Evaluation of Thin-layer Models for Kinetic Analysis in Unbleached Kraft Pulpboard Drying

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ABSTRACT: *The drying characteristics of unbleached Kraft pulpboard have been studied in convective drying equipment under different hot air temperatures and velocities. In this work, the drying experiments were conducted in the range of 80-100℃ and 1.87-2.48m/s, respectively. The results indicated that high air temperature and velocity are beneficial to increasing drying rate and decreasing drying time. Ten thin-layer drying models were evaluated to describe the drying kinetic of unbleached Kraft pulpboard for its suitability. Based on the statistical analysis, the Yun model could predict the pulpboard drying kinetic better than others in terms of fitting performance. Through calculation and fitting, the effective moisture diffusivity varied from* 2.077×10^{-10} *to* $3.631\times10^{-10}\,m^2/s$ *over the investigated temperature range and the average activation energy for moisture diffusion was 22.818kJ/mol.*

KEYWORDS: *Thin-layer model; Drying characteristics; Convective; Kinetic; Pulpboard.*

INTRODUCTION

Pulp is an important raw material for manufacturing paper, paperboard, and paper-based materials. It is usually made from plant fiber by chemical or mechanical processing methods to formulate a thin layer of fibrous material [1]. In 2019, pulp production was 72.07 million tons in China, among which 17.6% was wood pulp, 8.2% was non-wood pulp, and the remaining was recycled paper pulp [2]. For this 17.6% of wood pulp, drying is usually required to evaporate water from wet pulpboard for producing market pulp. In the drying process, a reasonable drying method and drying condition not only reduces energy consumption but also facilitates the design of drying equipment. The pulpboard that is made from non-wood fibers, e.g.: bleached alfa pulpboard and unbleached bulrush pulpboard [3, 4], also needs to be dried from manufacturing other paper-based products. Generally, the methods for drying pulpboard mainly include hot air convective drying, flash drying, and steam drying. The bleached alfa pulpboard was reported to be dried with a series of steam-heated cylinders [1]. However, hot air convective drying is widely used because of its high drying efficiency, simple equipment, and controllable drying conditions [5].

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Yun et al. [6] used hot air convection to dry the oil palm frond fibers and proposed a new model, which showed a high degree of fit. *Khamtree et al.* [7] proposed an indirect measurement technique for the moisture content during hot air drying of the rubberwood. It provided a good accuracy to achieve an alternative moisture content monitoring method for potential adoption by the rubberwood industries. *Fernando et al.* [8] proposed a mathematical model to describe the effects of hot air velocity, temperature, and particle size for the wood chip-packed bed drying process. *Kirsch et al.* [9] presented the manufacturing of wood fiber insulation boards by using the dry process and an innovative curing method combining hot air and hot steam, and the result reveals the positive physical effects of using hot air and steam in combination with the curing of pressure-resistant insulation wood fiber boards. The hot air temperature and velocity are the most important parameters that could affect drying characteristics and energy used during the commercial pulpboard drying process.

Hot air is acted as the medium for heat and mass transfer in traditional convective drying equipment [10]. In order to better understand the control parameters of this coupled transfer process, many theoretical and empirical thin-layer models were proposed to describe this process. *Liu et al.* [11] studied the effects of hot air temperature, velocity, and pulp molding thickness on the drying characteristics of pulp molding, and used the Logarithmic model to describe the pulp molding drying process. *Zhang* [12] studied the drying characteristics of molded pulp products and found that the Page model was the most suitable model to describe the pulp molding drying process. *Motta Lima et al.* [13] studied the difference between natural and forced convective drying of paper sheets, and successfully described the generalized drying rate curve by Hodges model. These studies provided a theoretical basis for studying the drying characteristics of pulp and paper products. However, there are few researchers have used drying kinetics to study the drying characteristic of pulp boards.

The objective of this work was to evaluate the thin-layer drying models describing the pulpboard drying kinetics based on the statistical analysis method. Ten well-known thin-layer drying models were used to describe the drying kinetics of the pulpboard. In addition, the effects of hot air temperature and velocity on the drying characteristics were studied. The effective moisture diffusivity and activation energy were also determined.

THEORETICAL SECTION

When the moisture transport during the pulpboard dehydration process mainly takes place in the falling rate period and the driving force is primarily controlled by the mechanism of liquid and vapor diffusion, the mathematical model of thin-layer drying could be used to describe the drying process [14, 15]. The thin-layer drying mathematical models include theoretical models, semi-theoretical models, and empirical models [16]. Among them, the calculation process of theoretical models is the most complicated, and the empirical model is derived from experimental results.

The theoretical model is based on Fick's second law of diffusion. Assuming the wet material is uniform and isotropic, the flow resistance of moisture is uniform in the material, the effective moisture diffusivity (*D*) is independent of the local moisture content, and the volume shrinkage is negligible [17]. Fick's second law of diffusion can be derived as follows:

$$\frac{\partial \mathrm{MR}}{\partial t} = D\frac{\partial^2 \mathrm{MR}}{\partial x^2} \tag{1}$$

Where t is the drying time (min), x is the diffusion distance along the thickness of pulpboard (m), D is the effective moisture diffusivity (m^2/s), and MR is the dimensionless moisture ratio of pulpboard, which can be expressed as follows:

$$\mathrm{MR} = \frac{X_t - X_e}{X_0 - X_e} \tag{2}$$

Where X_t is the moisture content at time t (g water/g fiber), X_0 is the initial moisture content (g water/g fiber), X_e is the equilibrium moisture content of the pulpboard (g water/g fiber).

Assumed internal mass transfer is the control mechanism and moisture transport in an infinite slab. *Crank* [18] gave the mathematical solution of Eq. (1) and expressed it as Eq. (3). It was proved that when the drying time was long enough, the terms after the two-term of Eq. (3) could be ignored and the first term could give a good estimation, as expressed in Eq. (4).

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2 D}{\delta^2}t\right] \quad (3)$$

$$MR=\frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D}{\delta^2}t\right) \quad (4)$$

where δ is the thickness of the dried pulpboard (m).

The drying rate (DR) of the pulpboard is defined as the differential of moisture content between the time interval and calculated by Eq. (5).

$$DR=\frac{dX}{dt} \quad (5)$$

Henderson and Pabis [19] simplified Eq. (4) based on the thin-layer dry moisture diffusion theory, which can be derived as follows:

$$MR=a\exp(-kt) \quad (6)$$

where a and k are empirical constants.

Sharaf-Eldeen et al. [20] selected the two-terms form of Eq. (3) to predict the drying rate of shelled corn fully exposed to air, which can be derived as follows:

$$MR=a\exp(-k_1 t)+b\exp(-k_2 t) \quad (7)$$

where a, b, k_1, and k_2 are empirical constants.

In order to emphasize that $MR = 1$ at $t = 0$ in the two-term model, the coefficient ‘b’ is modified to ‘$1\text{-}a$’, which can be derived as follows[21]:

$$MR=a\exp(-kt)+(1-a)\exp(-kbt) \quad (8)$$

Equation (8) is the approach of the diffusion model, where a, b and k are empirical constants.

Chandra and Singh [22] added a constant term on the basis of Eq. (6) to form the Logarithmic model, which can be derived as follows:

$$MR=a\exp(-kt)+b \quad (9)$$

where a, b, and k are empirical constants.

Midilli et al. [23]. added linear terms to Henderson and Pabis's model to form a new model, which can be derived as follows:

$$MR=\exp\left(-kt^n\right)+bt \quad (10)$$

Eq. (10) is the Midilli model, where a, b, n, and k are empirical constants. This model has four model constants and is found to be the best model at a high ratio by researchers.

The Lewis model is a special case of the Henderson and Pabis model, where intercept is unity. Lewis described that the moisture transfer from the materials is similar to the law of heat transfer from a body immersed in the cold fluid. By comparing this phenomenon with Newton's law of cooling, the drying rate is proportional to the difference between the actual moisture content and the equilibrium moisture content, which can be derived as follows [24]:

$$-\frac{dX}{dt}=k\left(X-X_e\right) \quad (11)$$

where X is the moisture content of the pulpboard at time t (g water/g fiber), X_e is the equilibrium moisture content of the pulpboard (g water/g fiber), k is the kinetic constant. Assuming the internal resistance of moisture movement and moisture gradients within the material are negligible. It considers the surface resistance, and the boundary condition is $X = X_0$ at $t = 0$, then Eq. (11) can be derived as follows:

$$MR=\exp(-kt) \quad (12)$$

where k is the kinetic constant. The Lewis model has only one empirical constant and is the simplest thin-layer mathematical model.

Page [25] added a dimensionless constant n to the Lewis model, which gives better prediction results of moisture loss in the early and late stages of drying.

$$MR=\exp\left(-kt^n\right) \quad (13)$$

where n is the empirical constant.

In order to clarify the meaning of each parameter in the model and improve the adaptability of the model, *Weibull* [26] first proposed the Weibull model, which can be derived as follows:

$$MR=\exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad (14)$$

Table 1: Mathematical models of the thin-layer drying.

Model name	Model equation	References
Henderson and Pabis	$MR = a\exp(-kt)$	[19]
Two-term	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$	[20]
Approach of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[21]
Logarithmic	$MR = a\exp(-kt) + b$	[22]
Midilli	$MR = \exp(-kt^n) + bt$	[23]
Lewis	$MR = \exp(-kt)$	[24]
Page	$MR = \exp(-kt^n)$	[25]
Weibull	$MR = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$	[26]
Yun	$MR = \frac{a+bt+ct^2}{1+dt+ft^2}$	[6]
Gaussian	$MR = a\exp\left[-\left(\frac{t-b}{c}\right)^2\right]$	[28]

where α is the scale parameter (min), which represents the rate constant during the drying process. α is approximately equal to the time required for the pulpboard to remove 63% of the moisture during the drying process. β is a shape parameter, and its value is related to the shape of the drying curve during drying [27].

The Gaussian model, as expressed in Eq. (15), has also been used to describe the drying process of some materials [28, 29].

$$MR = a\exp\left(-\left(\frac{t-b}{c}\right)^2\right) \tag{15}$$

where *a*, *b* and *c* are empirical constants.

Besides, we also referred to *Yun et al.* [6]. Because the authors proposed a better new model and demonstrated its goodness of fit among other drying models. The Yun model was presented below.

$$MR = \frac{a+bt+ct^2}{1+dt+ft^2} \tag{16}$$

where *a*, *b*, *c*, *d* and *f* are empirical constants.

Table 1 also presented the aforementioned ten mathematical models of the thin-layer drying to be used in the data fit analysis of this work.

EXPERIMENTAL SECTION

Materials

The raw materials used in this study were unbleached Kraft pulpboard from Canada, with the basis weight about 780 g/m^2. The equilibrium moisture content is 5.4% under the experimental condition. In order to facilitate the drying experiment, the original large-sized pulpboard was cut into small size with a dimension of 80 mm×80 mm. The sample weight is 5 g. After infiltrating a certain amount of water uniformly, the pulpboard samples with an initial moisture content of about 70% will be dried in the drying experiments. The physical image of the unbleached Kraft pulpboard material before and after the drying experiment is shown in Fig. 1.

Fig. 1: The physical image of the unbleached Kraft pulpboard.

Experimental method

The real image and schematic diagram of the convective drying equipment are shown in Fig. 2. The air entered the experimental equipment through 3 (Inlet valve), and the power was supplied by 4 (Blower). The air velocity was controlled by 5 (Control valve). After being heated by 8 (Electrical heater), it was sent to 9 (Drying chamber: section size ≥140×200mm). The velocity and temperature of the air were measured by 6 (Orifice flowmeter) and 7 (Inlet thermometer). The temperature of the drying chamber was measured by 10 (Wet-bulb thermometer) and 11 (Dry-bulb thermometer). The weight of pulpboard was weighed by electronic balance. A part of the dried exhaust gas was discharged through 1 (Exhaust valve), and the other was mixed with fresh air *via* 2 (Circulating valve) in order to recycle the exhaust.

In this work, selected hot air temperature and air velocity as experimental variables to analyze the drying characteristics of the pulpboard during the hot-air drying process. Before the start of the experiment, set experimental variables and ensured the consistency and stability of the external environment. When the system was stably operated for 5 minutes, the pulpboard was placed in 12 (Object stage) parallel to start the drying experiment. Since the weight of the dried pulpboard changed quickly at the beginning, for the first 10 minutes, took out the pulpboard quickly and put it into the electronic balance to record the weight of the pulpboard every 30 s, and then recorded every 60 seconds until the weight of the dried pulpboard remained substantially unchanged. Then, repeat the above experimental steps at different hot air temperature (80°C, 90°C, 100°C) and air velocity (1.87m/s, 2.00m/s, 2.48m/s) to obtain drying data of the pulpboard under different drying conditions.

Data analysis method

We use SPSS 21 software to fit the experiment values by the above-mentioned mathematical models and Origin 11 software to plot the drying curves. The coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (*RMSE*) were used to evaluate the goodness of fit of the tested models. The higher values of the coefficient of determination (R^2), and the lower values of the reduced chi-square (χ^2) and Root Mean Square Error (RMSE) indicate a high degree of fit and were chosen to fit the drying process of the pulpboard. These parameters can be calculated as (Eqs. (17)-(19)):

$$R^2 = 1 - \frac{\sum_1^N \left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_1^N \left(\overline{MR_{exp,i}} - MR_{pre,i}\right)^2} \tag{17}$$

$$\chi^2 = \frac{\sum_1^N \left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{18}$$

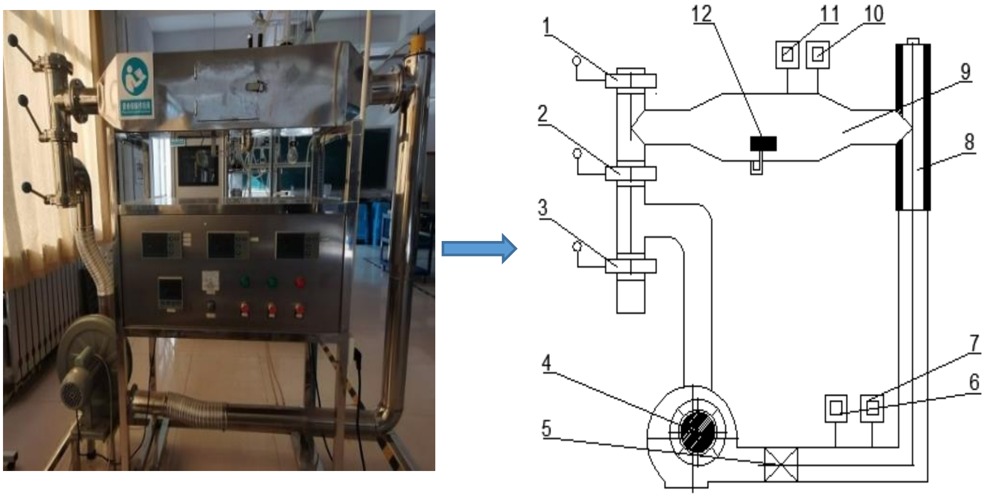
$$RMSE = \sqrt{\frac{\sum_1^N \left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \tag{19}$$

where MR_{exp} is the experimental moisture ratio, MR_{pre} is the predicted moisture ratio, *N* is the number of experimental measurements, *n* is the number of parameters in the regression model.

RESULTS AND DISCUSSION

Influence of air temperature on drying characteristics

The moisture content (*MR*) of the pulpboard under different drying air temperature levels is shown in Fig. 3. It can be observed with increasing of drying temperature, the drying time decreased and the drying rate increased in the drying process. The corresponding drying time decreased from 24 minutes to 17.5 minutes when the temperature rises from 80°C to 100°C under air velocity of 1.87m/s. This also can be observed that the hot air temperature has a positive effect on the pulpboard drying process under air velocity of



1-Exhaust valve, 2-Circulating valve, 3-Inlet valve, 4-Blower, 5-Control valve, 6-Orifice flowmeter，7-Inlet thermometer,
8-Electrical heater, 9—Drying chamber, 10-Wet-bulb thermometer, 11-Dry-bulb thermometer, 12-Object stage

Fig. 2: The real image and schematic diagram of the drying experiment equipment.

2.00m/s or 2.48m/s. The temperature provides driving force for moisture evaporation and affects liquid moisture viscosity. When the temperature increased, the temperature gradient for heat transfer in the pulpboard increased and liquid moisture viscosity decreased, which is beneficial for internal moisture migration and surface moisture evaporation. It leads to higher drying rates and shorter drying times for the pulpboard.

The drying rate of the pulpboard under different drying air temperature levels is shown in Fig. 4. There are two stages during the pulpboard drying process: the increasing rate drying period and the falling rate drying period. From the two sections, we can see that the temperature had less effect on the increasing rate drying period compared with the early falling rate drying period. We observed that the increasing rate drying period is shorter because the pulpboard is thin and the interior temperature of the pulpboard can quickly rise to the drying air temperature. Moreover, with the temperature increased, the drying time significantly decreased. It’s can be seen the corresponding maximum drying rate is increased from 0.16 to 0.24 g/(g·min) when the temperature is raised from 80°C to 100°C under an air velocity of 1.87m/s. In the early falling rate drying period, there are free water and bound water inside the pulpboard, the higher temperature led to a greater rate of evaporation and the drying rate. In the late of falling rate drying stage, because there is only bound water inside the pulpboard, the influence of drying temperature is no longer significant.

Influence of air velocity on drying characteristics

The moisture content of the pulpboard under different drying air velocity levels is shown in Fig. 5. It can be observed that increasing the air velocity is beneficial to decrease the drying time. This is due to enhance air velocity increased the convective heat transfer coefficient on the pulpboard surface, and improved the effect of convective mass transfer. In addition, we can see that the difference between the drying curves with air velocities of 2.48 m/s and 2.00 m/s is less than 1.87 m/s and 2.00 m/s under the same hot air temperature. It indicated that the effect of continuously increasing the air velocity on reducing the drying time will gradually decrease under the same drying condition. This is because the internal moisture migration rate determined the drying rate when the moisture content is low, which causes the improvement surface gasification conditions of the pulpboard didn’t reach the expected increase.

The drying rate of the pulpboard under different drying air velocity levels is shown in Fig. 6. It can be seen that there are also two drying periods. From the two periods, we found that the drying rate increased with the increase of air velocity, especially in the early falling rate drying period. It’s can be seen the corresponding maximum drying rate is increased from 0.15 to 0.20 g/(g·min) when the air velocity raised from

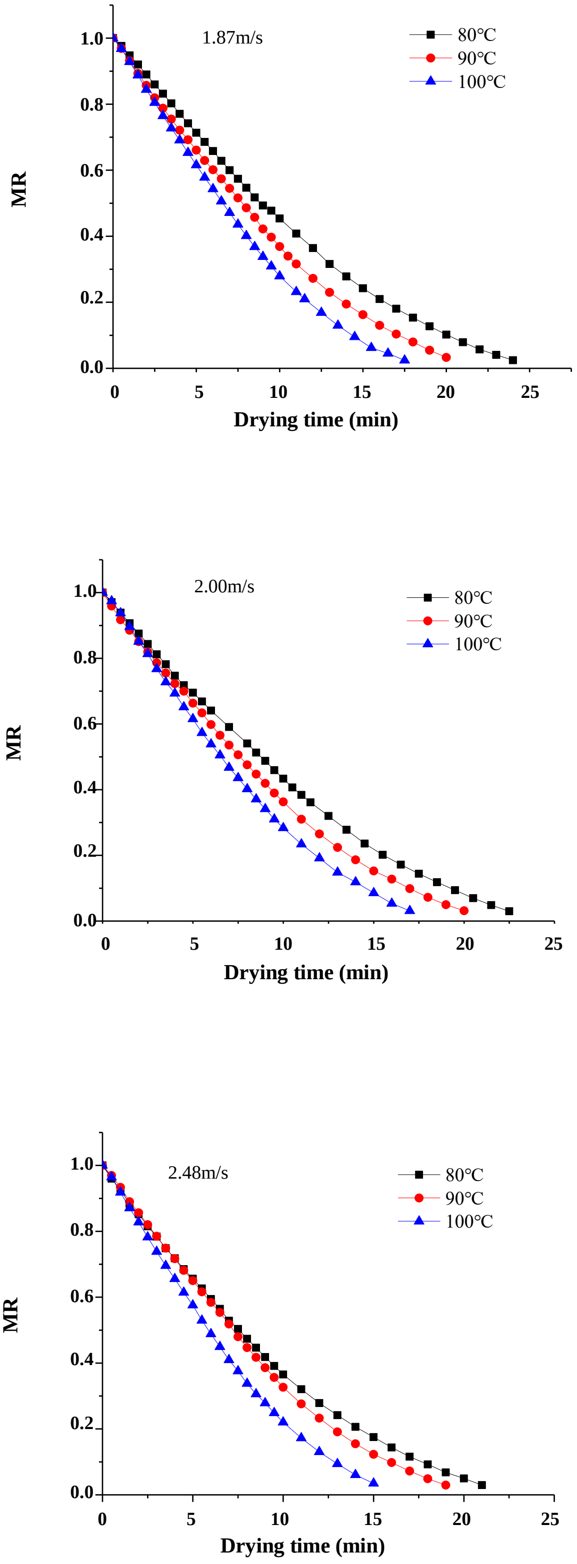


Fig. 3: Moisture content of the pulpboard under different air temperature levels.

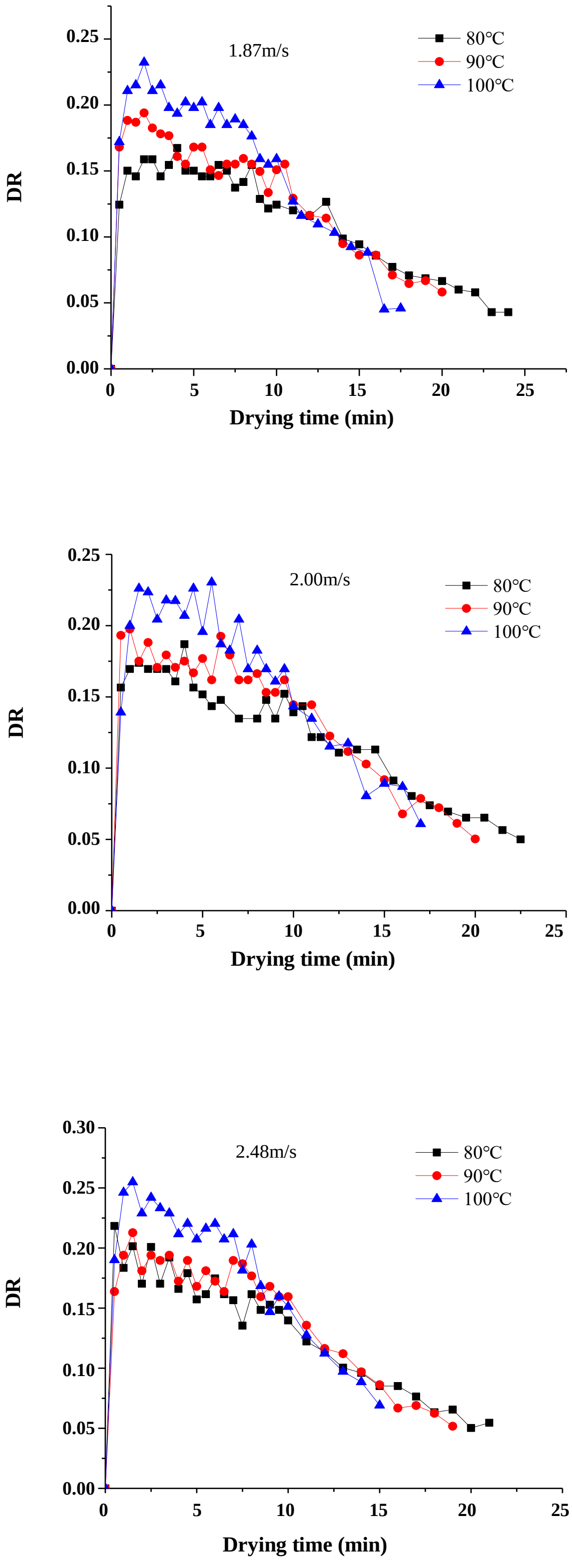


Fig. 4: Drying rate of the pulpboard under different air temperature levels.

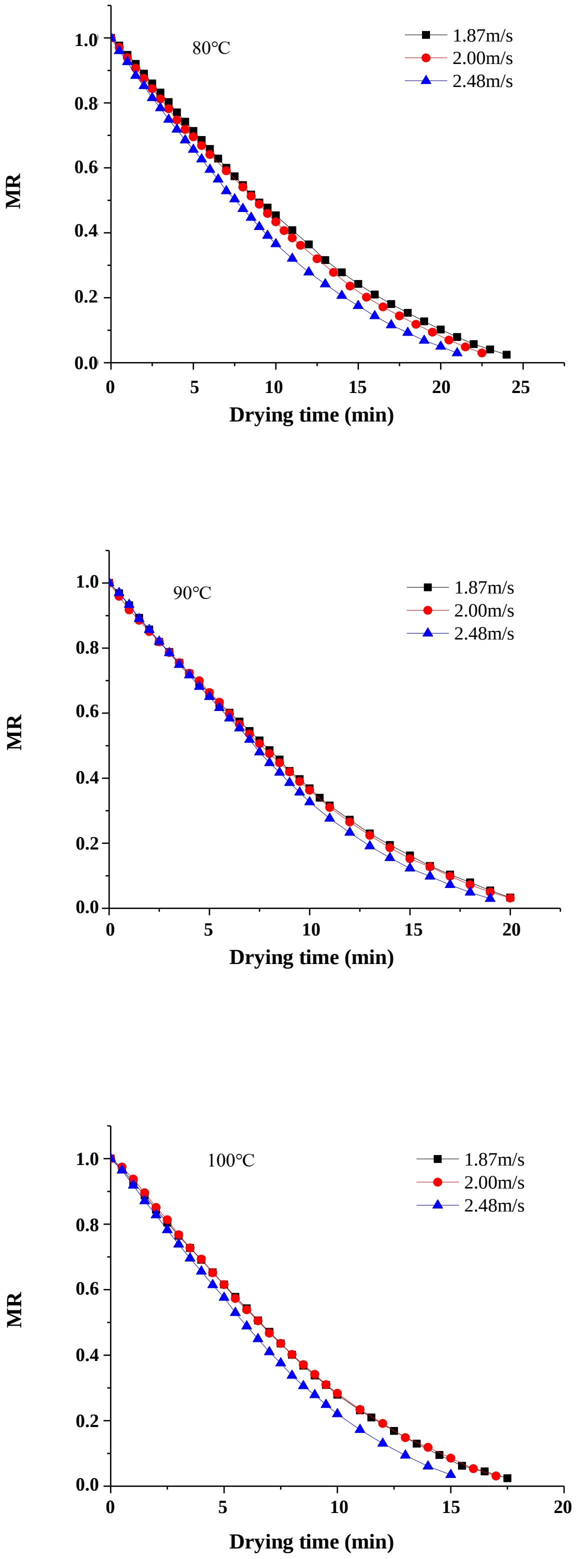


Fig. 5: Moisture content of the pulpboard under different air velocity levels.

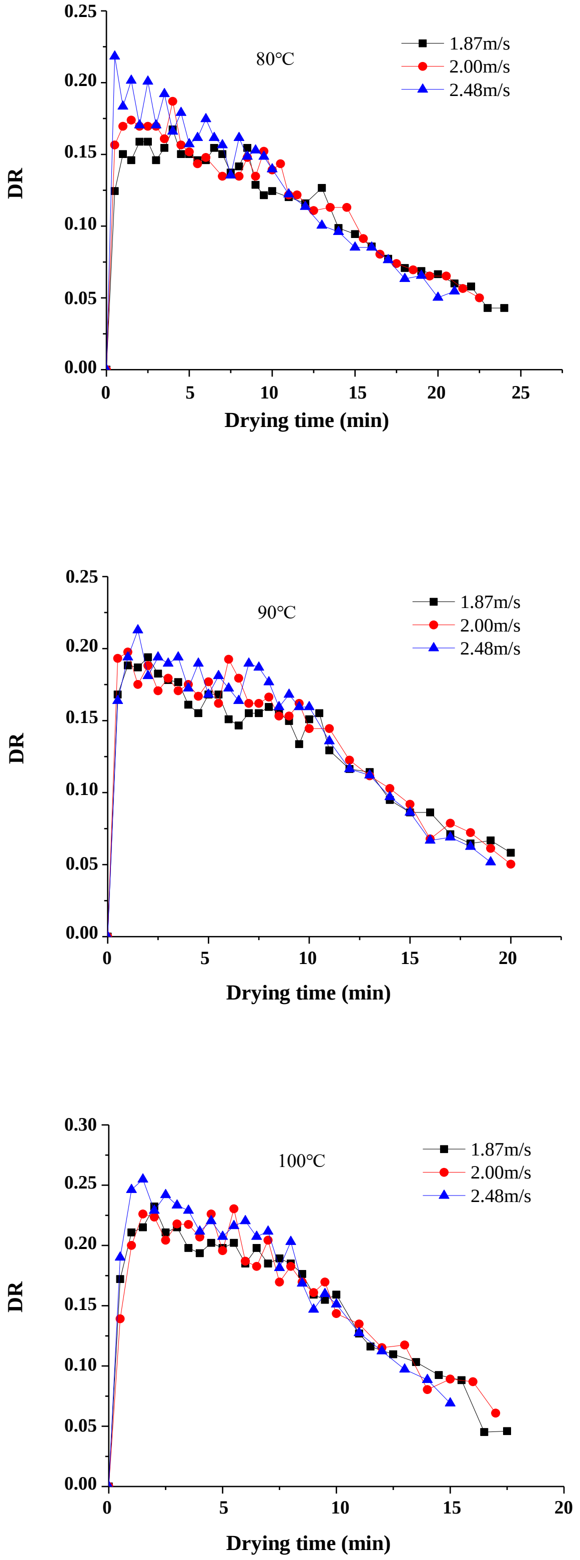


Fig. 6: Drying rate of the pulpboard under different air velocity levels.

Table 2: Statistical results obtained from the selected drying models.

Model name	Model constants	R^2	χ^2	RMSE
Henderson and Pabis	a=1.074 k=0.112	0.980 7	2.06×10^{-3}	0.044 3
Two-term	a=0.331 k_1=0.112 b=0.743 k_2=0.112	0.980 7	2.18×10^{-3}	0.044 1
Approach of diffusion	a=17.86 k=0.043 b=0.092	0.997 9	2.35×10^{-4}	0.014 7
Logarithmic	a=1.246 k=0.074 b=–0.223	0.997 9	2.35×10^{-4}	0.014 7
Midilli	a=0.979 k=0.052 n=1.249 b=–0.003	0.999 5	6.06×10^{-5}	0.007 4
Lewis	k=0.103	0.973 5	2.75×10^{-3}	0.051 7
Page	k=0.050 n=1.317	0.996 0	4.29×10^{-4}	0.021 0
Weibull	α=9.667 β=1.317	0.996 0	4.29×10^{-4}	0.021 0
Yun	a=0.998 b=0.001 c=-0.001 d=-0.075 f=0.001	0.999 8	1.29×10^{-5}	0.003 3
Gaussian	a=1.238 b=15.937 c=-7.66	0.998 9	1.18×10^{-4}	0.010 4

Table 3: Effective moisture diffusivity under different drying conditions.

Temperature (℃)	Air velocity (m/s)	Slope of Fitting Equation	Effective moisture diffusivity (m^2/s)
80	1.87	–0.123	2.077×10^{-10}
90	1.87	-0.144	2.432×10^{-10}
100	1.87	-0.186	3.141×10^{-10}
80	2.00	–0.130	2.094×10^{-10}
90	2.00	-0.152	2.567×10^{-10}
100	2.00	-0.193	3.259×10^{-10}
80	2.48	–0.152	2.567×10^{-10}
90	2.48	–0.171	2.888×10^{-10}
100	2.48	–0.215	3.631×10^{-10}

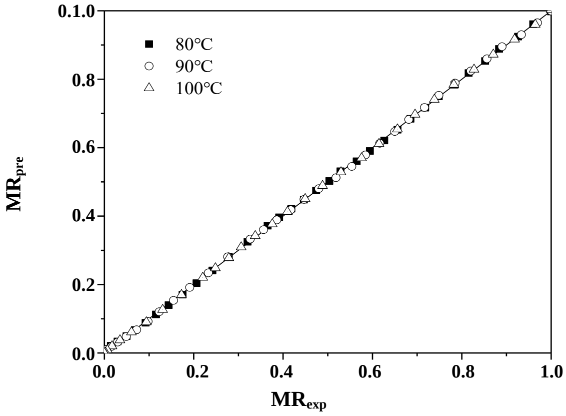


Fig. 7: Experimental and predicted moisture ratio of the Yun model.

1.87m/s to 2.48m/s under hot air temperatures of 80℃. It also can be observed the same phenomenon when the hot air temperature is 90℃ or 100℃. Moreover, we also found that the three curves gradually approached as increasing of hot air temperature under the same air velocity. It means that enhancing air velocity will not increase the drying rate effectively. This is because the surface of the pulpboard will be dried quickly at higher hot air temperature, which hinders the convective heat transfer on the surface of the pulpboard.

Drying kinetic model and verification

The mathematical models in Table1 are used to fit the drying kinetics of the unbleached pulpboard. The obtained statistical results under air temperature of 80°C and air velocity of 2.48m/s are shown in Table 2. Compared with the other nine mathematical models, the Yun model showed the best statistical results (R^2=0.9998, χ^2=1.29×10^{-5}, *RMSE*=0.0033). The same results have also been obtained under other drying conditions, which demonstrate that the Yun model could describe the drying process of the unbleached Kraft pulpboard more accurately. The experimental and predicted moisture ratio at different temperatures of the Yun model are shown in Fig. 7. It shows that the values obtained under three different experimental conditions are all around a straight line with a slope of 45°, which also indicates the good fitness of the Yun model.

Calculation of effective moisture diffusivity and activation energy

The effective moisture diffusivity reflects the comprehensive effects of the diffusion process in the drying process under the moisture concentration difference, the flow under the capillary pressure difference, the seepage under the pressure gradient, and the moisture migration caused by evaporation and condensation. Fick's second law can used to describe the drying process of pulpboard when the falling rate drying period is the main part of the drying process, and the moisture diffusion mechanism only considers liquid diffusion. Taking the logarithm of the simplified form of the analytic solution of Fick's second law (Eq. (4)), which can be derived as follows [14]:

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D}{\delta^2}t \tag{20}$$

where *MR* is the moisture ratio of the pulpboard, *D* is the effective moisture diffusivity of the pulpboard (m^2/s), *t* is the drying time (min).

Summarizing the experiment values of *MR* and *t* to fit the slope $-\pi^2 D/\delta^2$ of Eq. (20) by SPSS software. The values of effective moisture diffusivity (*D*) were calculated under different drying conditions and the results were shown in Table 3. It can be seen that the effective moisture diffusivity increases as the raising of air temperature and velocity. The maximum effective moisture diffusivity is 3.631×10^{-10} m^2/s at the temperature of 100°C and the air velocity of 2.48m/s, and the minimum effective moisture diffusivity is 2.077×10^{-10} m^2/s at 80°C and 1.78m/s.

The activation energy represents the energy required about evaporating a unit mass of water during the hot air drying process of the pulpboard. We also evaluated the difficulty and measure the energy consumption of the drying process by calculating the activation energy. Generally, the greater the activation energy, the more energy will be required. The value of activation energy is mainly related to the prosperity, composition, organization state, and geometry of the material. According to

Table 4: Diffusion constant and activation energy under different air velocities.

Air velocity (m/s)	D_0 (m^2/s)	E_a (kJ/mol)
1.87	6.434×10^{-7}	28.494
2.00	9.726×10^{-7}	29.873
2.48	2.208×10^{-7}	23.971

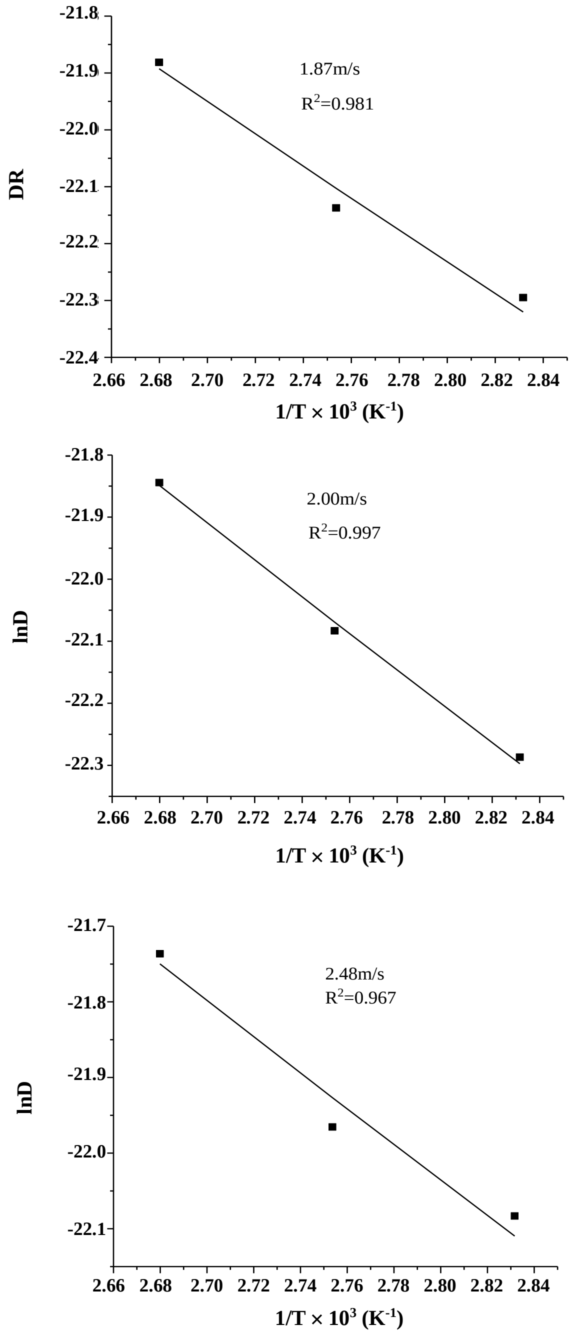


Fig. 8: The relationship of ln*D and 1/T under different air velocities.*

the Arrhenius equation [30], the relationship between the effective moisture diffusivity (*D*) and the temperature (*T*) can be derived as follows:

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{21}$$

where D_0 is the diffusion constant (m^2/s), E_a is the activation energy (kJ/mol), *R* is the universal gas constant (8.314J/(mol·K)), and *T* is the thermodynamic temperature (K).

The values of diffusion constant (D_0) and activation energy (E_a) under different air velocities are shown in Table 4. The average activation energy of the moisture diffusion was calculated to be 22.818 kJ/mol. Besides, we also find the effective diffusivity of the dried pulpboard (2.077×10^{-10}~3.631×10^{-10} m^2/s) is very close to the effective diffusivity of molded pulp (1.944×10^{-10} ~3.8667×10^{-10} m^2/s) obtained by *Liu et al.* [11]. Although the activation energy of the pulpboard in this work (22.818 kJ/mol) is a little higher than that of molded pulp (15.754 kJ/mol) obtained by *Zhang* [12], they are in the same magnitude order. Meanwhile, the relationship of ln*D* and 1/*T* under different hot air velocities is also presented in Fig. 8. It can be seen ln*D* and 1/*T* showed a higher linear relation from the regression results.

CONCLUSIONS

In this study, we selected temperature and air velocity as experimental variables to analyze the drying characteristics of unbleached Kraft pulpboard. Ten commonly used thin-layer models were employed to fit the drying kinetics. It can be seen that increasing the temperature and air velocity could effectively improve the drying rate, especially in the early falling rate drying period. From the fitting results, the *Yun* model provided the most accurate kinetic description during the unbleached pulpboard drying process, with a coefficient of determination of 0.9998. The values of effective moisture diffusivity ranged from 2.077×10^{-10} to 3.631×10^{-10} m^2/s, and increased with the raising of temperature and air velocity under different drying conditions. The average activation energy for moisture diffusion is 22.818 kJ/mol. It was also found that the effective diffusivity and activation energy of unbleached Kraft pulpboard in this work was in the same magnitude order as those obtained for molded pulp in the literature.

NOMENCLATURES

t	Drying time, min
x	Diffusion distance along the thickness, m
δ	Thickness, m
T	Drying temperature, ℃
MR	Moisture ratio
DR	Drying rate, g water/(g fiber·min)
X	Dry basis moisture content, g water/g fiber
D	Effective moisture diffusivity, m^2/s
D_0	Diffusion constant, m^2/s
E_a	Activation energy, kJ/mol
α	Scale parameter, min
B	Shape parameter
R	Universal gas constant, 8.314J/(mol·K)
N	Number of experimental measurements
R^2	Coefficient of determination
χ^2	Reduced chi-square
RMSE	Root mean square error
a、b、c、d、f、k、k_1、k_2、n	Empirical constant

Subscripts

E	Equilibrium
exp	Experimental
pre	Predicted

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