IMPACT OF THERMOMECHANICAL REFINING CONDITIONS ON FIBER QUALITY AND ENERGY CONSUMPTION BY MILL TRIAL

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Fiber thermomechanical refining is a critical step for the manufacturing of medium density fiberboard (MDF). To increase productivity and improve fiber quality with a reduction in energy consumption during refining, it is essential to determine appropriate refining conditions, such as the chips retention time (accumulated chip height, CH) in the pre-heater, feeding screw revolution speed (SR) in the chip feeding pipe, and the opening ratio of the discharge valve (OV) in the discharge pipe. Using multiple regression analysis, relationships between the response variables (the total fibers, the specific energy consumption obtained by the motor power consumption/the total amount of dry fibers, and the percentage of qualified fibers) and the predictor variables (OV, CH, and SR) were modeled. Specific energy consumption decreased with an increase in CH. When more chips were stored in the pre-heater, the chips were softened by the extended steam-treatment time, reducing the energy consumption. There were negative relationships between the percentage of qualified fibers and the predictor variables (OV and SR). It was reasoned that a greater proportion of coarse fibre was produced when the discharge valve opening ratio or the feeding screw speed increased. This resulted in a reduction in the percentage of qualified fibers. Due to the large sample size (1667 measurements for each variable) in this study, the resulting regression equations can be applied to estimate the productivity, energy consumption, and fiber quality during refining in an MDF mill.

Keywords: MDF; Thermomechanical refining; Fiber size; Productivity; Energy consumption; Multiple regression

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INTRODUCTION

With its dimensional stability, workability, flatness, smooth appearance, good bond strength, and screw-holding ability, medium density fiberboard (MDF) has become widely accepted by the furniture and interior decoration markets. During the production of MDF, the fiber thermomechanical refining process is placed high on the priority list in terms of product quality and energy cost.

Driven by the increase in energy cost, energy savings during fiber refining have drawn great interest. Over the past decades, a number of studies have been carried out to investigate the relationship between chip characteristics and energy consumption. A significant correlation between refining energy consumption and wood chip properties has been established (Eskelinen et al. 1982). Through measuring the impact energy absorption by using a pendulum tester, it has been shown that chip properties, including the transversal strength of the wood and the energy absorption of the chip in failure, are closely related to the fiber quality in mechanical pulping.

The refining energy consumption for Norway spruce was explored by Marton and Eskelinen (1982). The effects of specimen thickness, tester gap, temperature, specific gravity, and moisture content on the impact strength were examined. The results revealed that thicker chips consume more energy during fiber refining; however, the effect of softened chips on energy consumption was unclear.

In addition to its concerns about energy utilization, the MDF industry also has placed emphasis on fiber quality and the efficiency of the refiner. The size of the refined fiber plays an important role in board quality. The size reduction of chips during refining was studied by Strand and Mokvist (1989), from which a mathematical model describing the reduction of each chip size as a function of impact intensity and chip strength was developed based on the comminution theory.

Effects of refining conditions on the properties of MDF made from black spruce were investigated by Xing et al. (2007). The results indicated that the preheating retention time significantly affected both the modulus of rupture (MOR) and the modulus of elasticity (MOE), while the steam pressure significantly influenced the internal bond strength (IB), MOR, and MOE; however, it appeared that further work is needed to provide a more precise relationship between the fiber quality and the pre-heating retention time.

The influence of high defibration temperature on the properties of MDF made from laccase-treated hardwood fibers was examined (Widsten et al. 2003). With an increase in refining temperature, the reactivity of hardwood fibers during laccase-catalyzed oxidation was improved due to the progressive breakdown of the lignin polymer, rendering the substrate more amenable for interaction with laccase. The IB and thickness swelling properties of the boards were improved as the defibration temperature increased. If a higher pressure and temperature cannot be adjusted, extending the chip retention time in a pre-heater could be an option.

The effect of impact velocity on the fracture of wood during refining was examined by Berg (2001). Results showed that the size reduction of the chips during refining was dependent on the refining intensity and the chip strength, which was affected by the fracture mode, impact direction, chip dimension, temperature, rate of deformation, etc. A 50% increase in the impact strength was achieved by increasing the impact velocity from about 2.7 to 4.8 m/s. Although the revolution speed of the refining disc was not adjustable, chip defibration could benefit from softening the chips and extending the retention time.

Properties of MDF panels in relation to wood and fiber characteristics were investigated by Shi et al. (2006). The relationship of the board properties, such as MOR, MOE, IB, linear expansion, thickness swelling, water absorption, and fiber characteristics including wood density, and pH were studied using multiple linear regression based on laboratory experimental data. The tests showed that the MOE was negatively affected by the percentage of small particles (>200 mesh), which could be reasoned based on the likelihood that a large amount of lignin was broken into small particles during refining. Thus, it is desirable for fiber size to not be too small for producing panels with higher

MOE. IB negatively correlated with the fiber pH and positively correlated with the percentage of small particles (>200 mesh).

An energy model for MDF production was developed (Li et al. 2007). The thermal energy demand was estimated with input of annual production, operation hours, product grade, and fiber drying method; however, this model cannot be used to estimate the fiber quality and specific energy consumption during refining.

It was noticed that most previous studies on fiber thermomechanical refining were carried out on a laboratory scale, which may not fully represent the industrial manufacturing process. A mill trial incorporating the plantation poplar into wood chips (a mixture of larch and Masson pine) during fiber refining was completed (Hua et al. 2010). The results indicated that the incorporation of poplar played a favorable role in terms of fiber size and energy consumption. The higher the poplar content, the better the fiber quality, and the less energy was consumed, all due to the fact that poplar is softer than larch and Masson pine.

Based on data collected from a trial at a local MDF mill, the study herein was aimed at examining the influence of refining conditions, such as the chips retention time (accumulated chip height, CH) in the pre-heater, the feeding screw revolution speed (SR) in the chip feeding pipe, and the opening ratio of the discharge valve (OV) in the discharge pipe, on the energy consumption and fiber quality.

MATERIALS AND METHODS

The experiments were carried out at a local MDF mill with an annual production of 150,000 m^3 in Northern China. Having an average bark content of about 12%, a commonly used wood species mixture, Chinese poplar (*P. lasiocarpa Oliv.*) (about 24%) and various pine species (about 64%), were used in the experiments. The contents of the chips were examined once a day.

The 50-1 CP refiner (manufactured by Andritz) is shown in Fig. 1. The wood chips in the hopper were fed into the pre-heater (2) by a feeding screw. With an accuracy of ±0.1%FS, the steam pressure in the pre-heater was monitored by a gauge (1). Retention time was controlled by the height of the accumulated chips in the pre-heater. After steam-softening, the chips were discharged to the refiner through a feeding screw pipe (3) located under the pre-heater. The chips were defibrated in the 50″ refiner (5) with a rated power of 2,500 kW. Two 50SC020 refining disks with a tooth type of 50SA002 and a diameter of 1,270 mm were used for defibration at a revolution of 1,500 rpm. The fibers were unloaded through the discharge pipe (4) under steam pressure in the refiner. The amount of unloaded fibers was adjusted by the opening of a valve.

Typically, fiber quality after thermomechanical refining can be evaluated by fiber size, i.e. the screen mesh grades of the fibers. Large fibers would result in poor board appearance, while smaller fibers would reduce the strength of the boards (Shi et al. 2006). Although particles sized greater than 200-mesh were considered to be qualified fibers by Shi et al. (2006), this mill, based on its good practice in manufacturing, suggested that fiber size between a screen mesh of 20 to 120 to be appropriate for MDF. Fibers larger than 20 screen mesh needed to be further defibrated, while those smaller than 120 mesh were screened out, since they would result in a strength reduction for MDF boards. Apparently, additional energy consumption would result from unnecessary defibration.

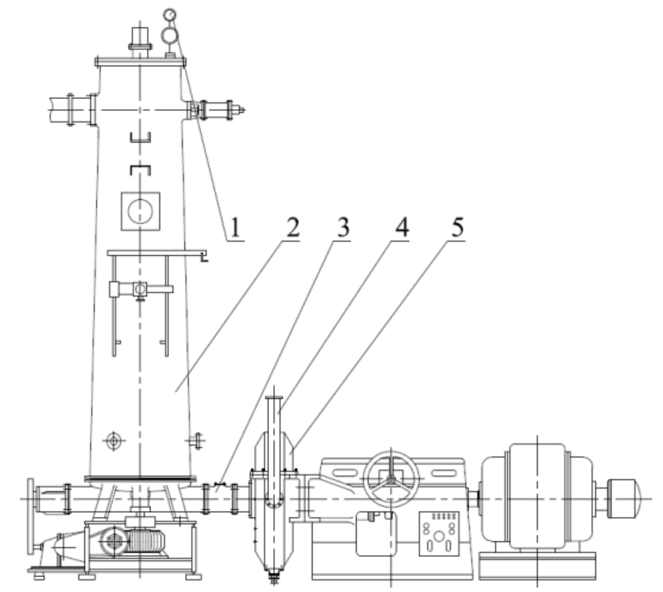

Fig. 1. The major components of the refiner: 1. Pressure meter of the pre-heater; 2. Pre-heater; 3. Feeding pipe; 4. Discharging pipe; and 5. Refiner

In fiber processing, productivity, energy consumption, and fiber quality are usually represented by determining the total amount of fibers (TF), the specific energy consumption (SEC, motor power consumption divided by total amount of dry fibers), and the amount of qualified fibers (QF), respectively. In this trial, for each measurement, about 10 grams of fibers was collected off the production line to determine the fibers sizes. Fibers with sizes between 20 to 120 screen mesh were considered to be QF. The percentage of the QF in the total amount of fibers collected was taken into account in the analysis.

All the data were measured and recorded hourly by sensors installed on the production line under normal production conditions. Although the gap between two disks in the refiner may vary with the amount of fibers produced, it was pre-set to 0.1 mm. The steam pressure at the entrance of the refiner remained constant during the trial. The measured (actual) steaming pressures normally varied with a mean value of 0.869 MPa and a standard deviation of 0.003 MPa (with a temperature average of 173°C and standard deviation of 24°C) during the pre-heating process.

Moisture content of the wood chips increased during washing and steaming; however, without any dilution water, a final moisture content of 50% was obtained due to the feeding screw squeezing the moisture from the chips in the feeding pipe. The total amount of fibers was estimated based on the screw revolution speed in the discharge pipe, the amount of fibers discharged per rotation, and the moisture content. The calculated TF values were on a dry basis.

In an attempt to examine the influence of thermomechanical refining conditions (CH in the pre-heater, SR in the chip feeding pipe, and OV in the discharge pipe) on TF, SEC, and QF, all the predictor and response variables were measured hourly. Among the predictor variables, CH ranged from 4.4 m to 5.9 m, SR varied from 40 rpm to 88 rpm, and OV fluctuated from 13.2% to 100%. A large sample size, 1,667 measurements for each variable, was used in this study.

It was hypothesized that the response variables (TF, SEC, and QF) during the refining could be empirically estimated by correlating the predictor variables (CH, SR, and OV). Multiple regression analysis was used in this study, from which the regression equations were directly applied to predict productivity, energy consumption, and fiber quality by mill personnel.

RESULTS AND DISCUSSION

Total Amount of Fibers (TF)

The average moisture content of the fibers was measured to be about 50%, of which the total fibers (TF) were expressed on a dry basis. The relationships of TF vs. OV and TF vs. SR are shown in Figs. 2 and 3, respectively. At the mill, the casing pressure of the refiner was un-adjustable during the production. The fiber production can increase by adjusting the discharge valve opening, while the steaming pressure may slightly vary due to the valve opening adjustment. As expected, the total fibers produced by the refiner increased with an increase in the opening ratio of the discharge valves, as shown in Fig. 2.

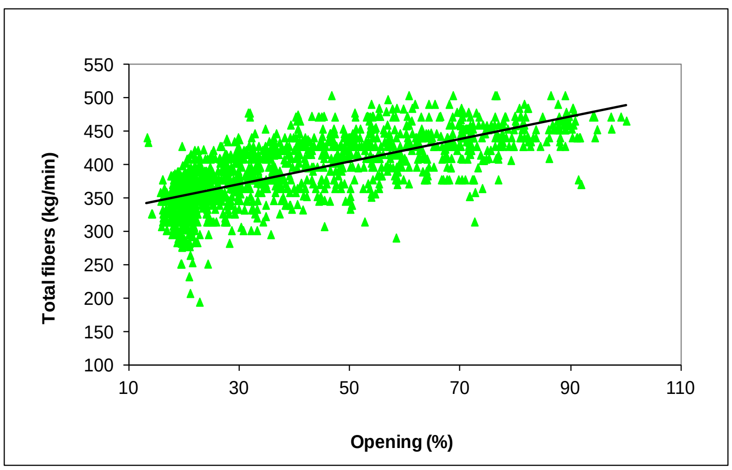

Fig. 2. The relationship between the total fibers and the valve opening

The feeding screw speed and the amount of chips fed is usually fixed for the fiber refiner in the mill. If the mill wants to increase fiber production over the capacity of the refiner, they may choose to increase the feeding screw revolution speed. Figure 3 shows that an increase in total fibers can be achieved by increasing the feeding screw revolution speed.

Although it is commonly expected that the amount of chips in the pre-heater does not affect the productivity, the additional chip softening from the extended steaming time probably has an influence on fiber production in the refiner. Thus, the variable of CH was taken into account for regression modeling.

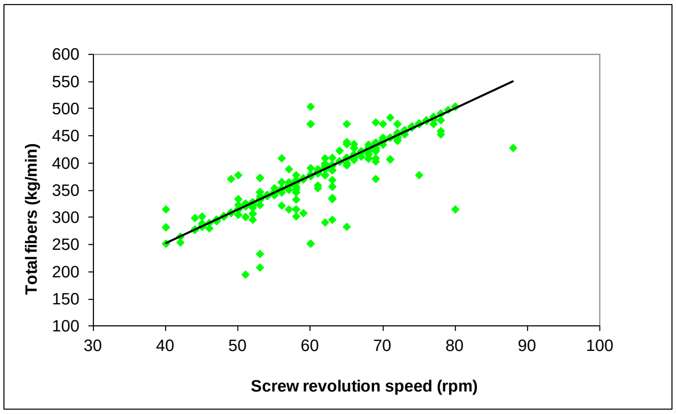

Fig. 3. The relationship between the total fibers and the feeding screw revolution speed

Using the NCSS software, the multiple regression model for TF can be obtained as follows,

$$TF = 28.7663 + 0.1571\ OV - 2.0480\ CH + 5.8869\ SR \quad (1)$$

$$R^2 = 0.9293$$

where TF is the total amount of fibers obtained from the refining (kg/min); OV is the opening ratio of valve in the discharge pipe (%); CH is the chip height in the pre-heater (m); and SR is the feeding screw revolution speed in the chip feeding pipe (rpm).

To evaluate the significances of predictor variables (OV, CH, and SR) on the total fibers, the regression analysis is presented in Table 1.

Table 1. Regression Analysis of the Total Amount of Fibers

Predictor Variable	Regression Coefficient	Standard Error	t-Value	P-value	Reject H0? (α=0.05)	Power of Test
Intercept	28.7663	6.1483	4.679	0.0000	Yes	0.9967
OV (%)	0.1571	0.0237	6.641	0.0000	Yes	1.0000
CH (m)	-2.0480	1.0650	-1.923	0.0546	No	0.4853
SR (rpm)	5.8869	0.0609	96.661	0.0000	Yes	1.0000

In Table 1, the standard error of the regression coefficient is the standard deviation of the estimate. The t-value (H0: bi=0) is from the t-test for testing the hypothesis that $\beta_i = 0$ versus the alternative hypothesis that $\beta_i \neq 0$ after removing the influence of all other variables. The significance test of the regression coefficient was determined using the probability level (p-value), which is the probability that this t-statistic will take on a value at least as extreme as the actually observed value, assuming that the null hypothesis is true. In general, a 5% or lower p-value is considered to be statistically significant. As Table 1 shows, the null hypothesis is rejected if the p-value is less than α=0.05. Power is the probability of rejecting the null hypothesis. High power means that there is a high probability of rejecting the null hypothesis when the null hypothesis is false. This is a critical measure of sensitivity in hypothesis testing.

Table 1 shows that TF was not significantly affected by the variable of CH, because the hypothesis of H0 was accepted. Thus, Eq. 1 can be simplified to Eq. 2 by removing the variable of CH. The regression analysis after the simplification is listed in Table 2.

$$TF = 18.6619 + 0.1411\ OV + 5.8887\ SR \quad (2)$$

$$R^2 = 0.9292$$

Table 2. The Regression Analysis of TF after Simplification

Predictor Variable	Regression Coefficient	Standard Error	T-Value	P-value	Reject H0? (α=0.05)	Power of Test
Intercept	18.6619	3.1950	5.841	0.0000	Yes	0.9999
OV (%)	0.1411	0.0222	6.367	0.0000	Yes	1.0000
SR (rpm)	5.8887	0.0609	96.623	0.0000	Yes	1.0000

Table 2 confirms that both predictor variables, OV and SR, are statistically significant. As the regression (Eq. 2) suggests, OV in the discharge pipe and SR in the chip feed pipe have positive influences on total fibers produced during refining.

Specific Energy Consumption (SEC)

The fiber production in the refiner positively correlates with the variables of OV and SR, as illustrated in Eq. 2. Generally speaking, it is expected that motor power increases as the amount of refined fibers increases; however, the effects of OV, CH, and SR on the specific energy consumption are not always positive. The relationships of SEC vs. CH and SEC vs. SR are shown in Figs. 4 and 5, respectively. The specific energy consumption during refining decreased with an increase in CH (Fig.4). The wood chips were steamed longer when more chips were stored in the pre-heater. As a result, these chips were softened by the extended steam-treatment time, which reduced the energy consumption.

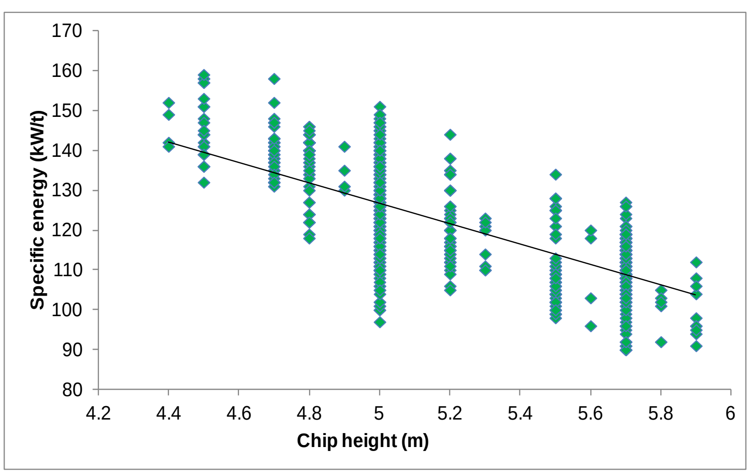

Fig. 4. The relationship between the specific energy consumption and chip height

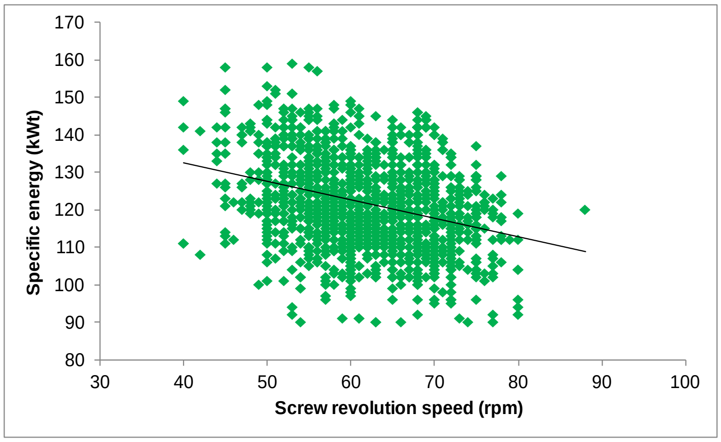

Fig. 5. The relationship between the specific energy consumption and screw revolution speed

This result confirmed the two previous laboratory findings: (a.) refining energy consumption correlating with the wood chip properties (Eskelinen et al. 1982), and (b.) energy consumption depending on the moisture content of the chips (Marton and Eskelinen 1982; Berg et al. 2009). Figure 5 shows that the specific energy consumption also was slightly reduced with an increase in feeding screw revolution speed. With a higher SR, a greater amount of fibers was obtained and a lower SEC was required.

The multiple regression models for the relationships between the response variable (SEC) and the predictor variables (OV, CH, and SR) are shown in Eq. 3,

$$SEC = 272.6183 + 0.1050\ OV - 26.0741CH - 0.3175\ SR \tag{3}$$

$$R^2 = 0.5348$$

where, SEC is the specific energy consumption (kWh/t); OV is the opening ratio of the valve in the discharge pipe (%); CH is the chip height in the pre-heater (m); and SR is the feeding screw revolution speed in the chip feed pipe (rpm).

The regression analysis for predictor variables (OV, CH, and SR) to the power consumption is illustrated in Table 3, which shows that all three predictor variables (OV, CH, and SR) are statistically significant. Thus, the regression equation (Eqn. 3) can be used to predict the specific energy consumption during refining.

Table 3. The Regression Analysis of the Power Consumption

Predictor Variable	Regression Coefficient	Standard Error	T-Value	P-value	Reject H0? (α=0.05)	Power of Test
Intercept	272.6183	3.8734	70.383	0.0000	Yes	1.0000
OV (%)	0.1050	0.0149	7.047	0.0000	Yes	1.0000
CH (m)	-26.0741	0.6709	-38.862	0.0000	Yes	1.0000
SR (rpm)	-0.3175	0.0384	-8.274	0.0000	Yes	1.0000

Qualified Fibers (QF)

The relationships of QF vs. OV, QF vs. CH, and QF vs. SR are shown in Figs. 6, 7, and 8, respectively. The percentage of qualified fibers obtained during refining increased as the opening ratio of the discharge valve or the feeding screw revolution speed decreased (Figs. 6 and 8). Three types of fibers were sorted according to the mill's suggestion: (1.) coarse fibers are those fibers greater in size than a screen mesh of 20; (2.) QF are those fibers between a screen mesh of 20 to 120; and (3.) fine fibers are those sized smaller than 120 screen mesh. When the discharge valve opening or the feeding screw speed increased, more coarse fibers were produced, resulting in a reduction in the percentage of qualified fibers.

The percentage of qualified fibers obtained during refining was reduced with a reduction in CH (Fig. 7). Higher accumulated chips in the pre-heater extended the steaming time, which resulted in better defibration due to the softened chips. On the other hand, more fine fibers were probably produced because of the weakened strength of the chips, which caused a reduction in the percentage of qualified fibers. As a result, MOE of the panel was negatively affected by the percentage of small particles (Shi et al. 2006).

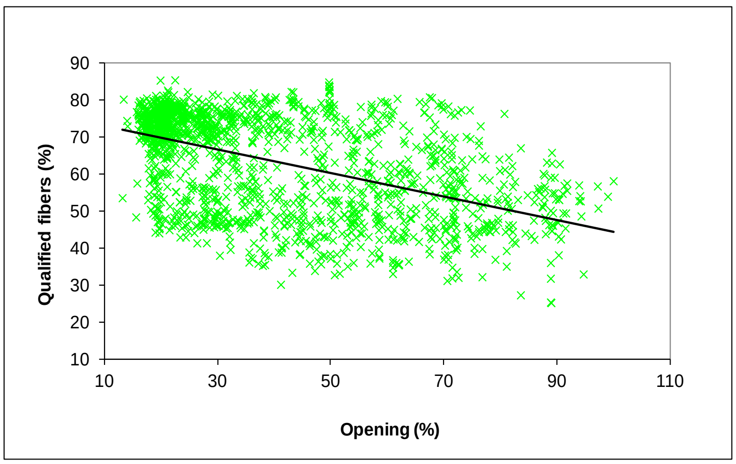

Fig. 6. The relationship between qualified fibers and valve opening

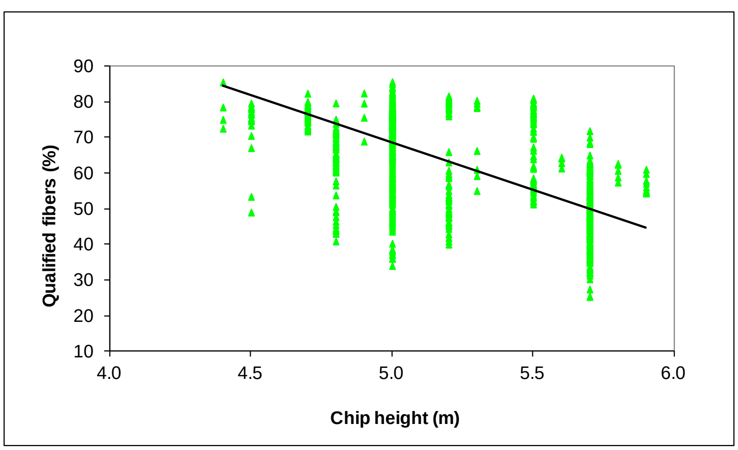

Fig. 7. The relationship between qualified fibers and chip height

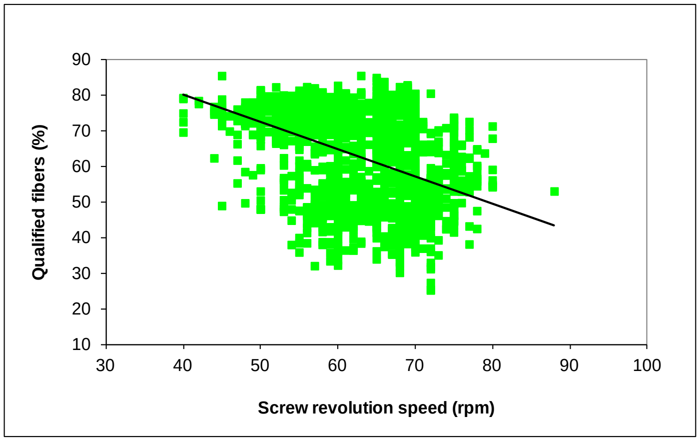

Fig. 8. The relationship between qualified fibers and feeding screw resolution

The QF regression model can be given by the following equation based on the coefficients estimated (Table 4),

$$QF = 200.8284 - 0.0636\ OV - 22.2355\ CH - 0.3134\ SR \qquad (4)$$

R^2=0.5226

where QF is the percentage of qualified fibers (between screen meshes of 20 to 120) in the total measured fibers (%); OV is the valve opening ratio in the discharge pipe (%); CH is the chip height in the pre-heater (m); and SR is the feeding screw revolution speed in the chip feed pipe (rpm).

The results of the regression analysis are listed in Table 4. Since all three predictor variables (OV, CH, and SR) are statistically significant, the regression equation (4) can be used to predict the qualified fibers produced during refining. The QF regression model (Eq. 4) shows that the percentage of qualified fibers is negatively affected by OV in the discharge pipe, CH in the pre-heater, or SR in the chip feed pipe.

Table 4. The Regression Analysis of the Qualified Fibers

Predictor Variable	Regression Coefficient	Standard Error	T-Value	P-value	Reject H0? (α=0.05)	Power of Test
Intercept	200.8284	4.3006	46.697	0.0000	Yes	1.0000
OV (%)	-0.0636	0.0166	-3.844	0.0001	Yes	0.9702
CH (m)	-22.2355	0.7449	-29.849	0.0000	Yes	1.0000
SR (rpm)	-0.3134	0.0426	-7.358	0.0000	Yes	1.0000

In addition to the relationship between QF and the three variables (Eq. 4), the regression equations between the fine/coarse fibers and the same variables were developed. Based on the different OV, CH, and SR, the fiber size distribution is illustrated in Table 5.

Table 5. Fiber Size as a Function of the Three Variables (OV, CH, and SR)

OV (%)	CH (m)	SR (rpm)	Qualified fibers (%)	Fine fibers (%)	Coarse fibers (%)
13.2	5	60	70.01	21.83	8.16
20			69.57	21.90	8.52
40			68.30	22.11	9.59
60			67.03	22.32	10.65
80			65.76	22.53	11.71
100			64.49	22.73	12.78
60	4.4	60	80.37	8.20	11.43
	4.8		71.48	17.61	10.91
	5.2		62.58	27.02	10.39
	5.4		58.14	31.73	10.13
	5.8		49.24	41.14	9.62
60	5	40	73.30	16.45	10.26
		50	70.16	19.38	10.45
		60	67.03	22.32	10.65
		70	63.90	25.25	10.85
		80	60.76	28.19	11.05
		88	58.26	30.54	11.21

Table 5 shows that as OV was increased, the percentage of qualified fibers was reduced and the percentages of fine/coarse fibers were increased. When CH was increased, the percentage of qualified fibers was reduced, the fine fibers were increased considerably and the coarse fibers were reduced slightly. When SR was increased, the percentage of qualified fibers was reduced and the fine/coarse fibers were increased.

CONCLUSIONS

Data from a large sample size (1,667 measurements for each variable) was collected from a mill trial. The relationships between the response variables (the total fibers, the specific energy consumption, and the percentage of qualified fibers) and the predictor variables, i.e. the chips retention time (accumulated chip height, CH) in the pre-heater, the feeding screw revolution speed (SR) in the chip feed pipe, and the valve opening ratio (OV) in the discharge pipe, were investigated. The following conclusions were drawn from the mill trial:

a. The specific energy consumption during the fiber thermomechanical refining process decreased with an increase in CH. The wood chips were softened due to the extended retention time in the pre-heater, which reduced the energy consumption.
b. The percentage of qualified fibers increased with a reduction in SR and OV. When the discharge valve opening ratio or the feeding screw speed increased, coarser fibres were produced (Table 5). This resulted in a reduction in the percentage of qualified fibers.

c. As a guideline, the resulting equations (2), (3), and (4) can be used to estimate the total fibers, energy consumption, and the percentage of qualified fibers under the limited range of OV, SR, and CH factors during thermomechanical refining. The estimation can assist MDF mill personnel in adjusting refining conditions appropriately to produce higher quality fibers with reasonable energy consumption.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science Foundation of China (NSFC) through grant number 31070499.

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Article submitted: January 13, 2012; Peer review completed: February 26, 2012; Revised version received and accepted: February 29, 2012; Published: March 3, 2012.