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Study of Parameters Affecting Drying Kinetics and Quality of Corns

Somboon Wetchacama[1], Somchart Soponronnarit[1], Somkiat Prachayawarakorn[1], Adisak Pongpullponsak[1], Wuttitat Tuntiwetsa [2] and Suprarat Kositcharoeankul[3]

ABSTRACT

The objectives of this research are to investigate factors affecting on drying rate of high moisture corn at high temperature with fluidisation technique and to develop a mathematical model for predicting drying rate. There were three following steps of drying process: 1) rapid drying using fluidised bed dryer at inlet drying air temperature of 130-170°C, 2) corn tempered for period of 40-180 minutes under the same temperature as drying from the step 1 and 3) drying with ambient air. Drying kinetic shows the inlet air temperature and the specific airflow rate significantly affecting the drying rate. Amongst three semi-empirical drying equations (Wang and Singh, Page and Lewis), Page's equation provides the best prediction.

This study also aims to study the quality of corn dried in each step. Corn qualities in terms of *aflatoxin* content, percentages of breakage and stress crack, and colour change have been considered. Experimental results show that *aflatoxin* content in dried corn does not change. Breakage and cracking depend strongly on final moisture content and are relatively dependent to temperature. Tempering provides the improvement of colour while inlet air temperature has no effect.

Key words: drying kinetics, grain, quality

INTRODUCTION

One of the most important agricultural products in Thailand is corn. The need of corn in the feed mill and the other food industries tend to be increased considerably. Corn can be produced in two seasons. The first one is grown in the period from April-May to July-August-September, which falls in the rainy season. The second crop is started from July-August-September to October-November-December and harvested at the end of the rainy season. Since a very large amount of corn produces in the first crop, a serious problem of poor corn quality has been faced if corn could not be immediately dried. This is by virtue of the fact that fresh corn is usually harvested at moisture content more than 23% wet basis. The micro-organism already infecting the corn can grow up easily under conditions of such moisture levels coupled with a suitable water activity especially higher than 0.85 (Wongurai *et al.*, 1992). Most species found in corn are likely to *A.flavus and A.parasiticus.* Both moulds can yield the poison substances known as *aflatoxin B-1* within 2-8 days (Laecy *et al.*, 1986) if the environmental conditions are suitable. This substance causes seriously the cancer at different organs of human. Drying can contribute to corn quality since moisture content is the most significant

1 King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand.
2 Division of Plant Pathology Section and Microbiology, Department of Agriculture, Ministry of Agriculture and Co-operatives, Bangkok. 10900, Thailand.

factor affecting changes in quality of corn. Numerous approaches can be applied for reducing moisture content. Each method has the advantage and disadvantage. The use of ambient air is the simplest one. When corn with moisture content higher than 23% wet basis was dried by blowing the ambient air through the bulk of corn. It showed that after its moisture content reduced to the desired value of 14 % wet basis, the level of *aflatoxin B-1* significantly increased to 250 ppb while the amount of *aflatoxin B-1* at the beginning was nil (Prachayawarakorn *et al*., 1995). This technique seems to spend so long drying time that some amounts of corn were infected and hence the *aflatoxin* could be occurred. The artificial drying method would therefore be an appropriate choice because of rapid removal of moisture contents in the process.

There are many types of artificial dryer being used in grain industries, for example LSU dryer (LSU = Louisiana State University), cross-flow dryer, spouted bed dryer and fluidised bed dryer. The latter one is of the main interest in this work. By fluidised technique, grains are transformed into a like fluid after thoroughly mixed with a sufficiently high air velocity. Under the fluidised state, the drags force on the grain particles balance the gravitational force pulling on them. Therefore, the grains remain in a semi-suspended condition. This inherent phenomenon provides the main advantages over the other types of dryer. The intensively mixed solids throughout the bed provide almost uniform temperature and moisture content. High heat and mass transfer rates are possible because of very good contact between air and solid. Thus, at high moisture level, a large proportion of water concentrated near the surface of solid particles can be removed quickly whilst the small one existing deeply inside the kernel still remains and is extremely very difficult to vaporise it although the capable of drying air allows to be powerful. There are some workers studying the corn drying using the fluidised bed technique (*e.g*. Soponronnarit *et al*., 1997a). They investigated the factors affecting the drying rate and the quality. They reported that moisture movement inside the kernel was controlled by diffusion and constant drying rate period was absent. The inlet air temperature is strongly influence to moisture reduction whilst the air velocity and the bed depth become relatively significant factor. In addition, when the drying was proceeded successively, the physical change was virtually found. The amount of corn tracing the stress crack and the breakage significantly increased following with the increased temperature and the reduced moisture content whilst it did not change with air humidity (Soponronnarit *et al*., 1997b). So far, the colour was relatively changed of which the value of "a" representing red increased with the increase of temperature and of drying time whilst the value of "b" representing yellow decreased.

Such changes lead to a serious problem in that the micro-organism, then inducing the occurrence of toxin substances, can easily attack the broken or cracked corn. In addition to easy infection, such physical damage is also an important measure of quality in processing operations such as cereal and snack food measuring. This cause took us to explore the way of improving the dried corn quality. One of the common approaches that can be improved its quality is a tempering process. This process allows the reduced moisture gradient inside the grain and eventually the moisture concentration at local positions inside the corn kernel becomes relatively identical. Foster (1973) showed that tempering process could reduce the degree of stress cracking during artificial drying of corn. For the paddy drying, Steffe and Singh (1980) also concluded that the additional tempering stage in the drying process was able to sustain head rice yield as compared the conventional one where the paddy was dried in a single pass. Despite its importance to grain quality, the research works have been less interest to provide an important information of tempering time. This fact may be useful not only for grain quality improvement but also for energy consumption.

The objectives of this work are to explore the effect of tempering period on the corn quality in terms of colour, stress crack and breakagibility and the operating parameters such as temperature, bed depth and airflow rate affecting the removal of moisture content of corn. Its moisture content was eventually reduced to 14% wet basis in order to inhibit the growths of *A.flavus* and *A.parasiticus*.

MATERIALS AND METHODS

Corn was dried by a batch fluidised bed dryer mainly composed of a cylindrical shaped stainless chamber with a 20 cm diameter and a 140 cm height, as shown in Figure 1. In order to save economically energy consumption, some proportions of the exhausted air are recycled and then mixed with the fresh air. The mixed air after reheated with 4 element heaters, each of elements having 3 kW power (total 12 kW), is flowed through

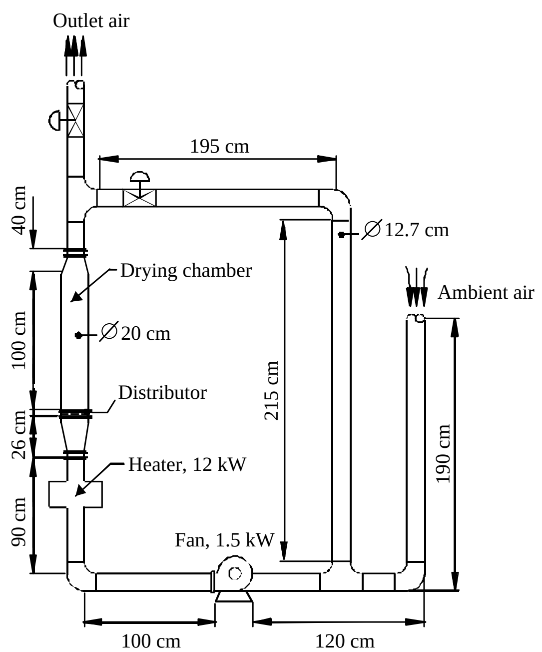

Figure 1 Schematic of experimental fluidized bed corn dryer.

the dryer again. A PID controller with an accuracy of ± 1°C was used to control the inlet temperature. In the fluidised bed system, it requires a high air flow rate and a high-pressure drop, so that a backward-curved blade centrifugal fan driven by a motor power of 1.5 kW was selected. In order to obtain a desired inlet air velocity and maintain performance of the system, a mechanical variable speed unit was chosen to control the revolution of fan.

Drying kinetics

Freshly harvested corn, type Suwan 1, was rewetted to obtain desired moisture content of 43% dry basis. The rewetted corn was then kept in a temperature-controlled room at 5-10°C for 5 or 7 days in order to get the uniform moisture content inside the grain kernel. The following rewetted corn was dried to moisture content of 23% wet basis. The experiments were carried out at the following conditions: inlet temperatures of 130, 150 and 170°C and bed depths of 4, 6 and 8 cm. The air velocity was kept at a constant value of 3 m/s throughout these experiments. This value is approximately 1.6 times higher than the minimum fluidisation velocity for corn of which the value was approximately 1.8 m/s (Soponronnarit *et al.*, 1997a). Such a value beyond the minimum velocity was certainly sure that every moist corn could rigorously mix with the drying air. The relatively similar moisture content throughout the bed is a consequent result. If the air velocity is set too high, then the corn is increasingly agitated due to the formation of large bubble size, detrimental effect on the interchange of heat and mass transfers between gas and solid phases. The samples drawn from the dryer in every minute were then kept in a hot air oven at a constant temperature of 103°C for 72 hours to determine the moisture content

Thin layer drying equations

Development of mathematical models to describe the drying of porous solids is of important topic in literature. Models are needed to enable process design and to minimise energy consumption and total costs subject to quality constraints. In the fluidisation technique, the sufficiently high air velocity provides the body of corns behaving like a liquid, so that at this stage the grains feel "weightless" and move randomly and severely within the bed. Every kernel is therefore suspended completely in the air. Such phenomenon results in the insignificant change of the air properties along the bed depth and the grain temperature increased rapidly and then approached to the inlet air temperature for a short period of time. So far, the moisture content at surface is reduced speedily and consequently equilibrated with the existing air. Under this condition, the theoretical diffusion model can explain the moisture transfer inside single kernel. Unfortunately, the theoretical model predicts inaccurately since the grain often has an irregular shape and the mechanism of moisture movement inside the grain has been being questioned. In practice, the empirical thin layer drying equation has therefore been applied. Three following forms of thin layer drying equation were proposed in this work. First, the Lewis' equation (1921) is given by

$$MR = \exp(-bt) \quad (1)$$

where b = drying constant depending on the operating parameter

t = drying time, min

$$MR = \text{moisture ratio} = \frac{M(t) - M_{eq}}{M_{in} - M_{eq}}$$

$M(t)$ = moisture content at time t

M_{in} = initial moisture content

M_{eq} = equilibrium moisture content

The equation (1), known as Newton's law of cooling, is assumed the negligible moisture gradient inside the grain kernel, indicating that the resistance of diffusion is insignificant. Wang and Singh (1978) was then simply modified equation (1) by adding one more drying constant. Wang and Singh's equation can then expressed as

$$MR = a \cdot \exp(-bt) \quad (2)$$

where a is drying constant similar to the constant b in equation (1). Finally, the purely empirical equation is demonstrated. Page's equation (1952) also expresses moisture ratio as a form of exponential function of drying as shown in equation (3),

$$MR = \exp(-bt^a) \quad (3)$$

Equation (3) is often described favourably the experimental data (Soponronnarit and Prachayawarakorn, 1994).

Drying constants determined from all these equations were analysed using the non-linear regression approach in the commercial package SPSS (Statistical Package for the Social Science). The equation to describe them is not based on the theoretical formulation. Simple or complex one may be chosen arbitrarily by fitting it with parameters influencing to drying rate such as specific airflow rate and temperature. Details will be discussed in the following section. However, the appropriate expressions proposed for *a* and *b* are given by

$$a = A_1+A_2T+A_3S_P+A_4T.S_P+A_5In(S_P) \quad (4)$$

$$b = B_1+B_2T+B_3S_P+B_4T.S_P+B_5In(S_P) \quad (5)$$

where A_1-A_5 and B_1-B_5 = constant

T = inlet air temperature

S_p = specific air flow rate

Quality test

The successful or failure in drying process can be justified from the grain quality obtained. The criterion for considering the grain quality in each species is very different. However, for corn, one of the most important qualities that market is often used is the amount of *aflatoxin* B-1 in corn, besides breakage, stress crack and colour. Four quality aspects for examples *aflatoxin*, breakage and stress crack were therefore subject to consider in this work. The amount of *aflatoxin* was detected by using HPLC with the corn sample of 50 g. In each condition, three samples were tested. One-way analysis of variance (ANOVA) was performed to examine whether the amount of *aflatoxin* before and after drying in each stage is changed or not by using 95% confident level.

For the stress crack and the breakage, the visual inspection under light was employed with 200 g of corn sample. Each kernel was classified into three classes: broken, cracked (multiple and single) and undamaged. The percentage for each class was normalised by dividing the weight of corn kernel in each category by the total weight. Multiple cracking was often found in this work. A colour meter, Juki JP 7100p, determines grain surface colour. The values of a, b and L in Hunter system corresponding to red, yellow and lightness, respectively were read. The corn samples after final drying stage were checked carefully the above mentioned qualities.

In testing quality, after the corn was dried to 23% dry basis, it was then tempered in an airtight container for periods of 40, 120 and 180 minutes respectively under the same inlet air temperature. Finally, the corn was dried again using ambient air until the moisture content reached 16% dry basis. To obtain the accurate results, the experiment in each condition was three replicates.

RESULTS AND DISCUSSION

Effects of parameter on drying rate

The inlet air temperatures used in this experiment as shown in Figure 2 are very high compared to other techniques that are normally operated at temperatures between 50°C and 70°C for drying grains. This may have crossed the minds of many scientists and innovators, but Soponronnarit and Prachayawarakorn (1994) showed that it was possible to dry grain at high temperature range without significant loss of grain quality if the drying process was controlled effectively. Figure 2 represents the influence of inlet air temperatures on the reduction of moisture ratio at 6 cm bed depth and 3 m/s air velocity indicating that faster moisture removal relates closely to higher inlet temperatures. This effect is increasingly important during the final period of drying at which the moisture content

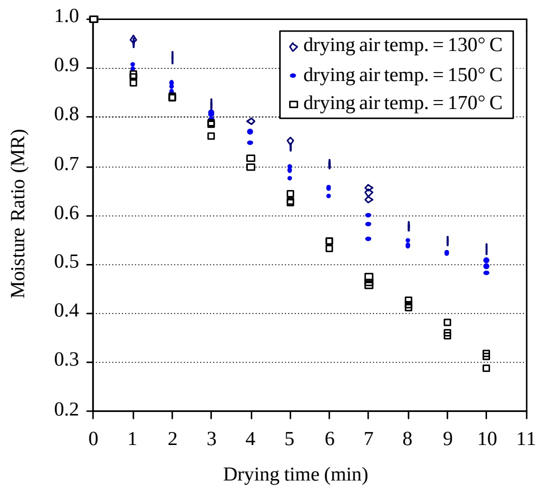

Figure 2 Effect of drying air temperature on moisture ratio (initial moisture content 43% d.b., drying air velocity 3 m/s and bed height 6 cm).

is rather low; more release of moisture content requires higher temperature difference between the solid and drying medium. As can be seen in Figure 2, the degree of moisture content at different temperatures starts remarkably different after 6 minutes whilst at the early period, the temperature is less important effect.

The drying rate is also relatively affected by the specific airflow rate, defined as the ratio of mass of drying air to dry mass of corn loaded into the chamber. As shown in Figure 3, moisture extraction relatively increases with the increase of specific airflow rate under the identical operating condition. In the configuration investigated, the quantity of corn in each case was different whilst the airflow rate was kept a constant value and the change in the amount of corn did not effect behaviour of fluidised corn. When corn was subjected to the drying air, some proportions of energy were transferred to the grains, resulting in some evaporation. By such a situation, the surrounding conditions inside the chamber were therefore changed with changing the amount of corn; the quantity of water vapour around the corn kernel directly related to the capacity of

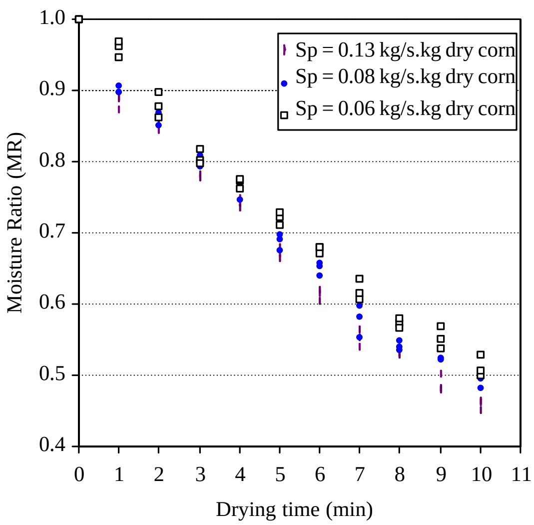

Figure 3 Effect of specific air flow rate (Sp) on moisture ratio (initial moisture content 43% d.b., drying air velocity 3 m/s and drying air temperature 150°C).

corn in the dryer. Hence, this effect results in drying rate.

Comparison of thin layer equations

Three thin layer-drying equations were used to validate the experimental data. The fitted data were obtained from the single pass of corn drying, starting from 43% dry basis until to 16% dry basis. All these equations can predict the moisture content insignificantly different at the beginning period of drying particularly higher moisture range of 23% dry basis as represented in Figure 4 whereas their predictions have a small difference near the end of drying period at which the moisture content is relatively low. Only Page's equation is found to yield the best fit to the experimental data. This may be because when the moisture content start reducing from such a high level to lower level, the large moisture gradient exists inside the corn, so that the equation (1) and (2) predict inaccurately.

Drying constants in those equations fitted statistically with the above-mentioned factors are thus given by the following equations:

Lewis's equation

$$b = 737 + 0.0006000T - 0.8420S_p + 0.003700T.S_p + 0.06590\ln(S_p) \quad (R^2 = 0.9778) \qquad (6)$$

Wang and Singh's equation

$$a = 0.3019 - 0.0002000T + 2.001S_p + 0.002000T.S_p - 0.2112\ln(S_p)$$

$$b = 0.09332 - 0.0005000T - 0.60888S_p + 0.003900T.S_p + 0.04171\ln(S_p) \quad (R^2 = 0.9782) \qquad (7)$$

Page's equation

$$a = -3.089 - 0.001000T + 2.703S_p + 0.1474T.S_p - 1.586\ln(S_p)$$

$$b = 0.6017 + 0.002100T - 0.07010S_p - 0.01790T.S_p + 0.2510\ln(S_p) \quad (R^2 = 0.9832) \qquad (8)$$

Based on the R^2 values, Page's equation is the most suitable equation that can describe the corn dying in the fluidised bed dryer. For the other conditions, the results also show similar trend to Figure 4.

Corn quality

In testing the corn quality, the experiments were performed at the conditions of 43% dry basis initial moisture content, 3.0 m/s air velocity, 8 cm bed depth and 170-180°C inlet air temperatures.

Aflatoxin

In testing the change of *aflatoxin* quantity by heat treatment, the corn samples were dried to 23 and 16% dry basis under the previously mentioned temperature range. One way-ANOVA shows that although the inlet temperature is increased, the *aflatoxin* is insignificantly changed in amount after completed the process of drying.

In fact, the *aflatoxin* could be removed by heat treatment (temperature of 250°C), at which it is the melting point (Feull, 1966). In contrast, Cucullu *et al*. (1966) reported that even though the

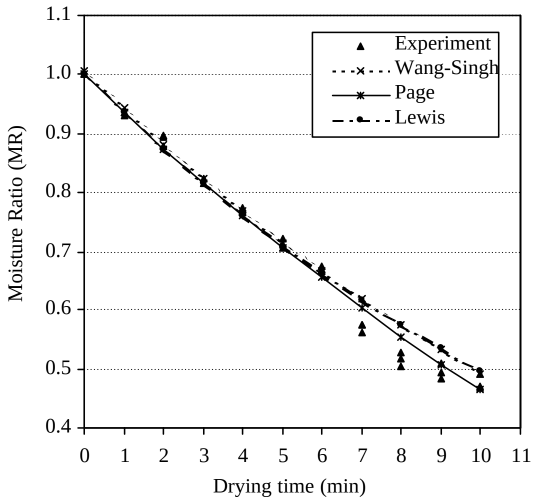

Figure 4 Comparison between thin layer drying equations and experimental results (initial moisture content 43% d.b., drying air velocity in drying chamber 3 m/s, bed height 4 cm and inlet air temperature 130°C).

temperature is not high enough to melt the *aflatoxin*, the quantity of the *aflatoxin* substance in peanut could possibly be reduced by roasting at a temperature of 150°C for 90 minutes. From that point of view, we tried exploring the heat treatment approach using the fluidised bed technique. But, corn can be not contacted with high drying air temperature for a long drying period due to the serious physical damage, as we will discuss in the following section. Thus, the corn was initially dried at temperature of 160°C and then followed with tempering for periods of 120 and 180 minutes under the corresponding temperature. The results still show the same trend as the previous ones, indicating invariable amount of *aflatoxin*. This is likely to treat the *aflatoxin* by such an approach ineffectively.

Breakageability and stress crack

Figure 5 shows the relationship between breakageability or stress crack and inlet temperatures under various final moisture levels. Major contribution of drying induced the stresses is the non-uniform moisture content. The stresses are tensional force near the boundary of dried material, so that they give the rise to the crack of dried body (Musielak, 2000). Refer to Figure 4, at the early stage of corn drying during which moisture content is higher than 19% wet basis, the moisture gradient inside the corn kernel expected to be very small, as indicated by Lewis's equation, so that such a small difference can not encourage the stresses. As a result of this, the percentage of stress crack is almost constant in spite of temperature increased as shown in Figure 5. In addition, the percentage of breakageability is not changed. When the corn was dried further and then approached to 14% wet basis, the percentage of stress crack increases to approximate 11.5% with respect to the previous one with showing value of 9.5% (see the cross symbol). The increase of stress cracking also contributes importantly to the breakagibility. The percentage of breakagibility in this case increases more than twice as compared to the one that corn dried to 19% wet basis. When using drying air at

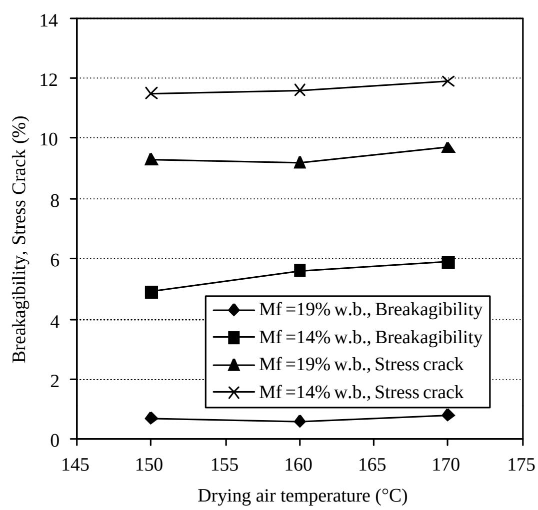

Figure 5 Influence of drying air temperature on the stress crack and breakage at difference final moisture contents, Mf (initial moisture content 30% w.b.).

170°C, the broken corn has a shape similar to the popcorn. From this figure, the temperatures seem to insignificant effect on the stress crack and the breakagibility for all cases whereas the moisture content plays an important role. Similarly, Peplinski *et al.* (1994) reported that the total number of kernel stress cracks did not change significantly over a wide range of drying temperatures.

However, the tempering period was then included between the drying stage by starting tempering since the corn was reduced to 23% dry basis. After that, it was dried to 14% wet basis with the ambient air. The corn quality is now improved. As shown in Figure 6, the number of cracked corn is relatively reduced following the increase of tempering time. By contrast, the percentage of breakagibility insignificantly changes despite the tempering time is increased with showing the value of approximate 5.5%. This value is almost exactly the same amount as the previous case that corn was dried to 14% wet basis shown in Figure 5. The explanation of this cause has not been cleared yet and it is subjected to more work being investigated.

Colour

Following previous work by Soponronnarit *et al.* (1997b) showed that a and b values changed with drying times and temperatures. In their work, the corn was dried continuously until its moisture content reached 16% dry basis. In order to improve the colours, the concept similar to the above-mentioned case was used, that is, the additional tempering period between drying stage. Figure 7 shows the evolution of a, b and L values with tempering periods at 160°C. The a values linearly increase with tempering time whilst b and L values monotonically decrease. At the tempering time more than 120 minutes, the tempered corn becomes much more intense colour than the normal level, related to the resulting change of a, b and L values. This result is similar to the work reported by Chotijukdikul (1997). On the contrary, the colour is acceptable at tempering period of 40 minutes. It was visually observed that the colours were insignificantly changed after the corn was tempered for period of 40 minutes in spite of the fact that before tempering, the corn dried at higher

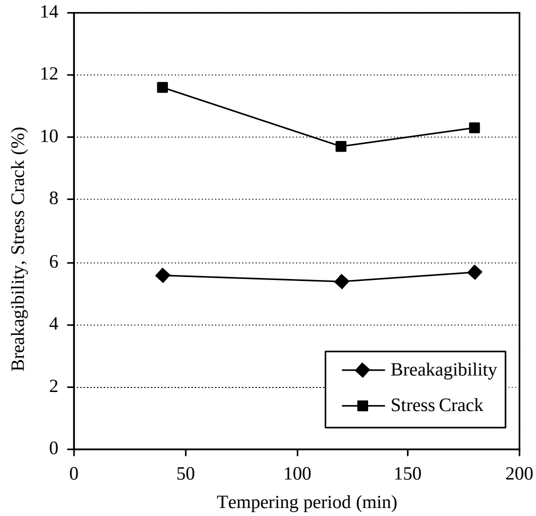

Figure 6 Effect of tempering periods on the breakage and stress crack (initial moisture content 30% w.b. and inlet air temperature 160°C).

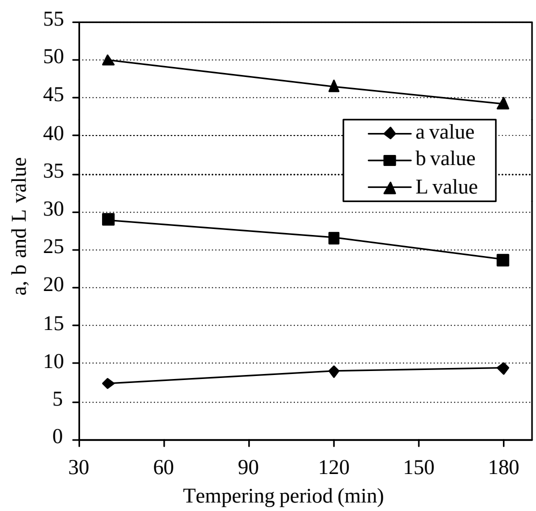

Figure 7 Effect of tempering periods on the value of a, b and L (initial moisture content 30% w.b. and inlet air temperature 160°C).

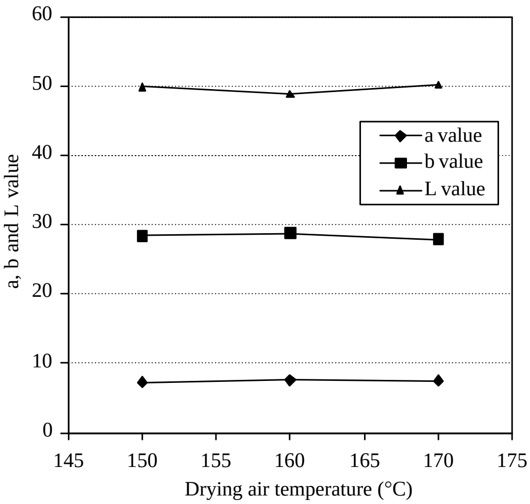

Figure 8 Effect of drying air temperature on the value of a, b and L (initial moisture content 30% w.b., final moisture content 19% w.b. and tempering period 40 minutes).

temperatures, resulting in lower moisture contents, had more intense colour. This can be seen in Figure 8 showing the values for a, b and L are all insignificant deviations with temperatures for the tempering period of 40 minutes. The explanation of such a cause may be because when the dried corn was subjected to temper in the airtight container only for a short period, some evaporation can occur, resulting in grain temperature reduced, and at the same time, the change of the colours cannot be transformed completely. The colours can, therefore, be recovered again. However, if it was corrected for a longer time, then the grain temperature increased and approached to a fixed temperature for tempering. Hence, the grain colours became poorer.

CONCLUSIONS

The results of this study can be concluded as the followings:

1) Specific airflow rate and inlet drying air temperature are important factors influencing drying rate of corn in fluidised bed dryer.

2) Amongst three popular thin layer equations, Page's equation is the most suitable equation predicting in agreement with the experiments.

3) The fluidised bed drying technique can inhibit the increase of *aflatoxin* level. With this technique, the *aflatoxin* is not enabled to destroy by heat treatment although the temperature range used is very high.

4) Final moisture content of corn is a main effect on breakagibility and stress crack whilst inlet air temperature is a less significant factor. Over range of high temperature, the corn should not be dried to 14% wet basis in a single pass. Tempering is recommended for corn drying.

5) Tempering period in drying process play a key role in improving the corn colours in terms of a, b and L values.

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