$\text{FACTORS AFFECTING THE SHEAR FORCES IN HIGH-CONSISTENCY REFINING}$

John Senger$^1$  Daniel Ouellet$^2$
$^1$University of British Columbia, Pulp and Paper Centre
2385 East Mall, Vancouver, BC, V6T 1Z4 Canada
$^2$ Pulp and Paper Research Institute of Canada
3800 Wesbrook Mall, Vancouver, BC, V6S 2L9 Canada

ABSTRACT

In order to elucidate the source of the considerable expenditure of energy associated with the refining process, we have studied the forces generated when a floc of high-consistency pulp is trapped between passing bars in a refiner. A conceptual model of the shear force is presented here. The model is similar to that proposed by Batchelor et al. for low-consistency refining [J. Pulp Paper Sci., 23(1997):1, J40-45] and assumes that the shear force is made up of two components: a friction component acting over the surface of the refiner bars, and a corner or ploughing component acting over the leading edge of the bars. The total shear force determines the power consumed during refining. The model demonstrates that the shear force is influenced significantly by the ploughing component. The ratio of the average shear force to the average normal force can be represented by an equivalent tangential coefficient of friction, $\mu_{eq}$, which includes the influence of both the friction and the ploughing components of the shear force.

Experiments performed on individual flocs in a single bar refiner have shown that $\mu_{eq}$ increases with increasing consistency and that this increase is larger for higher grammage flocs. The experiments also indicate that the sharpness of the bar edge has a significant influence on the corner force for flocs of sufficient thickness, resulting in lower values of $\mu_{eq}$ as refiner bars wear down. Data from the literature suggest that the type of pretreatment, alkalinity, and refining zone temperature have an influence on $\mu_{eq}$ as well. Taken together, these results indicate that $\mu_{eq}$ should be considered a variable in the refining process rather than a constant as treated previously. The results help to explain the mechanisms behind changes in the relationship between refining energy and pulp quality under different refining conditions.

KEYWORDS

bars, coefficient of friction, energy, flocs, force, high consistency, plate wear, pulp quality, refining, shear, stresses, temperature, mechanical pulps

INTRODUCTION

One of the goals of mechanical pulp refining is to develop the papermaking properties of fibres. This is accomplished through cyclic imposition of compression and shear forces on individual pulp flocs in a refiner. In this process, large amounts of energy are expended. This energy expenditure is directly proportional to the shear forces acting on the flocs. Thus, an understanding of the factors affecting the shear forces could reduce energy costs during mechanical pulping by helping to optimize both refiner control and fibre development.

Most of the attention given to the forces in refining has been in low-consistency applications. Gietz suggested that different refining effects could be explained by the relative magnitude of the forces applied [1]. Similarly, Page has suggested that a complete understanding of the refining process would require knowledge of the average stress-strain history of individual fibres [2]. Despite the recognized importance of forces in refining, little is known about the factors that affect the forces and about the effects that specific forces have on individual fibres. Early work on forces focused on measuring the pressure on refiner bar surfaces, but these results varied widely and did not look at the mechanisms contributing to the pressures, nor the effects on individual fibres. Two of these studies were in low-consistency applications [3, 4], while one was at high-consistency [5].

Martinez was the first to study the forces acting on individual flocs trapped between refiner bars [6, 7]. This work was later expanded by Martinez et al. and Batchelor et al. who developed theories to predict the normal and shear forces exerted on an ideal spherical floc as it passes through a refiner at low-consistency [8, 9]. Batchelor and Ouellet then adapted this theory to previously dried pulps and estimated the forces on individual fibres within a floc [10]. However, the theory assumes a linear elastic model for floc compression. Numerous studies have shown that high-consistency pulp mats under compression have non-linear elastic behaviour [11-15]. Experiments performed on pulp flocs in a laboratory single bar refiner have confirmed these findings [16].

International Mechanical Pulping Conference 2001
Thus, a different model is required to fully describe the forces produced at high-consistency. This paper will look at the forces produced during refining and discuss important variables that affect these forces.

**EXPERIMENTAL**

To study the forces experienced by flocs trapped between passing bars of a refiner, experiments were performed under a wide variety of operating conditions in a laboratory single bar refiner.

The single bar refiner apparatus has been described in detail elsewhere [6, 8, 16]. It consists of two opposing, horizontal plates on each of which a single bar is mounted. The bottom plate rotates at a low speed (<3 rpm) and is adjustable in height. Individual flocs are trapped between the bars on the rotor and stator as they cross, and both the normal and shear forces are recorded throughout the bar crossing. Both the rotor and stator bars used in these experiments were 3 mm wide and made from nickel-hardened steel, a common material used in industrial refiner plates.

Pulp flocs were modeled by cutting strips of various widths from mats of softwood TMP formed in a British handsheet machine (BHM). Mats were formed and removed from the BHM using a procedure similar to that used when making standard handsheets [17]. The grammage of a mat was varied by adding different amounts of pulp to the BHM during forming. Consistency was controlled by partially drying the pulp mats for various times on top of a blotting sheet in a handsheet dryer. The lid of the handsheet dryer was supported, so that no mechanical pressure was applied to the mats during drying. Flocs were tested over a range of consistency, plate gap, and floc grammage at two different levels of bar wear. New bars were used for the first set of trials. The leading edges of both the rotor and stator bars were then ground down to simulate bar wear, and the ground bars were used in a second set of trials. All of the flocs tested were approximately uniform in thickness and wider than the refiner bars.

In contrast to the work of Martinez et al. [8] and Batchelor et al. [9], who considered flocs to be spherical, we have modeled flocs as rectangular in shape, with a uniform thickness. In general, a situation close to this should occur since the gap between the bars in a refiner is typically much smaller than any floc dimensions. Thus, regardless of the initial shape of a floc when it enters the refiner, after one impact it should resemble a flattened disc. Since flocs typically see tens or even thousands of impacts during a passage through the refiner, depending on the type of refiner and operating conditions, it seems unlikely that they can persist for very long inside a refiner as objects having three roughly similar dimensions. In addition, if the diameter of a flattened floc is larger than the width of a refiner bar, then the length of the floc along the bar can be considered approximately constant during a bar crossing. This implies that the compressed area of any floc should be approximately rectangular.

It is recognized that the flocs used in our experiments are clearly a simplification of the type of flocs found in actual refiners. Indeed, Law has recently studied flocs exiting a CD300 pilot scale refiner and found them to have various shapes and sizes [18]. However, this simplification has allowed us to identify the different force components, and to examine how these components change under different refining conditions. As will be shown later, the results obtained in these experiments are consistent with what is observed in actual refiners.

**Experimental Force Profile**

As two refiner bars approach each other and trap a floc between them, the forces will start at zero, rise to some value as the bars cross over one another, and fall to zero as the floc is released from between the bars. Figure 1 illustrates an experimental force profile, generated during the compression of a uniform thickness floc in the single bar refiner. Here, the dotted line shows the normal force and the solid line shows the shear force as a function of the distance traveled by the rotor. Note that the area under the shear force curve is the energy expended on the floc during a bar crossing. The icons at the bottom of the figure depict the relative position of the refiner bars at the beginning, middle, and end of the profile. The floc is trapped, and the forces begin to rise, slightly before the leading edge of the rotor bar is aligned with the leading edge of the stator bar. The forces continue to rise as the rotor bar continues past the stator bar and the trapped area of the floc increases. The forces peak when the bars are completely overlapped at one bar width of travel. From this point the forces diminish as the trapped area of the floc decreases, until the floc is released slightly after the trailing edge of the rotor bar is aligned with the trailing edge of the stator bar (after two bar widths of travel).

The normal force has been examined in previous work [16]. The shear force profile is asymmetric, as seen in Figure 1, and the force generated over the first bar width of travel is noticeably larger than that generated over the second bar width of travel. The reason for the asymmetry in the shear force profile will be discussed below.
THEORETICAL FORCES

As suggested by Page [2] and demonstrated by Batchelor et al. [9], a pulp floc trapped between passing bars of a refiner will experience three different forces: a compressive force normal to the bar surfaces ($N$), a friction shear force parallel to the bar surfaces ($S_\parallel$), and a ploughing or corner force acting on the leading edge of the bars ($S_c$). These three forces are shown schematically in Figure 2. The schematic on the left side of the figure shows a pulp floc trapped between two refiner bars. The one on the right side of the figure illustrates the three forces mentioned above acting on the upper refiner bar. The forces on the pulp floc will act in opposite directions to those shown in the figure.

Note that the ploughing component of the shear force is assumed to act primarily on the front edge of the refiner bar, with only a negligible component in the normal direction. This ploughing force develops because flocs are thicker than the gap between the refiner bars (if they were not, then no significant forces would develop in any direction). As the refiner bars approach each other the floc is pinched and held stationary relative to one of the refiner bars. As the bars continue to overlap, a portion of the floc is compressed between the refiner bars, and another portion remains uncompressed in front of the refiner bar. The uncompressed portion offers resistance to the refiner bar in the horizontal direction (see Figure 2) as the refiner bar moves over the floc [2].
The model depicted here is based on physical evidence that flocs are generally not sheared apart during bar crossings. Thus, we are considering the shearing forces that arise due to a refiner bar sliding over a floc, as opposed to those that would arise from fibre to fibre friction as a floc is pulled apart. None of the flocs that were tested in our experiments in the single bar refiner were ever sheared apart by the action of the refiner bars. Further evidence that flocs remain intact comes from other experiments performed by the authors in a laboratory refiner. In this case, the refiner was fed with a mixture of bleached and dyed pulps. After refining, the dyed and bleached pulp flocs could easily be separated from one another, suggesting that flocs tend to persist as coherent units. This is in agreement with the work of Law, who collected coherent flocs at the outlet of a pilot scale refiner [18]. Finally, there is photographic evidence from work done on an industrial refiner which shows flocs stapled to one of the refiner bars (either the rotor or stator) and remaining intact throughout a bar crossing [19]. Note that we are not suggesting that flocs always remain intact after being caught between refiner bars, but only that the shearing apart of flocs is relatively rare.

The total shear force at any instant will be the sum of the friction and ploughing components:

$$ S = S_f + S_c $$  \hspace{1cm} (1)

If flocs are uniform in thickness then the ploughing component is expected to be constant. This is anticipated because the uncompressed portion of the floc in front of the leading refiner bar edge will have a constant thickness and offer the same amount of resistance to the bar as it moves over the floc. In addition, because “ploughing” requires a supporting surface on the opposite side of the ploughing bar edge to generate any force, the ploughing component of the shear force will only act until the refiner bars are completely overlapped, after which point it will fall to zero. This effect can be seen in the experimental force profile of Figure 1. After one bar width of travel there is a substantial decrease in the shear force, as a result of the ploughing component falling to zero. Over the final bar width of travel, only friction forces contribute to the total shear. The friction component ($S_f$) will simply be a scaled value of the normal force between the bars, $\mu N$, the scaling factor being the coefficient of friction between the refiner bars and the pulp floc, $\mu$.

A theoretical shear force profile for one complete bar crossing is depicted in Figure 3. Here, as the bars approach each other the floc is trapped and both the friction and corner force components contribute to the total shear. This situation lasts until the bars are completely overlapped (one bar width of travel), at which point the corner force drops to zero. The shear force is then entirely due to the friction component. This component drops steadily, as the trapped area of the floc decreases, until the floc is released after two bar widths of travel. A comparison between the theoretical shear force profile of Figure 3c and the experimental shear force profile of Figure 1 shows that they are in good agreement.

**REFINING VARIABLES**

In refiner control, five important variables are the net refining power ($P$), the throughput ($\dot{m}$), the specific energy ($E$), the axial thrust ($F_a$), and the pulp consistency ($C_p$). Generally, refiner operators control independently the axial thrust, throughput, and pulp consistency to reach a desired level of power and/or specific energy. The specific energy is the amount of energy expended per unit mass of oven dry fibre and is expressed:

$$ E = \frac{P}{\dot{m}} $$  \hspace{1cm} (2)
Figure 3: Theoretical shear force profile generated as two bars cross over one another, trapping a floc of uniform thickness between them. a) Friction component b) Corner force component c) Total shear force. The icons at the bottom show the relative position of the refiner bars at the beginning, middle, and end of the profile.

The axial thrust is balanced in the refining zone by a steam thrust ($F_s$) and a mechanical thrust from the pulp between the plates ($F_m$). The mechanical thrust and net refining power are related by the following equation [21, 22]:

$$P = \frac{h\mu \alpha (t_1 + t_2)F_m}{2} = h\mu \alpha F_{\text{m}}$$

(3)

where $h$ equals 1 for a single-disc refiner and 2 for a double-disc refiner, $\mu$ is the “tangential coefficient of friction” between the pulp and the disc it is sliding over, $\alpha$ is the rotational speed of the refiner, $t_1$ and $t_2$ are the inner and outer radii of the refining zone respectively, and $\bar{r}$ is the average radius of the refining zone.

The concept of a “tangential coefficient of friction” has been used by many researchers [15, 21-25], and implies that the shear forces in refining are related to the normal forces through a friction coefficient, $\mu$. But as shown in Figure 3, the shear force contains a significant corner force component in addition to a linear friction component. Since the corner force influences the shear and normal forces to different degrees, the concept of a linear friction model between the normal and shear forces in refining is not strictly true. However, it is useful to define an equivalent tangential coefficient of friction, $\mu_{\text{eq}}$, as the average value of the shear force divided by the average value of the normal force experienced by a single floc during one bar crossing in the refiner. This new term $\mu_{\text{eq}}$ then serves the same purpose as $\mu$, but emphasizes that the shear force is not simply a friction component of the normal force in refining. Equation (3) can then be written:

$$P = \frac{h\mu_{\text{eq}} \alpha (t_1 + t_2)F_{\text{m}}}{2} = h\mu_{\text{eq}} \alpha F_{\text{m}}$$

(4)

The parameter $\mu_{\text{eq}}$ plays an important role in refining as it determines the amount of energy put into the pulp fibres for a given mechanical thrust. If this parameter varies with refiner operating conditions, then changes in the energy-quality relationship can be expected because pulp flocs will be subjected to different combinations of compressive and shear forces during their passage through the refiner.

In this paper, individual pulp flocs have been compressed and sheared in a laboratory single bar refiner. These experiments have allowed the equivalent tangential coefficient of friction to be determined over a wide range of operating conditions. The results support observations reported in the literature and help clarify the mechanisms involved in refining.
RESULTS

Four series of softwood TMP flocs were tested in the single bar refiner using new (i.e. sharp) refiner bars. Each series was tested at constant grammage and plate gap. The plate gap was adjusted for each series to give similar normal stresses at any given consistency. Testing individual flocs at similar normal stresses can be interpreted as a refiner operating at constant mechanical thrust load. In addition, two more series of TMP flocs were tested at constant grammage and plate gap, using refiner bars in which the leading edges had been ground down to simulate bar wear. Results for the effects of consistency, grammage, and bar wear on the equivalent tangential coefficient of friction are presented below.

Effects of Floc Consistency and Grammage

Figure 4 shows the effect of floc consistency on the equivalent tangential coefficient of friction. Here, $\mu_{eq}$ has been plotted against floc consistency for each of the four series of TMP flocs tested with sharp refiner bars. It can be readily seen that $\mu_{eq}$ increases with floc consistency, and that this increase is larger for higher grammage flocs. Figure 5 displays the effect of floc grammage more clearly. Here, $\mu_{eq}$ has been plotted against floc grammage at constant consistency, using the regression curves of Figure 4 to obtain the data. At constant consistency, $\mu_{eq}$ increases rapidly with increasing grammage at first, and then tends to plateau at very high grammages. The corresponding normal stresses for the data reported above are plotted against floc consistency in Figure 6. It can be seen from the figure that the normal stresses for each series at any given consistency are in the same range, and thus any differences in $\mu_{eq}$ cannot be attributed to differences in refining thrust load.

Note that each data point in Figures 4 and 6 has been obtained from the compression of an individual floc in the single bar refiner, which produced a plot of the normal and shear forces, similar to that shown in Figure 1. The coefficient of friction is then calculated from the ratio of the average shear force to the average normal force, over the duration of the impact. It can be observed from Figure 6 that, at constant plate gap, the normal stresses begin to increase at consistencies above approximately 50%. An increase in normal stress would tend to decrease the equivalent coefficient of friction. However, as seen in Figure 4, $\mu_{eq}$ actually increases with consistency in this range. This occurs because the shear forces increase at a faster rate than the normal forces. The reason for the increase in the forces with increasing consistency will be discussed later.

Figure 4: Equivalent tangential coefficient of friction vs floc consistency for four series of TMP flocs, each series tested with sharp refiner bars at constant grammage ($W$) and plate gap ($T$).
Figure 5: Equivalent tangential coefficient of friction vs floc grammage at constant normal stress (~280 kPa). Each line is at constant consistency (labelled in % on the right).

Figure 6: Normal stress vs floc consistency for four series of TMP flocs, each series tested with sharp refiner bars at constant floc grammage (W) and plate gap (T).

Effect of Bar Wear

The effect of bar wear on the equivalent tangential coefficient of friction is displayed in Figure 7. Here, $\mu_{\text{eq}}$ is plotted against consistency for four series of flocs, each series at constant grammage and plate gap. The open symbols are flocs tested with sharp bars and the filled symbols are flocs tested with worn bars. For the higher grammage flocs, there is a substantial drop in $\mu_{\text{eq}}$ for flocs tested using the worn bars. In addition, there is less of an increase in $\mu_{\text{eq}}$ with increasing consistency for flocs tested with worn bars as compared to those tested with sharp bars. For the lower grammage flocs, $\mu_{\text{eq}}$ is practically the same with either the sharp or worn bars. Again, all flocs were tested at approximately equal normal stresses at a given consistency, as shown in Figure 8. The plate gaps were the same for worn or sharp bars: $T = 0.77$ mm for $W = 300$ g/m$^2$, and $T = 0.14$ mm for $W = 80$ g/m$^2$. This indicates that the normal stresses developed during refining do not appear to be influenced significantly by the degree of bar wear.
Figure 7: Effect of bar wear on equivalent tangential coefficient of friction. The plot shows \( \mu_{eq} \) vs floc consistency for four series of TMP flocs, each series tested at constant grammage (W) and plate gap. Open symbols: sharp bars. Filled symbols: worn bars.

Figure 8: Normal stress vs floc consistency for four series of TMP flocs, each series tested at constant grammage (W) and plate gap. Open symbols: sharp bars. Filled symbols: worn bars.

**DISCUSSION**

**Factors Affecting \( \mu_{eq} \)**

To understand how consistency, grammage, and bar wear affect the equivalent tangential coefficient of friction, consideration must be given to the mechanisms contributing to the shear force during a bar crossing: primarily, one must consider how the ploughing force influences the total shear force. The ploughing force develops over the leading edge of a refiner bar as the bar ploughs through the uncompressed portion of the floc. The magnitude of the ploughing force will be determined by the total amount of fibres offering resistance to the refiner bar, as well as by the difficulty the refiner bar encounters in ploughing through a given amount (thickness) of fibres. The total amount of fibres offering resistance to the leading bar edge is related to the difference in thickness between the uncompressed floc and the plate gap. This means that a thicker floc, and therefore one with a higher grammage, will have more fibres (or more fibre layers) in front of the leading bar edge. This effect is shown in Figure 9. Because of the greater amount of fibres in front of the leading bar edge, the larger grammage floc on the left of the figure results in a larger shear force and a
Figure 9: Two flocs of different grammages (W) trapped between refiner bars at equivalent normal forces (N) and friction shear forces (S). The floc on the left (1) has a higher grammage than the floc on the right (2), and the refiner bar has to plough through a greater thickness of floc in case 1 than in case 2. This develops a larger corner force (S_c) and total shear force (S), and explains why \( \mu_{eq} \) is higher in case 1 than in case 2.

larger \( \mu_{eq} \) than the floc on the right, at an equal normal force (N) and friction shear force (S). This effect can also be seen experimentally in the data of Figure 4, where \( \mu_{eq} \) is larger for flocs of higher grammage.

Both consistency and bar wear will affect the difficulty encountered as a refiner bar ploughs through a floc of a given thickness. The consistency of the pulp floc will determine the strength of the interactions between fibres within the floc. At consistencies above 35% to 40%, surface tension forces from the water present between fibres will strengthen the floc structure and the refiner bar will encounter greater resistance as it tries to push its way through the floc. At consistencies below that, where free water is present in the floc, surface tension forces between fibres are not expected to be significant [26]; thus, the difficulty encountered in ploughing through a floc should be smaller and relatively constant. Strengthening of the wet-web structure as consistency increases above approximately 35% has been reported in the literature [27, 28]. The effect is also evident in the upper three data series of Figure 4, where it is observed that \( \mu_{eq} \) is relatively unchanged for consistencies up to about 35% and then increases as consistency increases.

The sharpness of the bar edge will determine how much the edge digs into the floc. A sharp bar edge will act as a stress concentration point and result in a strong ploughing force, while a worn bar edge will result in a more gradual compression of the floc, as opposed to ploughing. As an analogy, consider replacing the rounded front of a toboggan with a sharp corner. The sharp corner will dig into the snow, producing a large resisting force (and a very short toboggan ride). This effect can be seen in the upper series of data in Figure 7, where \( \mu_{eq} \) decreases for the worn refiner bars. This effect does not occur in the lower series of data in Figure 7 because of the very low floc grammage used in these series. The low grammage flocs have only a small amount of fibres (fibre layers) in front of the leading bar edge and thus the sharpness of the bar edge does not have a large influence on the forces generated in this case.

**Interpretation of Results**

The results presented here have been obtained from experiments performed under laboratory conditions, at much lower strain rates and temperatures than those found in commercial refiners. Therefore, it may be asked whether these results can be applied to commercial refining operations. We have relied on three factors to explain the changes in the forces under different refining conditions: the thickness of the pulp floc in front of the leading bar edge, the increase in surface tension forces between fibres with increasing consistency above 35% - 40%, and the sharpness of the leading bar edge. All of these factors should still operate at higher strain rates or temperatures. Thus, it is anticipated that the trends observed in actual refining operations will be similar to those observed here. To support this claim, we have compared the results presented here with data from various refining trials in the literature.

Miles and Karnis have presented results indicating that the relationship between specific energy and axial thrust is linear, and exhibits different slopes depending on the type of pretreatment for hardwood (aspen) pulps [15]. In the same paper, they also presented data for softwood (spruce) which show a small but similar trend. To explain the differences in slope between the various types of pretreatment, Miles and Karnis suggested that the refiner...
was self-pressurizing during some of the tests. However, the refiner they used does not normally self-pressurize, and no temperature measurements were performed during the experiments in question in order to determine whether self-pressurization occurred. Since these trials were all performed at the same feed rate, this indicates that plots of motor load versus axial thrust would also show a linear relationship. Because the slope of the power versus axial thrust relationship is directly proportional to $\mu_{eq}$ in the absence of self-pressurization (c.f. Equation 4), an alternative explanation for the different slopes is that $\mu_{eq}$ depends on the type of pretreatment. It can be expected that the type of pretreatment will influence the flexibility of wood fibres and alter the ploughing component of the shear force, which would affect $\mu_{eq}$.

Franzen and Sweitzer have reported that $\mu_{eq}$ increases with increasing consistency and have shown data indicating that $\mu_{eq}$ decreases as bars wear down [21]. Miles and May have indicated that $\mu_{eq}$ is independent of consistency; however, they reported data only for discharge consistencies in the range 15% to 30% [22]. As mentioned above, we would not expect much difference in $\mu_{eq}$ at consistencies below about 35%, where free water is present in the floc. The data reported here indicate only a slight increase in $\mu_{eq}$ in this range of consistency, even for sharp bars and high grammage flocs (c.f. Figure 4). In the trials performed by Franzen and Sweitzer, a larger refiner was used than for those reported by Miles and May. Larger refiners typically operate at higher consistencies than smaller refiners and these higher consistencies, as well as differing degrees of bar wear, could explain any differences in the reported results.

Operational data from different sources are also in accordance with the results presented here. Strand and Hartler [29], and Stationwala et al. [30] have indicated that refining plate gap must be increased to maintain constant specific energy as discharge consistency is increased above 40%. The common explanation for this observation is that an increase in consistency causes an increase in pulp residence time, which results in a build-up of fibres between the plates and an increased plate gap [31, 32]. An alternative explanation is that the increased plate gap at constant specific energy is a result of an increase in $\mu_{eq}$ with increasing consistency.

McQueen et al. [33] have shown that motor load changes are inversely proportional to dilution flow rate adjustments at consistencies in excess of 40%, in agreement with changes in $\mu_{eq}$ in this range of consistency. Conversely, at refining consistencies in the range of about 20% - 35%, where $\mu_{eq}$ is relatively constant, we would expect motor load to be independent of consistency. Roche et al. have indeed found that motor load was insensitive to dilution flow rate adjustments at blow-line consistencies around 30% in second-stage TMP refining [34].

Roche et al. [34] also reported that primary motor load was more sensitive to changes in feed rate with new plates as compared with old plates. Strand and Hartler have indicated that plate gap must be reduced at constant specific energy, throughput, and discharge consistency as refiner plates wear down [29], and it is well documented that hydraulic pressure must be increased to maintain constant motor load as refiner plates age [35-38]. All of these results are consistent with a decrease in $\mu_{eq}$ as refiner bars wear down.

It should be noted that all of the effects reported above have been explained by a change in the corner force component of the shear force alone. Experiments performed by Senger using the single bar refiner, in which the corner force was a negligible part of the total shear force, have indicated that the coefficient of friction between the pulp and refiner bar surface ($\mu$) does not depend on consistency [16]. However, these experiments covered a smaller range of consistency than the present study and did not look at the effect of bar wear, or other factors such as chemical treatment. Thus, the real coefficient of friction between the pulp floc and the refiner bar may also have some influence on the results.

Two other factors deserve mention here: the alkalinity and the temperature at which pulp is refined. Engstrand et al. [23] have indicated that alkalinity affects $\mu_{eq}$ to some degree. Alkalinity affects the degree of swelling of the fibres [39-41], which could alter $\mu_{eq}$ by influencing the ploughing force, and it could also affect the coefficient of friction between the pulp and the refiner bar surfaces, which would alter $\mu_{eq}$ by influencing the friction shear force.

The temperature inside the refiner is another factor that could have an influence on $\mu_{eq}$, since temperature has a strong effect on the viscoelastic properties of wood [42-44] and pulp mats [45]. Refiners operate with temperatures anywhere from under 100 °C in smaller atmospheric discharge refiners, to over 180 °C under certain conditions in large commercial refiners [23]. Such a large range of refining temperature means that the stress-strain behaviour of pulp flocs can be vastly different in different types and sizes of refiners. Data from the literature indicate that temperature may indeed have an influence on the equivalent tangential coefficient of friction.
Figure 10 shows a plot of $\mu_{eq}$ versus refining zone temperature. The circles are data for a 914 mm non-pressurized refiner [22], and the squares are data for a 1067 mm self-pressurizing, atmospheric discharge refiner [46]. All data points are for first stage softwood pulps. Despite the large amount of scatter, the data suggest that $\mu_{eq}$ decreases as refining zone temperature increases. Such a trend would be expected from theoretical considerations because a higher temperature would result in more flexible fibres. More flexible fibres would offer less resistance to the bar edge as it ploughed its way through the floc. This decreased ploughing force would result in a lower value of $\mu_{eq}$.

![Plot of $\mu_{eq}$ versus refining zone temperature](image)

Figure 10: Equivalent tangential coefficient of friction vs refining zone temperature. Data obtained from various sources: the circles are data for a 914 mm non-pressurized refiner [22] and the squares are data for a 1067 mm self-pressurizing atmospheric discharge refiner [46].

**Energy-Quality Relationships**

The type of forces acting on the pulp flocs in a refiner will affect the resulting pulp properties. Normal forces have been shown to contribute to internal fibrillation of the fibre wall through transverse compression and bending of fibres [47, 48], while shear forces have been shown to cause external fibrillation [47]. It can also be surmised that fines are primarily generated from the shear forces in refining, although this has not been confirmed directly. It is clear from the data presented here and that reported in the literature, that the equivalent tangential coefficient of friction should be considered a variable in the refining process. As this parameter will determine the relative magnitude of compression and shear forces acting on pulp flocs in a refiner, it would be expected to have an influence on the quality of the pulp produced at a given energy.

In a recent paper, Alami et al. [49] showed a schematic of the effect of consistency on the energy-quality relationship in refining. This schematic has been reproduced in Figure 11. Three regions of consistency are defined: region I for consistencies above about 37%\(^1\), region II for consistencies in the approximate range of 23% to 37%, and region III for consistencies below about 23%. In region I, the energy consumption to a given pulp quality increases as consistency increases. In region II, the energy consumption to a given pulp quality is constant. In region III, both energy consumption and pulp quality decrease with decreasing consistency. Murton has also presented data confirming this energy-quality relationship, at least for regions I and II [32].

---

\(^1\) The transition points between regions are somewhat arbitrary and may be expected to depend on pulp furnish, refiner size etc.
The behavior in region III is well recognized as the inability to load the refiner at low consistencies. The result is a deterioration of pulp quality due to fibre cutting at very low plate gaps. This effect can be seen in the data of Figure 6 and Figure 8, where the normal stresses developed at a given plate gap begin to drop off at consistencies below roughly 20%.

The behavior in region I was described by Alami et al. as follows [49]:

“In region I decreasing consistency decreases the residence time of the pulp in the refining zone; refining intensity increases and the specific energy to a given pulp quality decreases.”

However, if this explanation were correct, it should be applicable to the whole range of consistency encompassing both regions I and II. Alami et al. recognize this fact and offer the following explanation for region II [49]:

“More difficult to understand are the reasons for the insensitivity of energy-quality relationship on consistency found experimentally in region II. It is conceivable that this is associated with the fibre saturation point, which may change the mode of refining (emphasis added) with the presence of free water in the refining zone.”

If the results from the experiments presented here can be applied to large refiners, then the change in the “mode of refining” can be explained by an increase in the normal stresses at a given plate gap as well as an increase in the equivalent coefficient of friction, with increasing consistency. Figure 6 and Figure 8 show an increase in normal stress at a given plate gap as consistency increases above about 50%, while Figure 4 indicates that \( \mu_{eq} \) increases as consistency increases above about 35%. Both effects can be ascribed to an increase in the strength of the floc structure due to increased surface tension forces between fibres. The ploughing component of the shear force may be more sensitive to surface tension forces between fibres than the normal force, and therefore \( \mu_{eq} \) exhibits an increase at a lower consistency than the normal stresses.

![Figure 11: Effect of refining consistency on pulp quality and energy consumption [49].](image)

In addition, the data of Figure 4, 6, and 8 also show that both the normal stresses and \( \mu_{eq} \) are relatively constant for consistencies between about 20% and 35% - corresponding to region II of Figure 11. This may explain why the energy-quality relationship is constant in this region.

CONCLUSIONS

Pulp flocs are acted upon by a combination of compressive and shear forces in refining. The shear force consists of a friction component acting over the surface of the refiner bars, and a corner or ploughing component acting over the leading edge of the bars. The ratio of the average shear force to the average normal force represents an
Equivalent tangential coefficient of friction, $\mu_{eq}$, and this parameter determines the power consumed during refining for a given mechanical thrust on the pulp in the refining zone.

Experiments performed on individual flocs in a single bar refiner have shown that $\mu_{eq}$ increases as consistency rises above about 35% and that this increase is larger for higher grammage flocs. The experiments also indicate that the sharpness of the bar edge has a significant influence on the corner force for flocs of sufficient thickness, resulting in lower values of $\mu_{eq}$ as refiner bars wear down. Data from the literature indicate that the type of pretreatment, the alkalinity of the pulp, and the refining temperature also have an influence on $\mu_{eq}$. Taken together, these results suggest that the equivalent tangential coefficient of friction should be considered a variable in the refining process. This parameter determines the relative magnitude of the shear and compressive forces acting on pulp flocs and will have an impact on energy-quality relationships. The results presented here offer an explanation for observed changes in energy-quality relationships under different refining conditions.

**NOMENCLATURE**

- $C_f$: consistency
- $E$: specific energy
- $F_a$: axial thrust
- $F_m$: mechanical thrust
- $F_s$: steam thrust
- $h$: constant (1 for a single-disc refiner, 2 for a double-disc refiner)
- $\dot{m}$: oven dry mass throughput
- $N$: normal force
- $P$: net instantaneous refining power
- $r_1$: inner radius of the refining zone
- $r_2$: outer radius of the refining zone
- $\bar{r}$: average radius of refining zone
- $S$: shear force
- $S_f$: friction component of the shear force
- $S_c$: corner/ploughing component of the shear force
- $T$: gap between the bars of the rotor and stator
- $W$: grammage (mass per unit area)
- $\mu$: coefficient of friction between pulp and refiner bar
- $\mu_t$: tangential coefficient of friction
- $\mu_{eq}$: equivalent tangential coefficient of friction
- $\omega$: refiner rotational speed

**REFERENCES**

32. Murton, K. D.: Effect of primary stage refining consistency on TMP pulp quality and energy consumption. 51st Appita Annual General Meeting, s.l., 1997, 87-94.


Mechanical Pulps – Added Value for Paper and Board

PROCEEDINGS

VOLUME 1

June 4–8, 2001
Helsinki Fair Centre, Helsinki, FINLAND