Effect of Refiner Plate Bar Angle and Pulp Properties on the Low Consistency Refining Efficiency in Terms of Power Consumption

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Abstract: Power consumption is the energy source of the impact on fibers or pulp during low-consistency (LC) pulp refining, and the strength of refining affects refining quality and efficiency. The pulp properties, operating parameters, and bar parameters of the refiner plates are important parameters affecting refining efficiency, which can be defined as the ratio of net to total refining power. In this study, LC refining trials for pulps with different consistencies and fiber lengths were conducted using five isometric straight-bar plates with different bar angles to explore the influences of the plate bar angle and pulp properties on the no-load power, impact capacity on fibers and refining efficiency. It was found that the no-load power of the LC refining process decreased with an increase in the plate bar angle while increased when pulp with higher consistency was refined under the same refining conditions. However, the effect of pulp consistency on the no-load power can be neglected when refining is conducted using plates with larger bar angles. Meanwhile, a critical bar angle for straight-bar plates in LC refining may exist, which has the strongest impact on the pulp and highest refining efficiency under the same refining conditions. In addition, the impact capacity of the plate on the pulp and refining efficiency in LC refining can be enhanced by appropriately increasing the pulp consistency and average fiber length when the bar angle of the refiner plate with a sector angle of 40° is less than 30°. Therefore, the efficiency and power consumption of the LC refining process can be adjusted by optimizing the pulp consistency and bar parameters of the refining plates.

Keywords: low-consistency refining; refiner plate; bar angle; pulp properties; no-load power; refining efficiency
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1 Introduction

Low-consistency (LC) refining is an important process for modifying the properties of pulp and fibers. Disc refiners are widely used in pulp refining. The raw materials were fed into the refining zone composed of rotor and stator plates during refining [1], and they experienced complex forces, such as normal, shear, and corner forces [2]. During the normal refining process, mechanical energy is transmitted from the main shaft to the refining zone and is then completely converted into fiber modification energy and heat [3]. The power consumption in LC pulp refining comprises the no-load power, which maintains the normal operation of the disc refiner, and the net power used for fiber modification. It has been found that the no-load power consists of the refiner bearing power loss and hydrodynamic power loss [4]. The net power directly affects the refining quality and efficiency under the same refining conditions; therefore, it is meaningful to explore the power consumption in LC refining.

The LC refining process is usually characterized by the refining intensity and specific refining energy. Most refining intensities, such as the specific edge load (SEL) [5], specific surface load (SSL) [6], and net normal force or tangential force per bar crossing zone [7], have been proposed and calculated based on the net power obtained by subtracting the no-load power from the total power [8–9] . This indicates that the accurate measurement or calculation of net power is important for controlling LC refining. Refining efficiency, defined as the ratio of net power to total power [10], can be improved by increasing the net power or reducing the no-load power, which is approximately in the range of 20%−50% of the total power in LC refining [11], and is related to refining devices, plate size, and other control or bar parameters [12]. The definition, calculation, and measurement methods for the no-load power have been summarized in previous studies [9, 12].

The plate size, rotation speed, pulp properties, and bar parameters of the refiner plates are the main factors affecting power consumption during refining. The no-load power of the disc refiner in LC refining increases with an increase in the plate size [13−14], and the efficiency of pulp refining conducted by plates with an internal and external diameter ratio of 0.6, is the highest compared to other configurations [14]. Typically, the net power of a disc refiner is proportional to the plate rotation speed, whereas the no-load power is proportional to its cube [9, 12]. The properties of the fluid in the refining zone directly affect the power consumption during LC refining. The no-load power of a disc refiner filled with water was found to differ from that of disc refiner filled with pulp [10,15−16]. However, few studies have explored the effects of fiber length and pulp consistency on power consumption and refining efficiency during LC refining. In addition, the bar structure of the plates is also a major factor affecting the no-load power and refining efficiency, and a linear relationship between the no-load power and groove depth is observed during LC refining [17]. The no-load power is increasing when the pulp is refined using a refiner plate with a higher groove depth [18−20]. The design of the bar angle should be further explored based on refining characteristics and power consumption. The bar angle of the refiner plates affects the pulp-pumping performance, refining efficiency, and quality of the refining process [21−22].

The objective of this study was to explore the effect of plate bar angle and pulp properties on the refining efficiency and the impact of refining zone on the pulp or fibers during LC refining. Five isometric straight-bar refiner plates were designed and used to study power consumption in LC refining trials. The no-load power, impact of the refining zone on the pulp, and refining efficiency of different refining trials were analyzed.

2 Experimental

2.1 Refining

2.1.1 Disc refiner and refining plates

LC refining trials were performed using a MD3000 single-disc refiner system (Regmed, Osasco, Brazil), as shown in Fig. 1. Five isometric straight-bar plates with different bar angles, as listed in Table 1, were used in the refining trials at a constant speed of 1460 r/min. Except for the bar angles, all other bar parameters of the refiner plates were identical, as listed in Table 2.

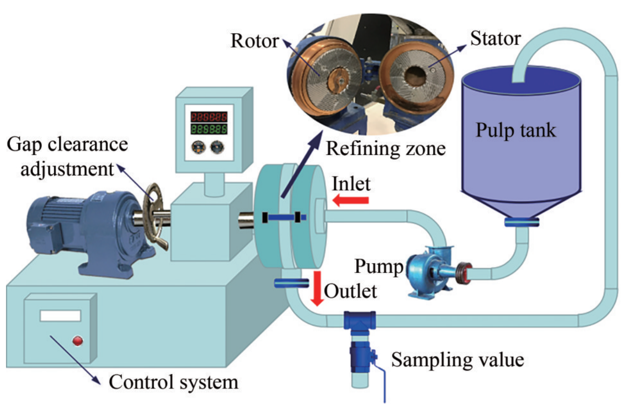


Fig. 1 MD3000 single-disc refiner

The definitions of the bar parameters can be found in the references [23−24].

2.1.2 Materials

In the pulp-refining trials, a bleached sulfate eucalyptus hardwood (HW) pulp board, an unbleached softwood pulp (SW) board, mixed pulp of different mixed rates, and water were used. The length-weighted average fiber lengths of the SW and HW pulp were 2.42 mm and 0.92 mm, respectively. Meanwhile, the Canadian Standard Freeness values before refining were basically the same at 787 mL and 762 mL. The properties of the raw materials used in the ten different trials for each refining plate are listed in Table 3. The raw material was first soaked in distilled water for 2 h and then dissipated using a pulp disintegrator (PD10, Techlab Systems, San Sebastian, Spain), and the consistency of the pulp was adjusted to 1%, 2%, and 3%.

2.2 Experimental scheme and data collection

Fifty LC refining trials were conducted using five refiner plates with ten types of raw materials, as shown in Table 3. The refining power, including the no-load power, net power, and total power, was measured by adjusting the gap clearance in the range of 0−5 mm.

The no-load power of refining can be measured when the gap clearance is sufficiently large, usually approximately 2.5 mm [4, 9]. In this study, the average value of the power when the gap clearance was in the range of 2.5−5 mm was considered as the actual no-load power for a specific refining trial. The net power was determined as the difference between the no-load power and the total power.

Table 1 Bar angle and structure of five straight-bar plates

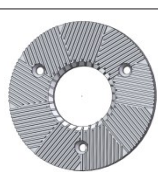
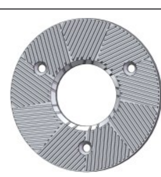
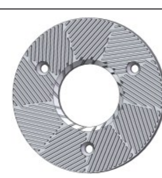
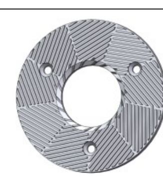
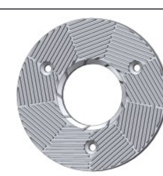
Plate code	S0	S5	S22	S39	S50
Plate structure					
Bar angle	0°	5°	22°	39°	50°

Table 2 Common parameters of five refiner plates

Bar width/mm	Groove width/mm	Bar height/mm	Sector angle/(°)	Internal radius/mm	External radius/mm
2	3	4	40	41.25	101.5

Table 3 Detail parameters of the pulp properties used in different refining trials

Refining trials	Pulp type	Mixed ratio of HW and SW	Length-weighted average fiber length/mm	Pulp consistency/%
1	Water	–		0
2	HW	–	0.92	1
3				2
4				3
5	HW+SW	4:1	1.22	1
6				2
7				3
8	HW+SW	3:2	1.52	1
9				2
10				3

In the effective operation stage, the total power increases with a reduction in the gap clearance. To better characterize the impact of the refining zone on the pulp in different refining trials, the maximum adjustable range of net power and refining efficiency, was calculated. The critical gap clearance (gap_c) of each trial was determined as the point at which the gap clearance decreased when power began to increase. A larger gap_c represents a wider adjustable power range for refining, which means that more types of pulp properties can be obtained by adjusting the gap clearance or power using the same refining equipment.

3 Results and discussion

3.1 Power-gap clearance curve

Usually, the refining intensity of the LC refining process can be adjusted by the gap clearance, which significantly affects the power. Gap_c, which characterizes the beginning of effective refining or power change, exists during LC refining. Some studies [16, 25–26] have found that the total power is inversely proportional to the change in gap clearance below the gap_c. It was also found that total power increases with the decrease in gap clearance during the SW and HW mixed pulp refining, and sharply increases when the gap clearance is less than 0.3–0.5 mm [27–28]. However, a different result was obtained by Bordin et al [10], who found that the power first decreased with a decrease in gap clearance until it reached a minimum value at the gap_c, and then sharply increased.

In this study, a unique power gap relationship curve exists, as shown in Fig. 2, which is obtained by the refining process of refiner filled with water. It can be concluded that constant power, power reduction, and power increase stages were present when the gap clearance was adjusted in the range of 0–5 mm, which is consistent with the results of a previous study [10].

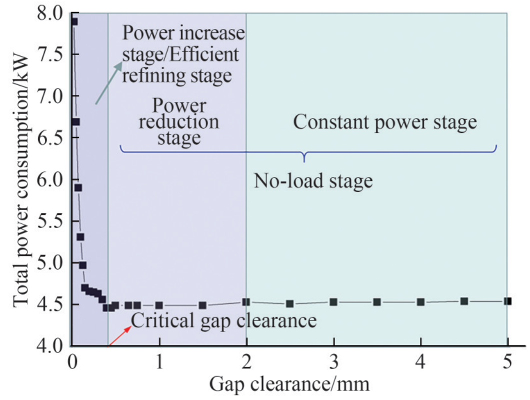


Fig. 2 Power-gap relationship of the refining process when filling with water

As shown in Fig. 2, the constant power stage refers to the total power during LC refining when the gap clearance is sufficiently large (typically larger than 2 mm). In addition, the power in this stage was almost constant and insensitive to volume changes in the refining zone. During the power reduction stage, the gap clearance was typically in the range of 0.5–2 mm, and the total power decreased slightly with decreasing of gap clearance. Owing to the relatively small change in total power, both the constant-power and power-reduction stages could be considered as no-load stage, and no refining effect occurred. In the power increase stage, the mechanical force applied by the plates acted directly on the pulp, and the friction between the bar and fibers increased sharply with the reduction in gap clearance; most of the energy in this stage was used for the modification of the fiber properties.

3.2 Effect of bar angle on the no-load power

The bar angle of the isometric straight-bar plates directly affects the refining quality and pulp pumping effects in the refining zone[22], while the no-load power varies with the plate bar angles during LC pulp refining. In this study, the no-load powers of different trials were recorded based on the total power when the refiner operated under constant power, and the effect of the plate bar angle on the no-load power was explored.

As shown in Fig. 3, the no-load power of LC refining decreases with an increase in the plate bar angle under the same refining conditions, which means that a reasonable increase in the plate bar angle can effectively reduce the no-load power of the refining. In addition, the pulp properties had a significant effect on the no-load power during LC pulp refining, which increased with an increase in pulp consistency under the same refining conditions. However, the change in the no-load power ($\Delta P_{\text{no-load}}$) affected by the pulp consistency decreased when the pulp was refined using a plate with a larger bar angle, as shown in Fig. 4. When the bar angle of the straight-bar plates with a sector angle of 40° was less than 30°, the no-load power could be effectively reduced by decreasing the pulp consistency. In addition, the average fiber length had little effect on the no-load power during the LC refining process, as shown in Fig. 3. The no-load power of the disc refiner increased slightly with an increase in the average fiber length when the pulp consistency was 1%, whereas the average fiber length had almost no effect on the no-load power when the pulp consistency was 2% or 3%.

3.3 Characterization of the impact capacity of refining zone on the pulp

During LC pulp refining, the impact capacity of the refining zone can be characterized by a variety of pulp or fiber properties and some refining parameters, such as gap_c, and an adjustable range of net power in the effective refining region. Although the first is not the focus of this study, it focuses on the analysis of the power-gap clearance curve under different refining conditions to characterize the impact of LC refining in another way.

3.3.1 Critical gap clearance

The beginning of the effective refining process during LC pulp refining can be characterized by the gap_c. It directly determines the adjustable range of gap clearance or power, as well as the pulp properties of specific refining processes. As shown in Fig. 5, the size of gap_c in LC refining is directly related to the effective refining region, in which the gap clearance is less than gap_c. The larger gap_c, the more capable it is of producing more types of pulp (or a higher impact capacity on the pulp) using the same refining equipment. In addition, the effective refining region can be divided into three sections: too heavy, too light, and the proper impact sections, according to the strength applied by the refiner on the pulp [29], as shown in Fig. 6. The proper operating parameters for LC refining, such as gap clearance or power, should be determined based

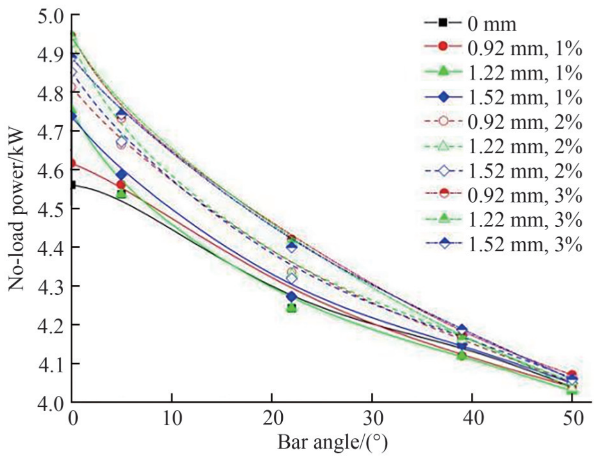


Fig. 3 Effect of the plate bar angle on the no-load power in LC refining under various pulp properties

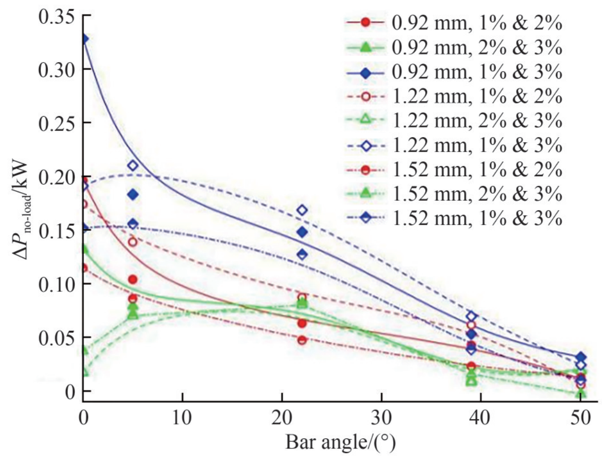


Fig. 4 Relationship between the no-load power increment and bar angles of vanous pulp properties

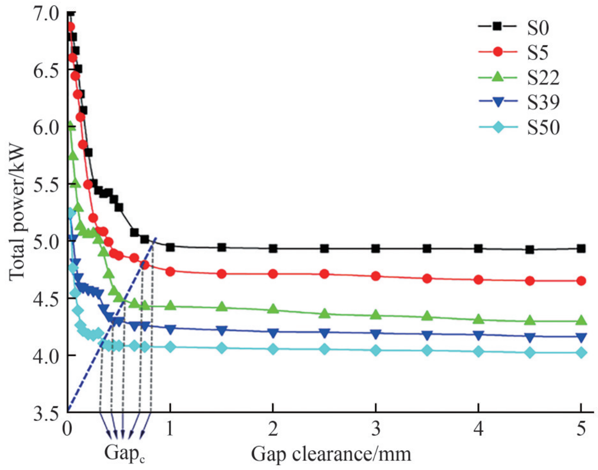


Fig. 5 Gap$_c$ of the LC refining conducted by different plates (average fiber length of 1.22 mm, and pulp consistency of 2%)

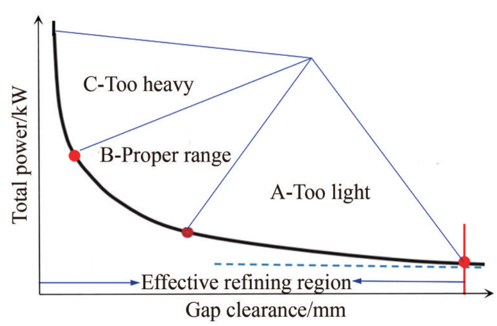


Fig. 6 Typical curve for the effective refining region [29]

on the raw material and process requirements.

As one of the angular parameters of a straight-bar plate, the bar angle directly affects the impact capacity on the pulp under the same refining conditions by influencing gap$_c$. As shown in Fig. 7, gap$_c$ in the disc refiner during LC refining gradually decreased with an increase in the plate bar angle. This means that the impact capacity of a straight-bar plate with a smaller bar angle on the pulp is stronger, and the adjustable range of fiber modification in the same LC refining conducted by a plate with a smaller bar angle would be wider.

Pulp consistency and average fiber length are two important raw material properties used in LC pulp refining. As shown in Fig. 7, an obvious increase in gap$_c$ can be obtained by increasing the pulp consistency under the same refining conditions. Moreover, the effect of the average fiber length on gap$_c$ was weaker than that of pulp consistency on gap$_c$. A slight increase

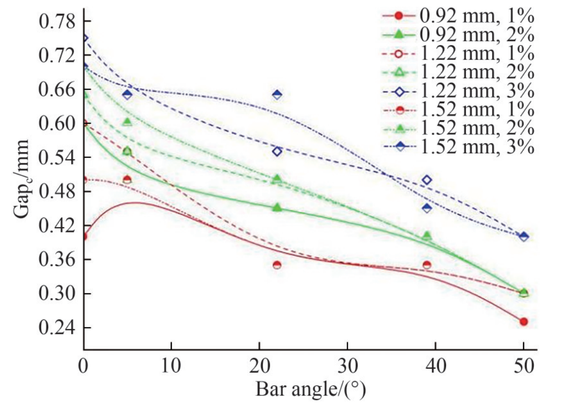


Fig. 7 Effect of bar angle on gap$_c$ in LC refining under different conditions

in gap$_c$ occurred with an increase in fiber length, which was more obvious when the pulp consistency is higher. Therefore, gap$_c$, which represents the adjustable range of impact capacity on the pulp of the refining zone, can be properly increased by appropriately reducing the bar angle of the straight-bar plate or increasing the pulp consistency.

3.3.2 Adjustable range of net power

In addition to gap$_c$, the maximum adjustable range of net power (ΔP_{max}), the difference in the maximum total power and no-load power in the effective refining region, can be used to measure the impact capacity of the refining process on pulp. Additionally, the LC refining process with the larger ΔP_{max} indicates that the net power can be adjusted more flexibly, which can induce a diverse modification of pulp properties using the same refining equipment.

As shown in Fig. 8, the influence of the plate bar

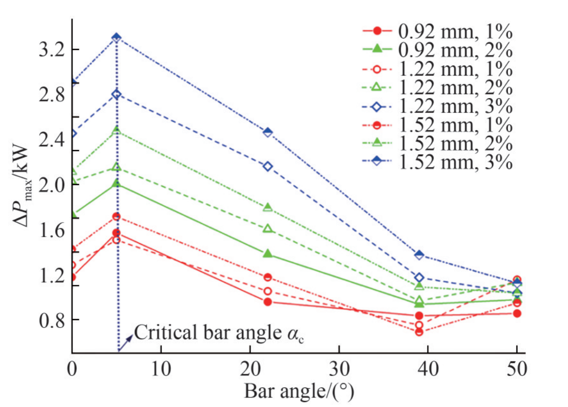


Fig. 8 Effect of plate bar angle on ΔP_{max} under different refining conditions

angle on the ΔP_{max} in LC pulp refining was explored in this study. The value of ΔP_{max} in LC refining increased with an increase in the plate bar angle until it reached the maximum value, and then gradually decreased. The plate bar angle, when the ΔP_{max} reaches the maximum value under the same refining conditions, is called the critical bar angle, α_c. The adjustable range of net power was widest when the LC pulp refining process was conducted using a straight-bar plate which sector angle is 40° with a bar angle of α_c, usually less than 10°. This means the straight-bar plate with a smaller angle has a greater capacity to exert the impact on the pulp, while straight-bar plates with a larger angle, greater than 30° in this study, is not suitable for the LC refining due to the low ΔP_{max}.

As shown in Fig. 8, pulp properties, such as pulp consistency and average fiber length, also affect the ΔP_{max} of the effective refining region in LC pulp refining. It can be found ΔP_{max} increased with the increase in pulp consistency under the same refining conditions. However, the effect of pulp consistency on ΔP_{max} gradually weakened when the bar angle of the straight bar plates with a sector angle of 40° was greater than 35°. Increasing the average fiber length can slightly increase the ΔP_{max} of the effective refining region in LC refining. However, its effect on ΔP_{max} was weaker than that of pulp consistency on ΔP_{max}. Similarly, there was almost no effect of bar angle on the ΔP_{max} of the effective refining region when the pulp was refined by the plate with a larger bar angle. Therefore, under the same refining conditions, a proper increase in pulp consistency is helpful in increasing the P_{max} of the effective refining region in LC refining, and various pulp properties can be realized by net power adjustment.

3.4 Refining efficiency

Refining efficiency is an important indicator for measuring energy utilization in an effective refining process, and is affected by many factors, such as bar parameters, pulp properties, and control parameters. As shown in Fig. 9 and Fig. 10, the refining efficiency gradually increased with a decrease in the gap clearance during the effective refining process, which indicated that the proportion of energy used for fiber modification gradually increased. In this study, the effects of the plate bar angle, pulp consistency, and average fiber length on the refining efficiency of LC pulp refining under different conditions were explored.

As shown in Fig. 9 and Fig. 10, the efficiency of the disc refiner in LC pulp refining was directly affected by the plate bar angle. It can be concluded that the refining efficiency is higher when the pulp is refined by a straight-bar plate with a smaller bar angle under the same refining conditions, which is conducive to energy saving in LC pulp refining. In particular, the refining efficiency of LC refining conducted using a plate with

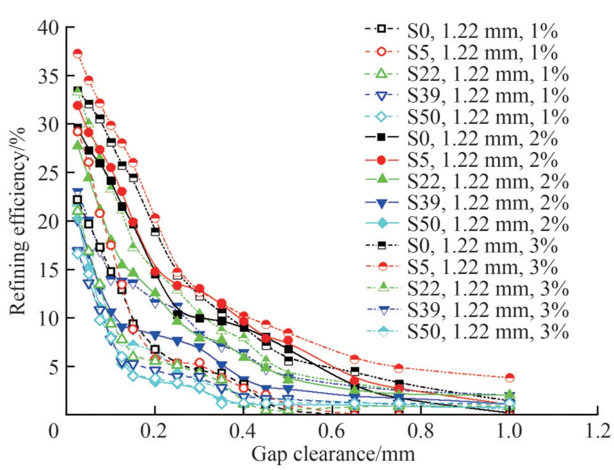


Fig. 9 Relationship between gap clearance and refining efficiency at different conditions (constant average fiber length, 1.22 mm)

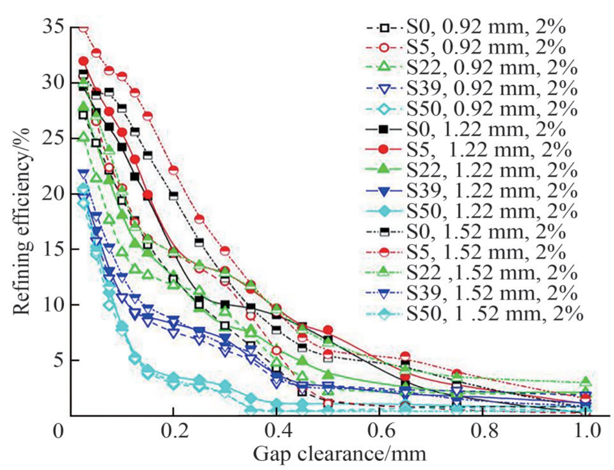


Fig. 10 Relationship between gap clearance and refining efficiency at different conditions (constant pulp consistency, 2%)

a bar angle of 5° was slightly higher than that with a bar angle of 0°. It can be inferred that α_c existed for the straight-bar plate with a specified sector angle, while it should be verified by more trials in the future. Therefore, the refining efficiency of the LC pulp refining gradually increased with the increase in the plate bar angle, until reaching the maximum value, and then decreased, which is similar to the variability of ΔP_{max}. According to the concept of the average bar crossing angle, γ [7, 23–24], a critical average bar crossing angle, γ_{sc}, exists and is influenced by the plate bar angle. The size of γ is more important than the bar angle, which combines the bar and sector angles of the refiner plate. Therefore, bar and sector angles should be reasonably designed to enhance the efficiency of the LC refining process.

The efficiency of LC pulp refining was also affected by pulp consistency under the same conditions, as shown in Fig. 9, the higher the pulp consistency, the higher the efficiency of LC refining under the same refining conditions. This can be explained by the fact that the ability of the pulp to withstand loading applied by the refining plates increases when pulp with higher consistency is refined. As the proportion of fibers or components of the fiber network in the refining zone increases, the energy required for effective refining increases. However, it should be noted that the effect of pulp consistency on the refining efficiency is directly related to the plate bar angle. As shown in Fig. 9, there was a strong effect of pulp consistency on the refining efficiency in LC pulp refining when the pulp was refined by smaller-bar-angle plates, while it could be neglected when the pulp was refined by larger-bar-angle plates, such as 50°.

In addition, the average fiber length had a slight effect on the refining efficiency in LC pulp refining conducted using a plate with a smaller plate bar angle, as shown in Fig. 10. The refining efficiency of LC pulp refining increased as the average fiber length increasing when the plate bar angle was less than 22°, while there was almost no effect of fiber length on the refining efficiency when the plate bar angle was larger than 39°, which may be induced by its weak loading ability. Therefore, the efficiency of the LC pulp refining process can be improved by a reasonable design of the plate angular parameters and the selection of pulp consistency.

4 Conclusions

The effects of the bar angle of the isometric straight-bar plate and pulp properties on the no-load power, impact capacity of the refining zone on the pulp, and refining efficiency in LC pulp refining were explored in this study. The main conclusions are as follows:

4.1 The operation of LC pulp refining can be divided into a no-load region and an effective region according to the power change and gap clearance. The no-load region is composed of constant power and power reduction stages, whereas the effective refining region refers to the sharply increasing power stage when the gap clearance is less than gap_c. However, the decrease of power in the power-reduction stage is very small and can be neglected.

4.2 Plate bar angle and pulp consistency are two important factors affecting the no-load power in LC pulp refining. It gradually decreased with an increase in the plate bar angle and pulp consistency under the same refining conditions. However, the effect of pulp consistency on the no-load power is more obvious when it is refined by a plate with a sector angle of 40°, which bar angle is smaller, usually less than 30°.

4.3 Gap_c and ΔP_{max} in the effective refining region are two important parameters for measuring the impact of the refining zone on the pulp during LC pulp refining. Gap_c gradually decreases with a proper increase in the plate bar angle or with a decrease in pulp consistency, whereas the average fiber length has little effect on it under the same refining conditions. In addition, the critical bar angle, α_c, was present in LC refining, allowing the maximum adjustable range of net power. Therefore, it can be concluded that the impact capacity of plates on the pulp in LC refining can be improved by the proper design of angular parameters and determination of pulp consistency.

4.4 The refining efficiency of LC pulp refining gradually decreases with an increase in the plate bar angle, whereas properly increasing the pulp consistency can improve the refining efficiency under the same refining conditions. The average fiber length had little effect on the refining efficiency of LC pulp refining, particularly for refining plates with a larger bar angle.

Acknowledgments

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