Appropriate Operating Parameters for Fluidized Bed Corn Drying

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ABSTRACT

A commercial scale fluidized bed paddy dryer was modified for corn drying. The performance of this dryer and the effects of operating parameters on energy consumption were investigated. The experimental results clearly showed that fluidized bed dryer was effective for corn drying at high initial moisture content. The quality after drying in terms of breakage and stress cracking of corn kernels was still maintained at the following conditions : reducing moisture content from 18 % - 23 % dry-basis to 16 % - 19 % dry-basis and from higher than 28 % dry-basis to 19 % - 30 % dry-basis using inlet hot air temperature of 130 °C - 175 °C. The simulated results indicated that both inlet hot air temperature and bed depth affected drying kinetics of corn in fluidized bed dryer. However, for energy consumption, it was affected by bed depth, inlet hot air temperature, feed rate and fraction of air recycled. The optimum condition for corn drying was as follows : bed depth of 17 cm, inlet hot air temperature of 170 °C and fraction of air recycled of 0.8 - 0.9.

1. INTRODUCTION

Drying, as a thermal process, intensively requires energy. The amount of thermal energy used for drying is of great practical significance having a direct effect on the operating cost and thus on the market price of dried product because the influence of dryer type is more involved to its energy consumption [1]. Energy consumption for drying materials with fluidized bed dryer is rather high [2]. It is because this technique requires high superficial air velocity, approximately 1.5 times of superficial air velocity at minimum fluidizing condition in practice. In this condition, thermal efficiency, defined as ratio of heat for removing the moisture within grain kernel to total heat input, is rather low with fluidized bed dryer with no air recirculation or recovery heat. However, it is practicable to improve thermal efficiency of this dryer ; for example, by using high inlet air temperature until grain temperature exiting from dryer reaches that of deterioration of grain quality and to recycle exhaust air. In spite of a large amount of energy consumption, this technique possesses many more eminent features than the conventional deep bed dryer and moving bed dryer [3] as follows :

- Drying air flowing through the bed is locally mixed well and consequently heat and mass transfer rates between drying air and solid particles are relatively high and thus drying time is short.
- Rapid heat and mass transfers make high inlet hot air temperature to be used.

- Isothermal bed temperature yields a desired product quality and makes continuous dryer to be controlled easily.
- Size of dryer is small but with high capability. Therefore, installation and equipment costs are low .

In addition to energy consumption, grain quality at the end of drying is also important. In general, the important factors affecting on grain quality are temperature, final moisture content and relative humidity. In case of paddy drying, it was found that as inlet hot air temperature was higher than 150 °C, milled rice became more intense yellow, due to non-enzymatic browning reaction [4]. Besides, head yield of paddy reduced rapidly when moisture content from any high moisture levels was reduced to a moisture level lower than 19 % wet-basis at the condition of inlet hot air temperature higher than 70 °C [4,5]. For corn drying, stress cracks in corn kernels became greater with the increase of inlet hot air temperature [6] and breakage susceptibility also increases as drying rate was further increased [7]. In contrast, deterioration of corn quality due to stress cracks and breakage susceptibility is reduced by high relative humidity of drying air [8].

The experimental works as mentioned above indicated that corn quality was damaged easily with high drying rate. Thus corn drying with fluidized bed technique has rather more influence on corn quality. The knowledge of optimum conditions of corn drying without any damage in corn quality is very important. Therefore, it is necessary to conduct experimental work to investigate the conditions of maintaining corn quality and then to prove the mathematical models that predict the drying characteristics and energy consumption. In this paper, the focus is on the simulation to study effects of operating parameters on energy consumption under condition of acceptable product quality.

2. MATHEMATICAL MODELS FOR CONTINUOUS DRYER

The assumptions made to simplify the mathematical models for grain drying in homogeneously fluidized bed are as follows :

- Shrinkage of particles during drying is negligible and physical properties of dry corn is independent with time.
- Drying process is controlled by internal diffusion and therefore convective mass transfer can be neglected.
- Movements of grain and drying air are in plug flow.
- Drying air is in thermal equilibrium with the grain kernels

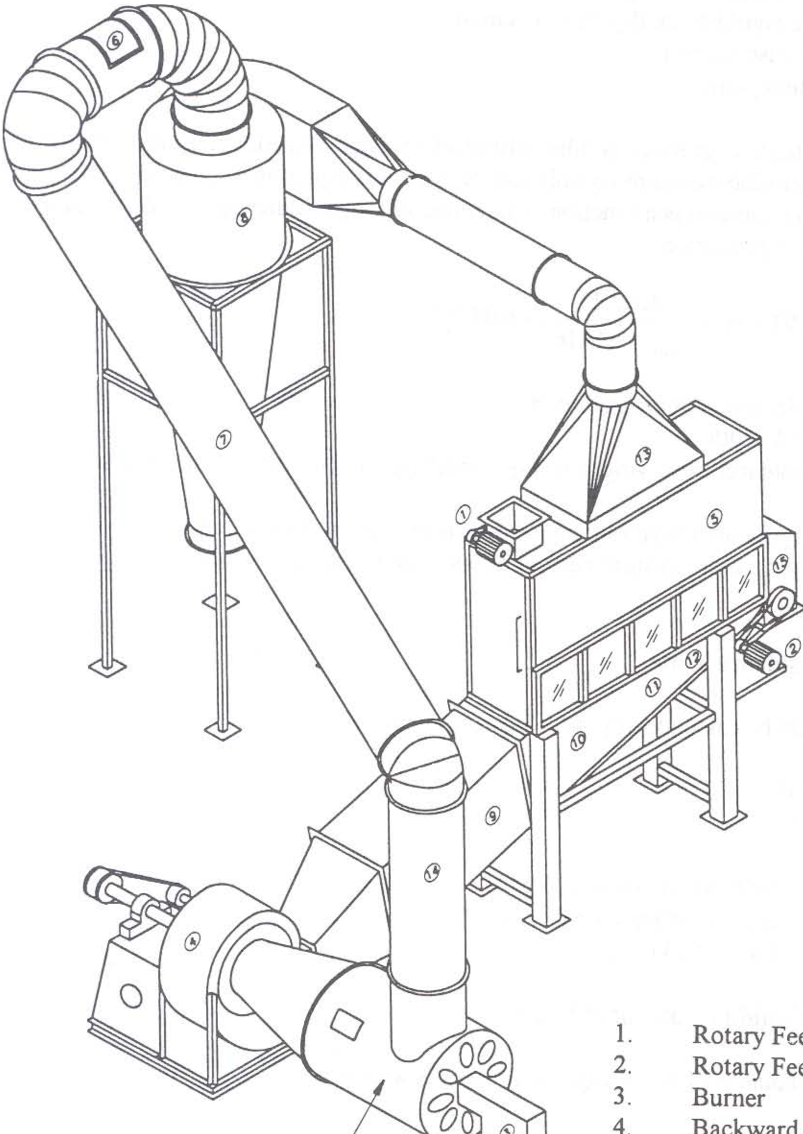
Models are somewhat similar to that presented by Soponronnarit and Prachayawarakorn [4]. Fig. 1 presents the sections of fluidized bed dryer such as a drying chamber, a combustion unit, recycled line and a fan for the derivation of equations of mass and energy conservation.

2.1 Drying Rate Equation

Based on experimental work by Satayaprasert and Vanishsriwatana [9] moisture transfer in corn kernels could be described well by Lewis' equation [10] as follows :

$$\frac{M(t) - M_{eq}}{M_{in} - M_{eq}} = \exp(-kt) \tag{1}$$

where $M(t)$ = average moisture content at time t, dry-basis decimal



1. Rotary Feeder, Inlet
2. Rotary Feeder, Outlet
3. Burner
4. Backward Curved Blade Centrifugal Fan
5. Drying Chamber
6. Exhaust Air
7. Air Recycled
8. Cyclone

9-15. (Position 0f Temperature Measurement)

Fig. 1. Fluidized bed dryer.

M_{in} = initial moisture content , dry-basis decimal
M_{eq} = moisture equilibrium, dry-basis decimal
k = drying constant, min^{-1}.
t = drying time, min.

This equation assumes that temperature equilibrium and internal mass transfer resistance in corn kernels is negligible. To determine moisture equilibrium of corn, the equation was developed by Phudphong et al. [11]. Drying constant is a function of inlet hot air temperature and bed depth, and can be depicted by the following equation:

$$k = 75.93\ \exp(-\frac{2662.21}{T_{mix} + 273.16}) - 0.087H \tag{2}$$

where T_{mix} = inlet hot air temperature, °C
H = bed depth, m

To calculate moisture content at any drying time, Eq. 1 is differentiated with time and then solved by finite differences.

Dividing corn bulk in dryer into n layers along the direction of grain flow (directions of air and grain flow are perpendicular), the exit moisture content of corn can be calculated successively from the first layer to n^{th} layer.

2.2 Equation of Mean Residence Time

Mean residence time can be calculated by the following equation :

$$\tau = \frac{\rho AH}{F} \tag{3}$$

where ρ = bulk density of corn, kg/m^3
A = area of drying chamber, m^2
F = feed rate, kg/min

2.3 Equation of Outlet Humidity Ratio at i^{th} Layer

The relation of a mass balance of water vapor at i^{th} layer is written as:

$$W_{f,i} = R(M_i - M_f) + W_{mix} \tag{4}$$

where $W_{f,i}$ = outlet humidity ratio of air at i^{th} layer, kg water/kg dry air.
W_{mix} = inlet humidity ratio of air at i^{th} layer, kg water/ kg dry air.
M_i = average inlet moisture content at i^{th} layer, dry-basis decimal .
M_f = average outlet moisture content at i^{th} layer, dry-basis decimal .
R = ratio of dry mass of corn to dry air.

2.4 Equation of Exhaust Air Temperature at i^{th} Layer

The energy balance of drying air can be written as the following equation:

$$T_{f,i} = \left[Q / m_{mix} + C_a T_{mix} + W_{mix}(h_{fg} + C_v T_{mix}) - W_{f,i} h_{fg} + RC_{pw} T_{mix} \right] / \left[C_a + W_{f,i} C_v + RC_{pw} \right] \quad (5)$$

where
$T_{f,i}$ = exhaust air temperature at i th layer, °C
Q = heat loss, kW
C_a = specific heat of dry air, kJ/kg °C
C_v = specific heat of water vapor, kJ/kg °C
C_{pw} = specific heat of moist grain, kJ/kg°C
h_{fg} = latent heat of moisture evaporation, kJ/kg
m_{mix} = mass flow rate of drying air, kg/s

Average outlet humidity ratios of drying air and exhaust air temperature are obtained by arithematic mean from those of drying air at each layer.

For other calculation such as mixing of temperature between exhaust air and fresh air, and energy consumption at the fan and the combustion unit, the first law of thermodynamics can be applied for these solutions.

The equations were solved by iteration method. Firstly, average outlet humidity ratio of dry air was assumed. The equations of moist air properties developed by Wilhelm [12] were employed.

3. MATERIALS AND METHODS

A fluidized bed dryer with 1.6 tons/h - 3 tons/h capacity is shown in Fig. 1. The system is mainly composed of 4 parts : a drying chamber with dimension of 0.7 m x 2.1 m x 1.3 m, a diesel oil burner, a conventional cyclone separator and a backward curved blade centrifugal electric fan driven by a 25 hp three phase motor. Mass flow rate of corn fed in and out the dryer is controlled by each rotary feeder. Bed depth of corn is regulated by a weir. Corn in the dryer flows in perpendicular direction with inlet hot air passing through the bed of which temperature is controlled by a thermostat with an accuracy of +/- 3 °C. In order to collect impurities such as husk, large particle and immature grain, exhaust air is flowed through the conventional cyclone separator. Then a small part of exhaust air is delivered to atmosphere and the rest is recycled, mixed together with the fresh air and then reheated to a desired temperature in the combustion unit. In this research, we concentrated on corn drying at high temperature levels, approximately 130 °C - 175 °C, due to high ability of fluidized bed dryer in terms of heat transfer rate as compared with other dryers. A fixed air flow rate was 3.39 m^3/s, corresponding to 2.7 m/s superficial air velocity (1.5 times at minimum fluidizing velocity),and fraction of recycled air varied between 0.78 and 0.84 depending on initial moisture content and bed depth. Initial moisture content of freshly harvested corn varied between 18 % dry-basis and 40 % dry-basis, bed depth of corn was in a range of 17 cm and 22 cm and residence time varied between 3 and 7 minutes depending on feed rate and bed depth. When the system became adjustable to steady state, temperatures at various positions as shown in Fig. 1 were measured by K-type thermocouple from which signal was transferred to a data logger (accuracy of +/- 1 °C). In addition, diesel oil consumption was also recorded each hour during the operation. For grain temperature, corn kernels exiting from dryer were put into an insulation container and measured with a thermometer.The samples were determined for moisture content and qualities in terms of breakage and stress cracking of corn kernel. For reference samples, corn was dried by natural air.

To determine the moisture content of corn, the samples were placed in a hot air oven at a fixed temperature of 103 °C for 72 hours.

The percentage of stress cracks, which was defined as ratio of weight of stress cracked corn to total weight, was determined by the inspection of 150 g of corn kernels for each sample. A wooden box with a fluorescent lamp was used to inspect each corn kernel. For the percentage of breakage, it was defined as ratio of weight of broken corn to total weight.

4. RESULTS AND DISCUSSION

4.1 Experiment

As shown in Table 1, when low moisture content of corn(lower than 22 % dry-basis) was dried by fluidized bed technique, energy was intensively employed, approximately higher than 15 MJ/kg water evaporated. In contrast, energy consumption was 5 MJ/kg- 7 MJ/kg water evaporated with corn drying at high moisture level (higher than 28 % dry-basis). This is because corn surface was relatively wet at high moisture level and therefore water at that surface evaporated rapidly due to high heat transfer rate. But at low moisture level, corn surface became rather dry and rate of moisture movement inside the kernels was relatively low as compared to heat transfer rate. For corn quality, it was found that in reducing moisture content of corn from 18% - 23% dry-basis to 16% - 19 % dry-basis using inlet hot air temperature of 130 °C, 150 °C, 170 °C and 175 °C, percentage of stress cracked corn kernel and that of breakage were low, but as reduced to 14 % dry-basis, the percentage of stress cracked corn kernel was increased rapidly while the percentage of broken corn kernel was nearly the same as reference samples. The corn quality obtained by drying conditions was acceptable if the outlet grain moisture content was higher than 19% dry-basis. Corn with high moisture content subjected to

Table 1. Corn quality testing.

Drying hot air temp. (°C)	Air recycled	Inlet moisture content (%db)	Outlet moisture content (%db)	Outlet grain temp. (°C)	Breakage		Stress cracks		Testing hours	Capacity
					Dryed in fluidized bed (wt%)	Reference (wt%)	Dried in fludized bed (wt%)	Reference (wt%)		(tons/h)
130[a]	84	22.2	19.12	68.3	1.91	1.04	0.59	0.19	2	1.8
130[a]	78	38.28	30.79	68.1	-	-	-	-	6	2.0
140[b]	78	32.72	27.21	74.3	-	-	-	-	10	3.0
150[a]	78	28.19	19.20	-	-	-	-	-	7	2.0
150[a]	84	18.56	16.73	74.0	1.81	1.72	1.03	0.59	2	1.8
160[a]	78	40.32	26.32	-	-	-	-	-	4	1.8
170[c]	84	21.14	14.16	97.4	2.82	2.44	32.69	0.62	5	1.6
175[a]	84	22.77	18.18	95.9	1.34	1.55	3.34	0.79	7	1.8

a 15 cm bed depth, b 17 cm bed depth, c 20 cm bed depth environments with high drying potential in a short period of time may not fissile because corn kernel was still elastic after drying [13].

4.2 Accuracy of Mathematical Model

Fig. 2 showed the comparison between simulated and experimental results in outlet moisture content of corn. It was found that outlet moisture content of corn predicted from Eq. (1) in case of high initial moisture content of corn was more accurate than that in case of low initial moisture content. This was due to limitation of use of Eq. (1) at high moisture level. For predicting the exhaust air temperature, it was found that the mathematical model predicted the exhaust air temperature relatively well for high moisture corn but quite poor for low moisture level as shown in Fig. 3. The model was valid for high moisture level.

The results indicated that corn drying with fluidized bed dryer was very effective at high moisture level. However, the conclusive results were not obtained. Therefore, the developed mathematical model was employed to determine the appropriate drying strategy. The operating parameters such as inlet hot air temperature, bed depth, fraction of air recycled and feed rate were investigated. The assumptions are as follows : 1) The fluidized bed dryer with a dimension of 0.7 m x 2.1 m x 1.3 m has a maximum capacity of 3 tons/h ; 2) Due to a limited power of the fan, maximum bed depth of corn is 17 cm; 3) maximum inlet hot air temperature at which corn quality after drying is still maintained is 170 °C; 4) Superficial air velocity is fixed at 2.7 m/s. 5) Initial moisture content of corn is 40 % dry-basis (normally at the beginning of harvesting season); 6) Outlet moisture content should not be lower

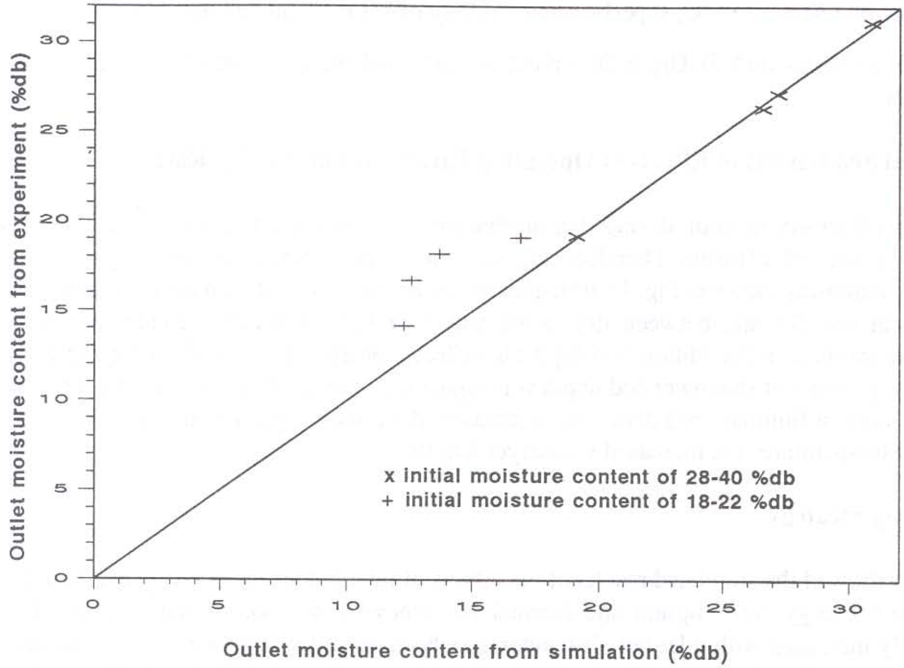


Fig. 2. Comparison between experimental and simulated outlet moisture contents (Inlet hot air temperature of 130 °C -175 °C, superficial air velocity of 2.7 m/s and bed depth of 15 cm - 20 cm).

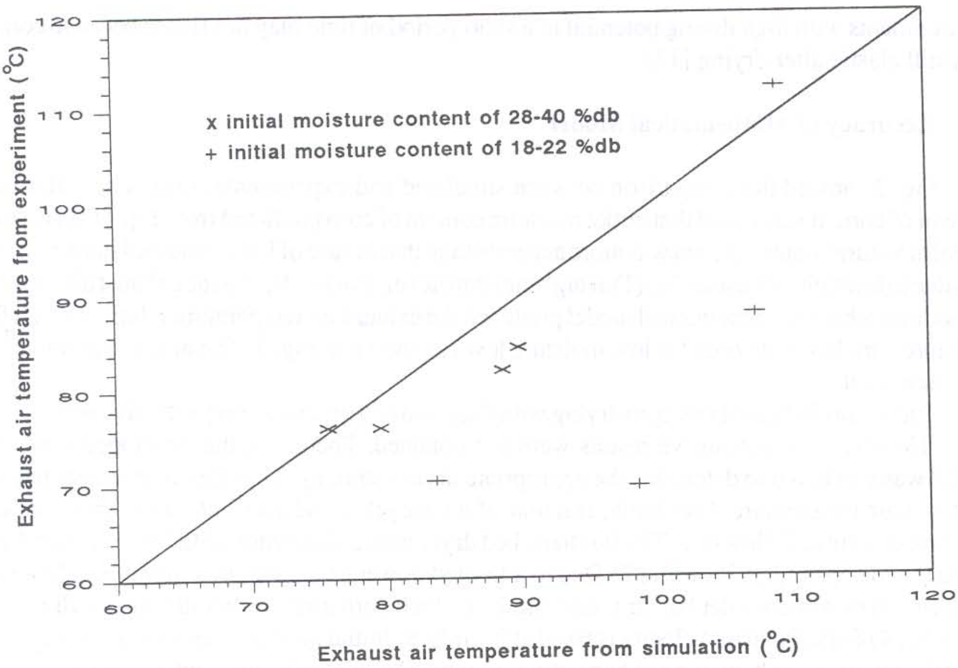


Fig. 3. Comparison between experimental and simulated exhaust air temperature (Initial hot air temperature of 130 °C -175 °C, superficial air velocity of 2.7 m/s and bed depth of 15 cm - 20 cm).

than 20 % dry-basis and 7) Dry-bulb air temperature and relative humidity are 37 °C and 70, respectively.

4.3 Simulated Results of Effects of Operating Parameters on Drying Rate

It is well known in grain drying that mechanism of moisture transfer inside a corn kernel is controlled by internal diffusion. Therefore, the most important factor affecting on drying rate is inlet hot air temperature as shown in Fig. 4 : drying rate of corn was increased with inlet hot air temperature because heat transfer rate between drying air and corn kernels became greater and then corn temperature was higher. In addition, bed depth also affected on drying rate, as shown in Fig. 5, because the corn temperature at shallower bed depth was higher than that at deeper bed depth. The moisture profiles of corn in fluidized bed dryer was decreased along with dryer length while the profiles of exhaust air temperature was increased with dryer length

4.4 Drying Strategy

Fig. 6 showed the simulated results of the effects of inlet hot air temperature and bed depth on total primary energy consumption and thermal efficiency. It was found that thermal efficiency significantly increased with inlet hot air temperature because water evaporation rate was increased while drying time was fixed. In addition, thermal efficiency increased with bed depth because of the increase of effective surface area between corn kernels and drying air, resulting higher heat and mass transfer rates. Total primary energy consumption could be divided into energy for heating air and

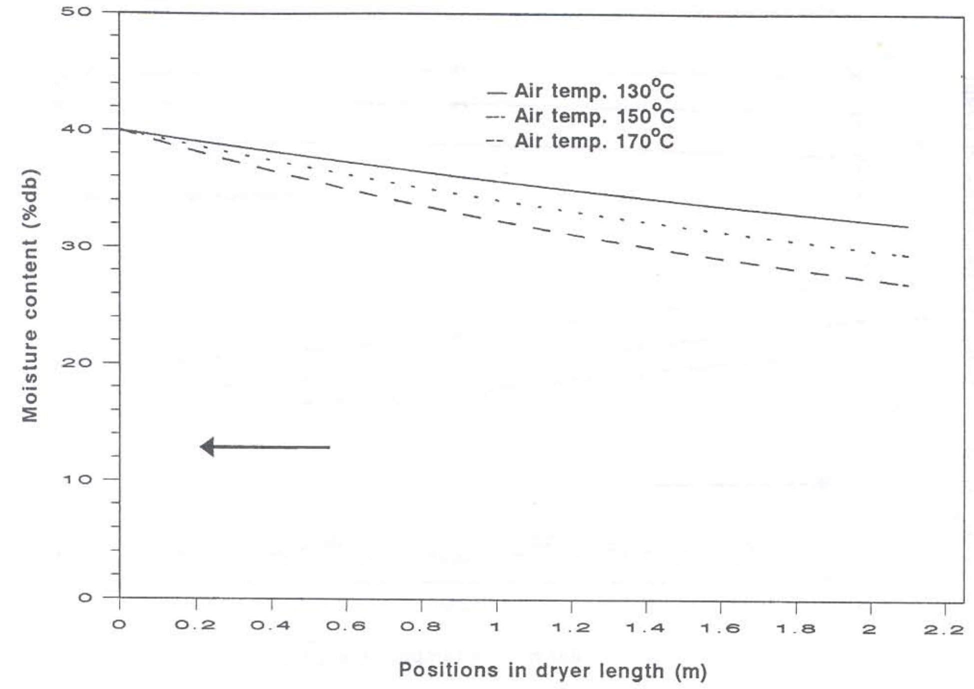


Fig. 4. Effects of inlet hot air temperature on moisture content (simulation) (Bed depth of 17cm, recycle ratio of 80%, feed rate of 3000 kg/hr and initial moisture content of 40%db).

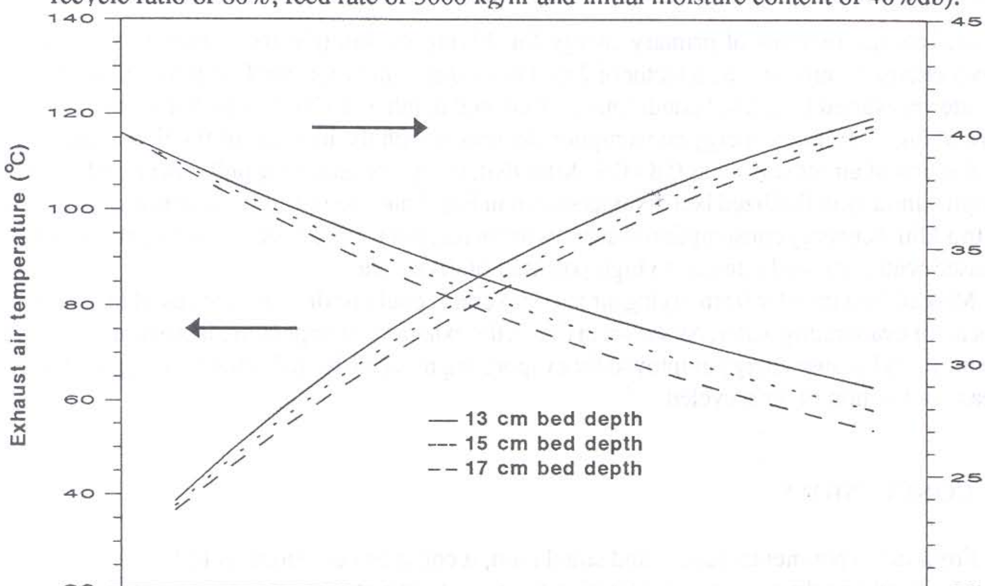


Fig. 5. Effects of bed depth on moisture content (simulation) (Feed rate of 3000 kg/h, inlet hot air temperature of 170 °C, recycle ratio of 80%, and initial moisture content of 40%db).

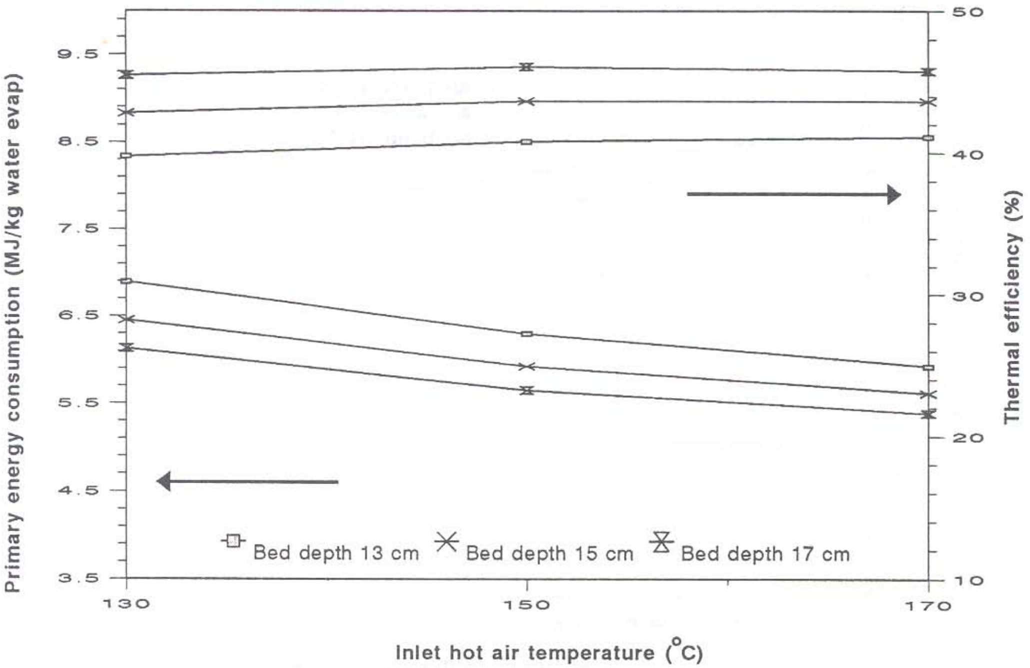


Fig. 6. Effect of air temperature and bed depth on primary consumption and thermal efficiency (simulation) (Feed rate of 3000 kg/h, recycle ratio of 80% and initial moisture content of 40% db).

electrical energy in terms of primary energy for driving the fan (electrical energy is converted to primary energy by multiplying a factor of 2.6). For further simulation, the fraction of air recycled and feed rate was varied by a fixed condition of 17 cm bed depth and 170 °C inlet hot air temperature as shown in Fig. 7. Primary energy consumption decreased with the increase of fraction of air recycled until fraction of air recycled was 0.8 - 0.9. After that, energy consumed rapidly increased because of too high humidity in fluidized bed dryer as shown in Fig. 8 and the resulting reduction of evaporation rate. In addition, energy consumption reduced with increase of feed rate because water evaporation rate increased with corn feed rate due to high potential of drying air.

Most of heat transfer from drying air to corn kernels could be divided into sensible heat for corn and heat for evaporating water. As shown in Fig. 9, the exhaust air temperature increased with fraction of air recycled because energy employed for evaporating reduced due to higher humidity in dryer with increase of fraction of air recycled.

5. CONCLUSIONS

From the experimental results and simulation, it could be concluded as follows:

1. Fluidized bed dryer was very effective for corn drying at high moisture content. In reducing moisture content from 18 % - 23 % dry-basis to 16 % - 19 % dry-basis and from higher than 28 % dry-basis to 19 % - 30 % dry-basis using inlet hot air temperature of 130 °C - 175 °C, the corn quality in terms of breakage and stress cracking was still maintained as compared to reference samples

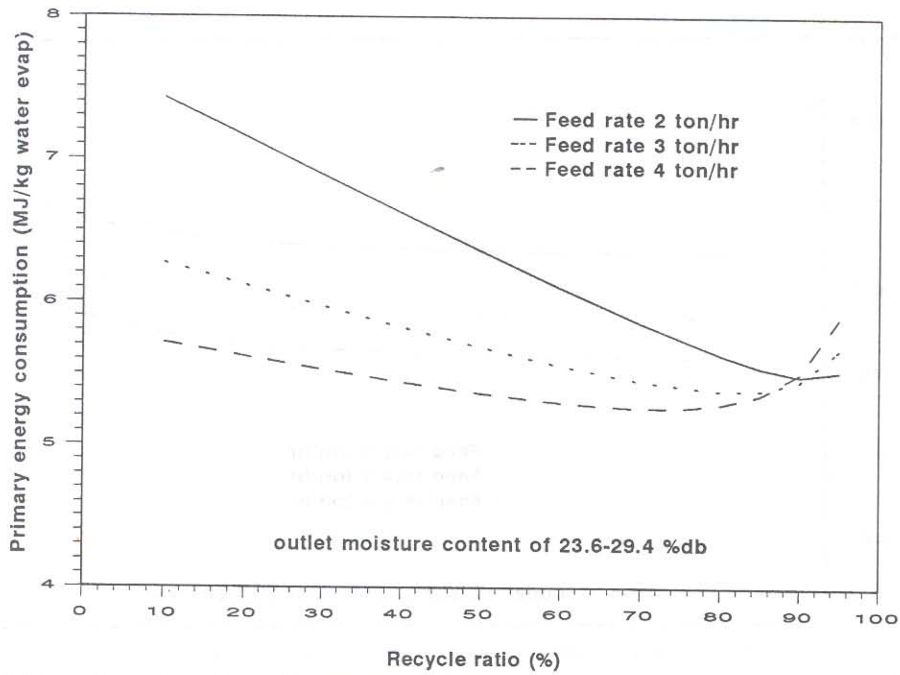


Fig. 7. Effect of recycle ratio and feed rate on primary energy consumption (simulation) (Bed depth of 17 cm, initial moisture content of 40%db and inlet hot air temperature of 170 °C).

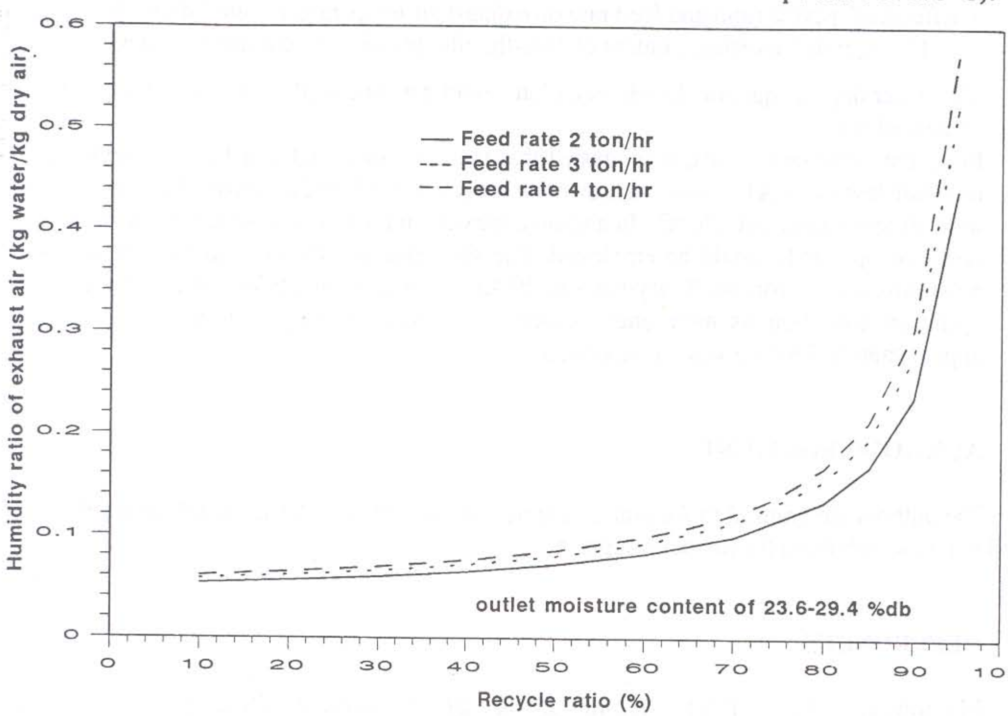


Fig. 8. Effects of recyle ratio and feed rate on humidity ratio of exhaust air (simulation) (Bed depth of 17 cm, initial moisture content of 40 % db and inlet hot air temperature of 170 °C).

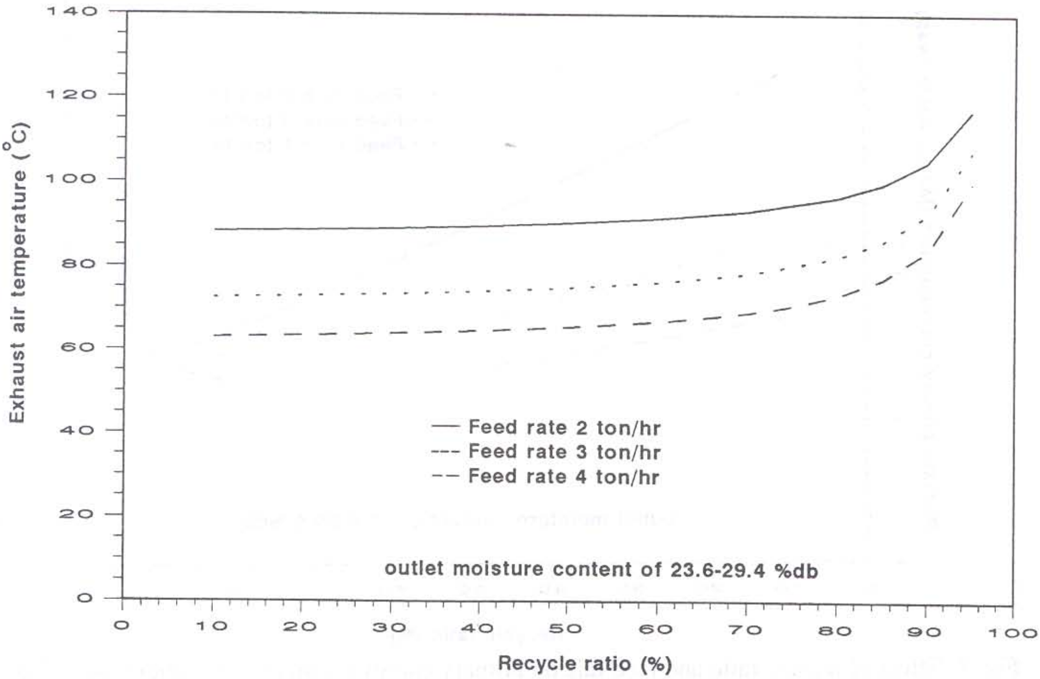


Fig. 9. Effects of recycle ratio and feed rate on exhaust air temperature (simulation)(Bed depth of 17 cm, initial moisture content of 40%db, inlet hot air temperature of 170 °C).

2. Thin layer drying equation, Lewis' equation, could describe well the results at high moisture content of corn.
3. From the simulated results, it suggested that the optimum condition for corn drying at high moisture level was as follows : fraction of air recycled of 0.8, bed depth of 17 cm and maximum inlet air temperature of 170 °C. In addition, maximum feed rate, at which fluidized bed dryer could be operated, should be employed. The simulated results were found that in reducing moisture content from 40 % dry-basis to 29.40 % dry-basis using feed rate of 4 tons/h at the optimum condition as mentioned before, minimized primary energy consumption was approximately 5 MJ/kg water evaporated.

6. ACKNOWLEDGMENT

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