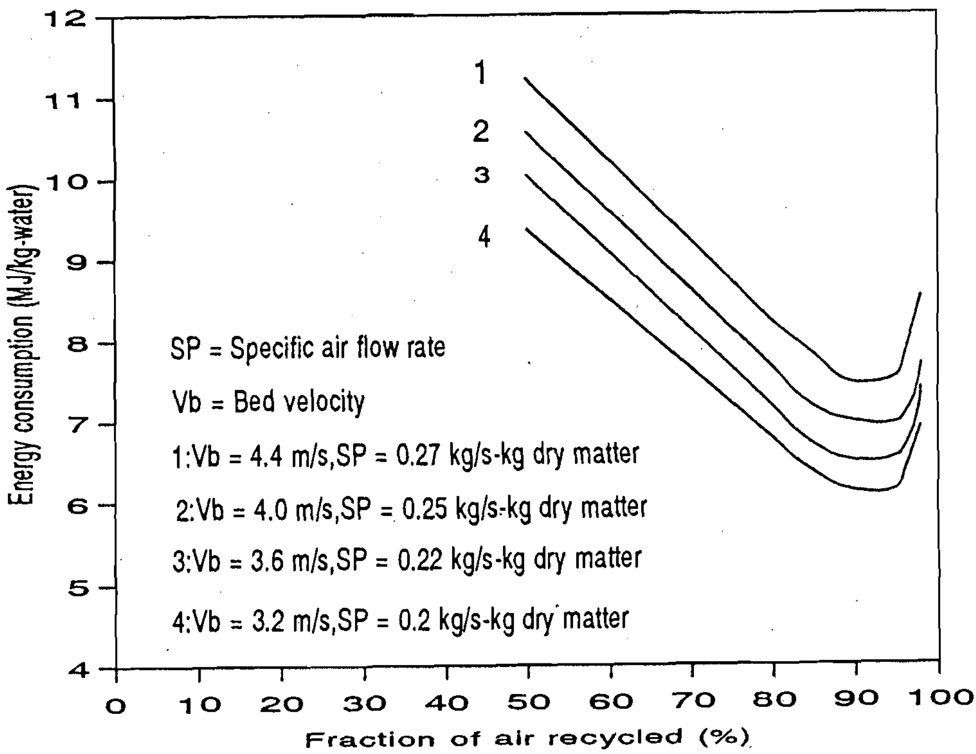

Figure 13. Simulation results of effect of fraction of air recycled on primary energy consumption
[Temperature = 115 C,Bed depth = 4.5 cm,Mi = 38.50 % db]
[Mf = 25.00 % db]

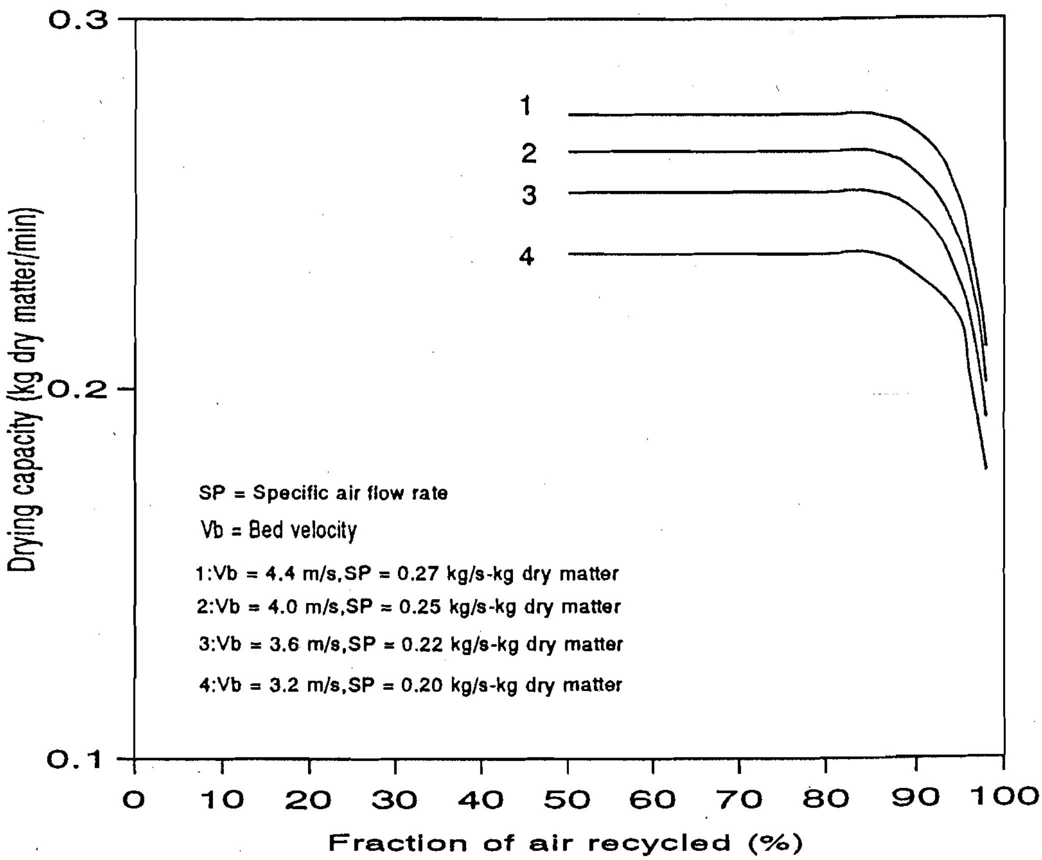

Figure 14. Simulation results of effect of fraction of air recycled on drying capacity
[Temperature = 115 C,Bed depth = 4.5 cm,Mi = 38.50 % db]
[Mf = 25.00 % db]

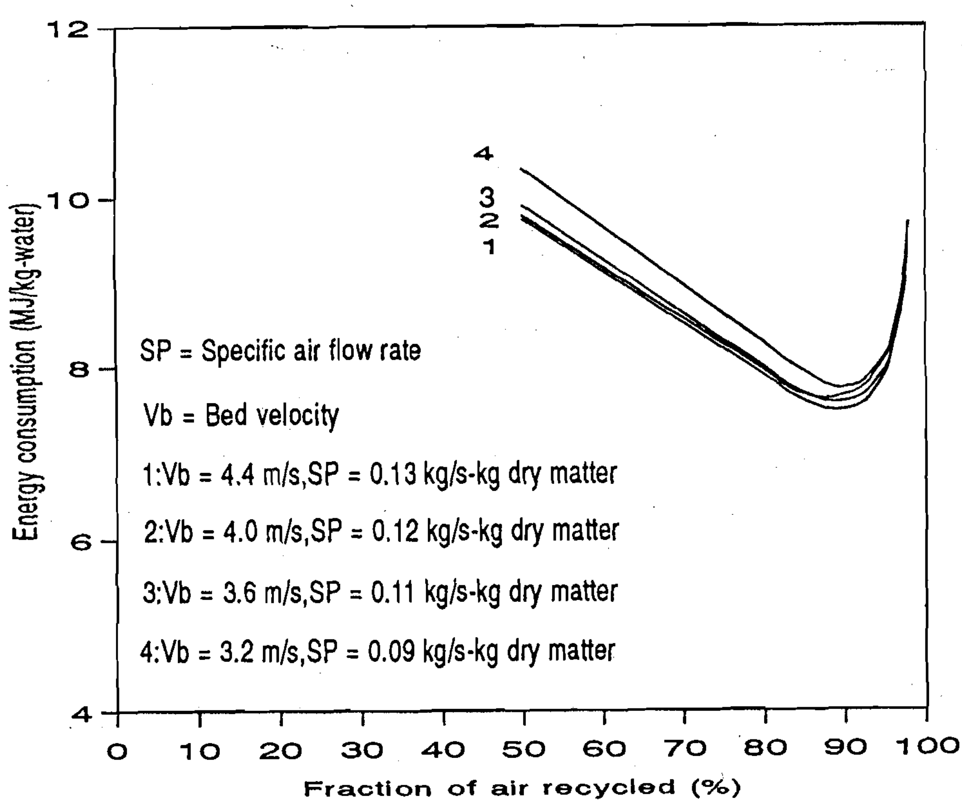

Figure 15. Simulation results of effect of fraction of air recycled on primary energy consumption
[Temperature = 115 C,Bed depth = 9.5 cm,Mi = 38.50 % db]
[Mf = 25.00 % db]

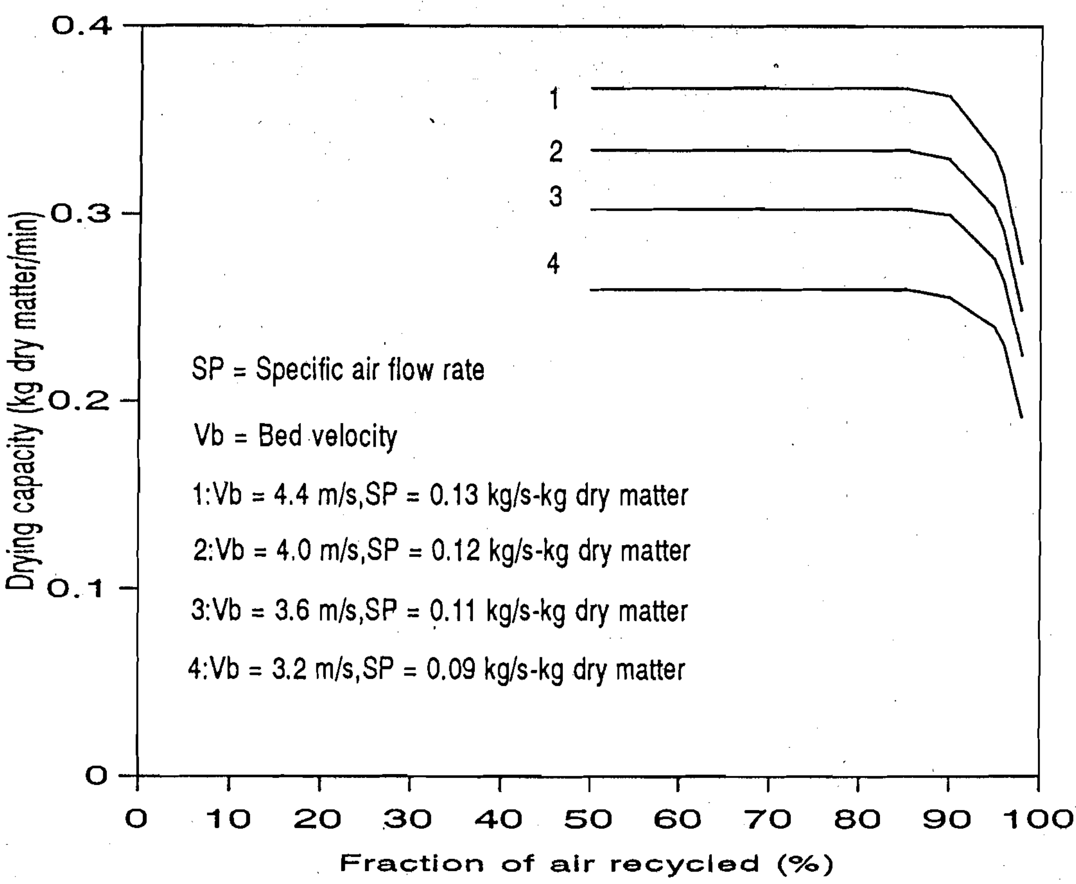

Figure 16. Simulation results of effect of fraction of air recycled on drying capacity
[Temperature = 115 C,Bed depth = 9.5 cm,Mi = 38.50 % db]
[Mf = 25.00 % db]