# New technique for measuring clearance in low-consistency refiners

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## SUMMARY

Refiner action depends on forces applied to fibres, and stresses on fibres are functions of strains reached, which in turn are related to the actual gap clearance. Hence, bar gap clearance has a major impact on fibre treatment, and this has been pointed out in previous studies. However, gap clearance measurements reported in the literature are questionable and in this study we obtained measured values that are significantly larger.

The experimental values obtained in this study, carried out with a linear variable differential transformer (LVDT) displacement gauge to measure gap clearance, indicate some new features of the mechanical behaviour of refiner. Firstly, an "out-of-tram" effect producing a lack of parallelism has been shown to be a feature on low consistency refiners. Secondly, the disc closing force when pulp is flowing cannot be achieved when only water is flowing.

We discuss the consequences of this new experimental evidence and clarify some previous observations reported in literature, in terms of our gap clearance measurement procedure.

Finally, a new protocol to measure the absolute value of the gap clearance is proposed.



### KEYWORDS

Disc refiner, force, friction coefficient, gap clearance, low-consistency, mathematical model, measurement protocol, wood pulp refining, sensor.


## INTRODUCTION

The main goal of pulp refining is the development of papermaking properties of fibres. Refining action takes place by imposition of cyclical stresses on fibres, which create new surfaces on the outer layer (external fibrillation) and delamination of the cellular wall (internal fibrillation). Stresses are a consequence of the stapling forces on fibre bundles, which lie on the leading bar edges, when rotor and stator bars overlap each other.

After refining, the final quality of pulp is therefore a consequence of forces applied on fibres during the process and the number of cycles which the fibres undergo.

It is difficult to measure these elementary forces applied by bars to fibres. Therefore, since Smith's papers (*1,2*) on a Valley beater at the beginning of the last century, refining action has been described mainly by a couple of parameters. Nowadays, and since Wultsch and Flucher (*3*) investigations, they are mainly related to power and energy refining consumption. One of these parameters takes into account the number of cycles of stress (the specific energy consumption). The second takes into account the mean impact intensity (specific edge load).

However, the refiner effect is based on forces applied on fibres (*4*): the energy parameters described above represent their "transposition" in measurable parameters.

Stresses exerted on fibres in the crossing areas are a function of strains applied in the refiner. Indeed, the rheological behaviour shown by fibres is a consequence of several parameters, such as the heterogeneity of the bar edge coverage, the leading edge rounding, the quality of fibres and their refining state, the strain rate or the gap clearance. Moreover, the strain applied to the fibres is directly linked to the gap clearance. In this way, gap clearance has a major role on fibre treatment.

Hietanen (*5*) has considered gap clearance as an indicator of pulp treatment. More recently, some experimental evidence of the importance of gap clearance has been presented. For example, Mohlin (*6*) has demonstrated a relationship between gap clearance and refining intensity. The results indicate that refining intensity is proportional to the inverse of gap clearance. Lundin and Batchelor (*7*) have simultaneously measured gap clearance and net power consumption of a laboratory scale refiner. They have pointed out the presence of a critical gap (already outlined by Roux (*8*)). Furthermore, they emphasise the relationship existing between power consumption, strain of fibre bundles and gap clearance.

Gap clearance appears to be a basic parameter in physical modelling of refining, as it is in the hydromechanic theory (*8*) and C-factor theory (*9*). Gap clearance allows us also to link the force developed during bar crossing to properties of fibre bundles, fibre length, fibre coarseness or floc dimensions (*10,11*).

In summary, gap clearance is a key variable in studying beating or refining.

Industrially gap clearance is not yet considered as a way to control a refiner and its measurement has been developed essentially for research purposes on pilot-scale refiners (although some research has been carried out with eddy current non-contact displacement transducers mounted on commercial refiners (*12*))

The measurement of gap clearance has been carried out by two means: either by eddy current non-contact displacement transducers or by LVDT gauges. The first method has been used on a chip refiner (*13*), a disc refiner and a conical refiner (*14*). In these studies, the gauge has been installed directly inside a stator bar or at the outer radius of the stator. Out-of-tram and run-out problems have been detected on chip refiners and their consequences on the gap measurement have been analyzed (*13,15*). Difficulties in the contact point determination were experienced (*14*). The "Contact point" is defined as the point at which discs are in contact and gap clearance is assumed to be zero: gap clearance is measured using this point as a reference.

Methods to measure gap clearance with LVDT gauges have also been developed at EFPG. A brief description of this measurement system is given in the experimental method section of this paper. This method has already been described in several earlier publications (*16,17,18*). As in the first method, difficulties in the contact point determination were experienced. Indeed, only relative variations in gap clearance could be measured.


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It has to be emphasised that there is general agreement on the magnitude of the changes in gap clearance during a refining trial (*7,14,16,17,18*). However, there is no general agreement about the absolute amplitude of the gap clearance: Nordman et al. (*14*) have found gap clearances as narrow as 10 µm for softwood pulps; more recently, Mohlin (*6*) and Batchelor et al. (*7*) found larger gaps. Radoslavova (*19*) measured gap clearance in a Voith laboratory beater between 100 and 500 µm.

However, in this previous work, no details are available on the chosen measurement protocol. Further investigations on the disc contact position must be carried out to propose a measurement protocol to reach the absolute value of gap clearance.

In the following sections, we discuss the LVDT solution for gap clearance measurements. The possible sources of error are also investigated (laboratory equipment section). New experimental evidence related to the refiner behaviour is discussed. The sources of error are then explained and quantified in the experimental results section. A new protocol for gap measurement is then proposed in the discussion section.

Finally, it is shown that gap clearance values, measured with the new proposed protocol are in agreement with other indirect characterisations of the pulp behaviour in a disc refiner.

## LABORATORY EQUIPMENT AND DISCUSSION

A schematic view of the set-up used for gap clearance measurements with a LVDT gauge is presented in Figure 1.

An LVDT gauge is a current transformer with a primary coil and two secondary coils. The mutual induction between them is assured by the mobile ferrite core. Differences among inducted coil voltages are linearly linked to the core position.

The ferrite core of the LVDT gauge is mounted on an iron bar, which is screwed directly on the rotor plate centre. The induction coils are direct mounted on the stator plate, which is mounted on the refiner case. The rotor disc is mounted on the centre shaft. Gap clearance is controlled by the centre shaft, whose axial movement is generated by a motor.

This gauge has been mounted on a pilot-scale single-disc refiner. It is characterised by an external radius of 0.15 m and an internal radius of 0.065 m. The maximum operating power is 45 kW.

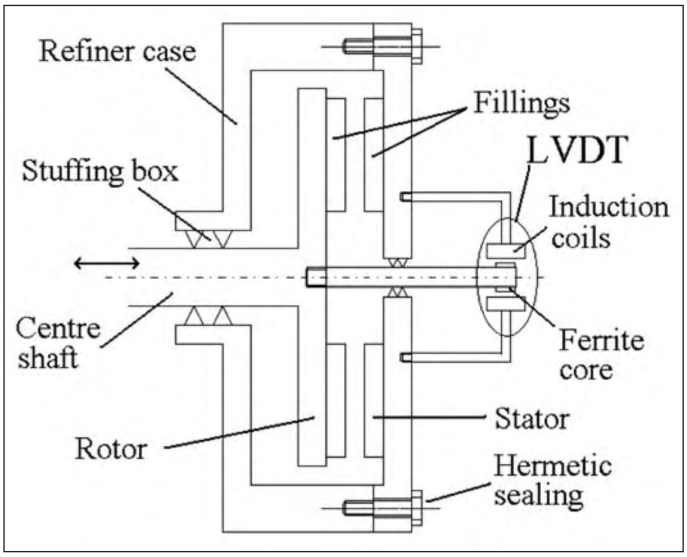


**Fig. 1 Schematic view of the gap clearance measurement method. This scheme is out of scale and proportions do not match.**

Two different plate patterns were used during the experiments:

1. grinding code (3-3-4) in 1/16 inch, grinding angles +10°/+15°, sector angle 22.5°;
2. grinding code (3-3-4) in 1/16 inch, grinding angles +5°/-5°, sector angle 22.5°.

The two plate patterns gave similar results. In the following sections experimental results obtained with the second pattern are shown. The interested reader is asked to refer to (*20*) for the geometrical definitions.

Using a LVDT gauge for gap clearance measurement has several practical advantages compared to other direct measurement solutions with proximity gauges. Firstly, it can work without any contact. Furthermore, it is suitable for a corrosive environment. Finally the gauge is located externally of the refiner case so that any eventual disc clashing has no effect on the gauge.

Gap clearance values are determined with respect to a reference position: the disc contact point. However, from Figure 1 it is obvious that the relative position between the ferrite core and the induction coils can be affected by the setting of the refiner during operation. In particular, the three following parameters could influence the gap clearance measurement:

1. pulp suspension temperature: the temperature, increasing during refining trial, could induce differential thermal expansions in the refiner case and, hence, deformations;
2. disc normal net closing force: disc closing net force $F_C$ represents the force, normal to the disc surfaces, that pushes them against each other, minus the pressure force generated by the suspension flowing through the discs. The net force $F_C$ can induce deformation in the refiner structure;
3. hydraulic pressure in the refiner case: pressure variations during operation can also induce deformation in the refiner structure.

Hence, a measured contact position between discs is strictly only valid for the same value of these three parameters. We show later however, that because of the geometry of the refiner case and of the LVDT gap clearance gauge, pressure in the refiner case has almost no influence on the gap measurement.

Several methods to determine the disc contact point have been proposed. Chaussy (*17*) and Mayade (*16*) suggested that the contact point is almost achieved when a non-specified huge power is absorbed by the refiner during a refining session. Nordman et al. (*14*) defined the contact point in a conical refiner as the point at the end of the refining test with an empty refiner case, when, with the motor disconnected but the disc still rotating, the rotor is pushed into metallic contact with the shell of the stator.

The temperature influence on the contact point position was taken into account by Dietemann (*18*), however, only gap clearance variations are shown in his work. A detailed procedure to evaluate the influence of the temperature of the flowing suspension on the gap clearance is also given in his paper.

To assure metal contact between discs, and not just an 'increased bruising', it is our contention that water, rather than pulp suspension, should circulate in the refiner case. Moreover the contact point should be settled at the same conditions in which gap clearance will be measured. This means that the contact point should preferably be settled at the same temperature conditions, at the same closing force and at the same hydraulic pressure in the refiner case at which gap clearance measurement takes place during refining. However, the same functioning point at which gap clearance will be measured cannot be achieved when only water is flowing (instead of pulp), as will be shown later, and consequently the influence of each parameter listed above on the contact point must be evaluated separately.

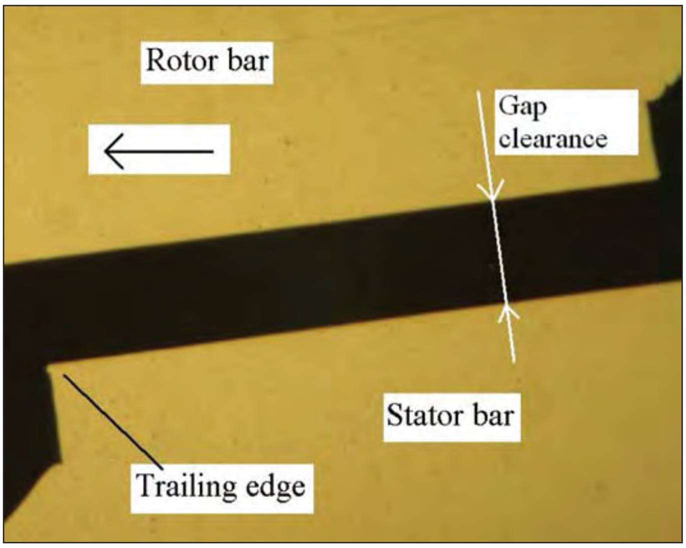


**Fig. 2 Example of a prepared imprint slice to determine gap clearance.**

## NEW EXPERIMENTAL EVIDENCE

In the following sections some new experimental observations on a refiner are reported, and consequences on gap clearance measurements will be discussed.

### "Out-of-tram"- lack of parallelism of refiner discs

Gap clearance between discs has been measured at several points of the refining surface. A replicating compound (Microset rubber replicating compound, produced by MICROSET PRODUCTS LTD, http://www.microset.co.uk/) was poured on the bar surface. Then the refiner door was closed until the compound set. The imprint was then included in fluid rubber of a different colour to be sliced and visualized. Cross sections were digitally photographed and analysed with Matlab software (a Math Works Inc. software http://www.mathworks.com) to calculate the gap clearance separating the two surfaces. An example illustrates one of the slices (Fig. 2).

In Figure 3, a typical example of the spatial distribution of the gap clearance determined by this method is shown.

Several refiner discs have been tested on both pilot refiners with similar gap distributions. But a constant gap distribution was observed when the rotor was rotated after several refining tests and re-mountings of the fillings. This is clear evidence of an "out-of-tram" problem as Stationwala et al. (*15*) have already discovered for double disc chip refiners. What is significant is that gap variations, due to this lack of parallelism, are of the same magnitude, or greater, than the gap clearance classically measured in low-consistency refining (20-200 µm).

### Closing force versus power consumption determined in water

We pointed out in the laboratory equipment section that the contact point should be settled at the same functioning conditions at which gap clearance will be measured, in terms of disc net closing force, pressure in the refiner case and temperature. However, when water is flowing in the refiner, this functioning point can not

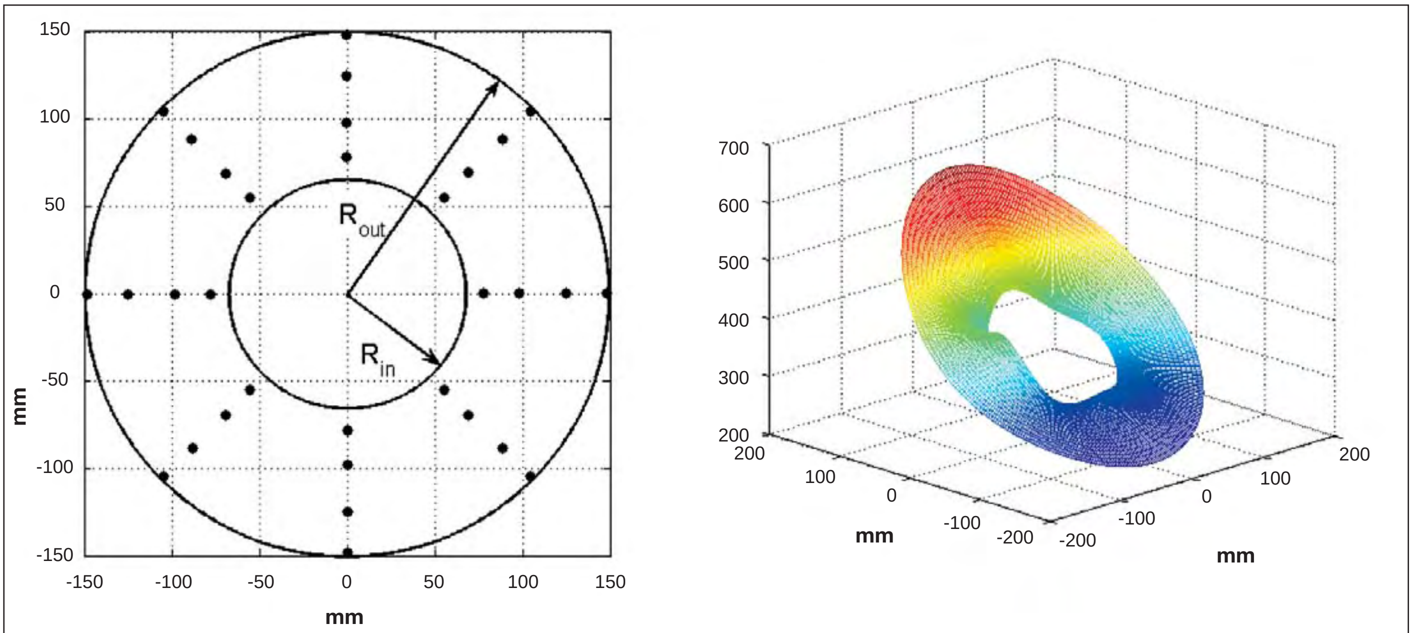


**Fig. 3 On the left (a), points where gap clearance has been measured are indicated. Measured gap clearances have been interpolated with spline functions (b). In both figures, the (0,0) position corresponds to the rotor and stator centres.**

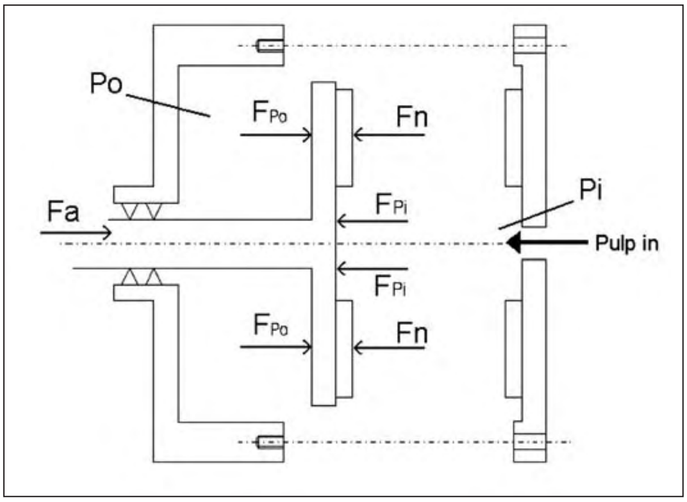


**Fig. 4** **Forces acting on the rotor disc are shown. This schematic view is consistent with Figure 1. *Fa* is the axial force, *Pi* and *Po* are the inlet and the outlet pressure which generate $F_{Pi}$ and $F_{Po}$ forces respectively, Fn is the force acting on the refining corona.**

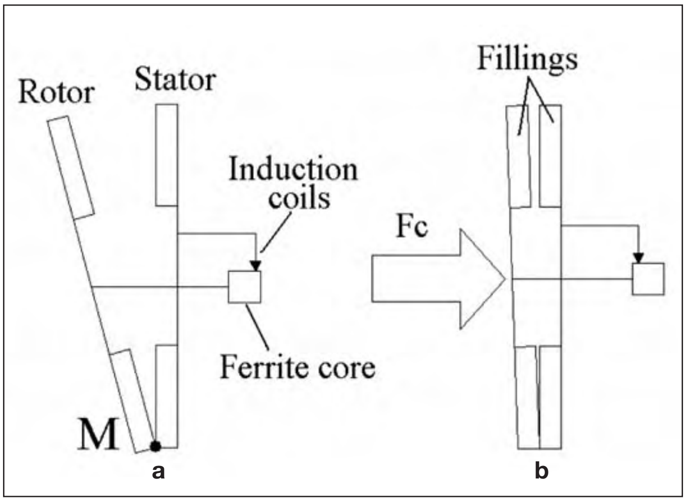


**Fig. 6** **Contact point position variation when closing force $F_C$ is applied from a) to b).**

be achieved. Indeed, from the balance of forces acting on the rotor disc (Fig. 6), the normal net closing force $F_C$ is defined as the difference between the normal force $F_N$ acting on the refining corona at the load stage (discs into contact) and the no-load stage (no contact between discs). Forces were calculated when the rotor was rotating and water flowing through the refiner case. The rotor disc was moved axially to control gap clearance, and the centre shaft was equipped with a force gauge.

In Figure 5, the total power consumption of the refiner and the closing force are drawn for the same disc closing event. From a physical point of view, when water is flowing, $F_C$ represents the normal force developed in the iron-iron contact surface between discs.

Idling power can be found from Figure 5 (b), to be about 10 kW. Net power is defined as the difference between the total power when discs are in contact and the total power absorbed by the refiner when discs are not in contact (back-away position).

For a net closing force $F_C$ of about 3000 N, the total power absorbed is about 16 kW. With water, higher net power consumption cannot be achieved because of the potential damage to the discs.

For this pilot refiner, net serration forces classically measured during a refining trial lie between 3000 and 9000 N.

A net closing force $F_C$ of about 3000 N is achieved for a net power of about 8 kW when pulp is flowing (Table 3). Indeed, as expected, the friction coefficient when pulp is flowing is different from the friction coefficient when water is flowing.

### Consequences on gap clearance measurement of the new evidence

Disc out-of-tram has been measured when no serration force is applied on discs. However, as previously pointed out for a chip refiner (*13,15*), refining forces have the positive effect of reducing the disc tilting. Hence, the evolution of the non-parallelism must be considered when closing force is gradually applied to the discs. Geometrically, it means that the contact point, measured at the initial contact between rotor and stator bars, does not correspond to the contact point when refining forces are applied and disc tilt is reduced (point M, Fig. 6).

From Figure 5 and from the discussion in the previous paragraph, it can be inferred that iron-iron friction coefficient

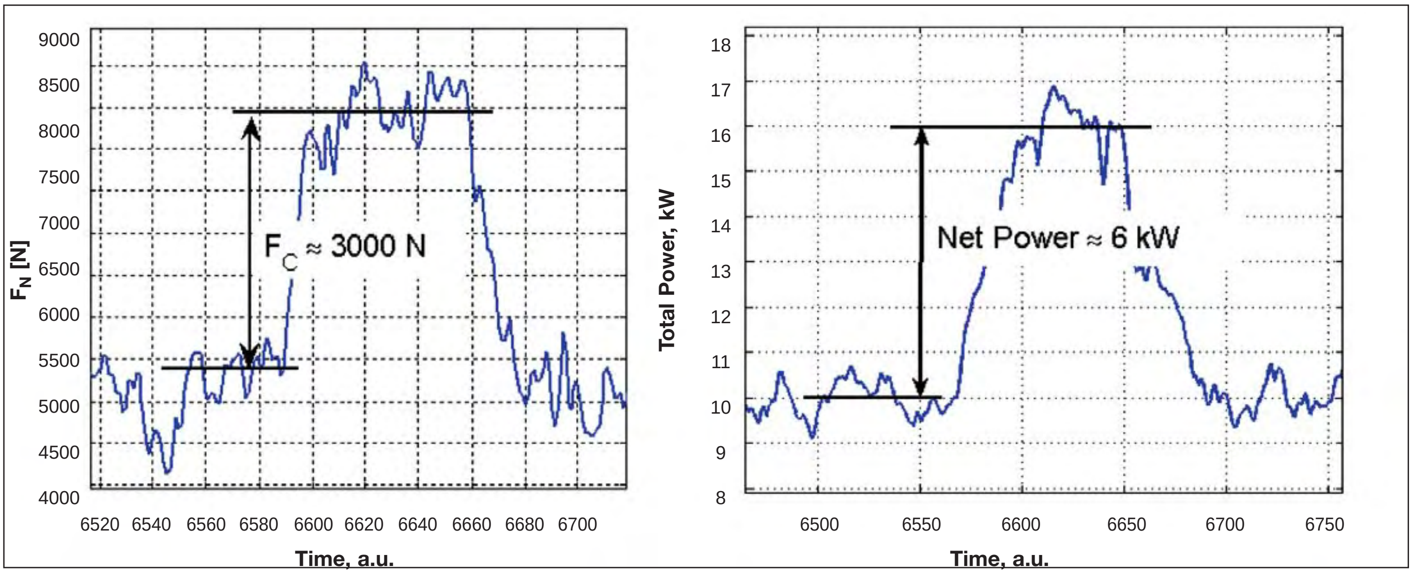


**Fig. 5** **In figures a and b the closing force and the total power are shown for the same approaching event, when water is flowing. Closing force (a) is calculated with the equilibrium equation of the rotor disc. Total power absorbed by the refiner was measured by a wattmeter. Time is given in arbitrary units.**

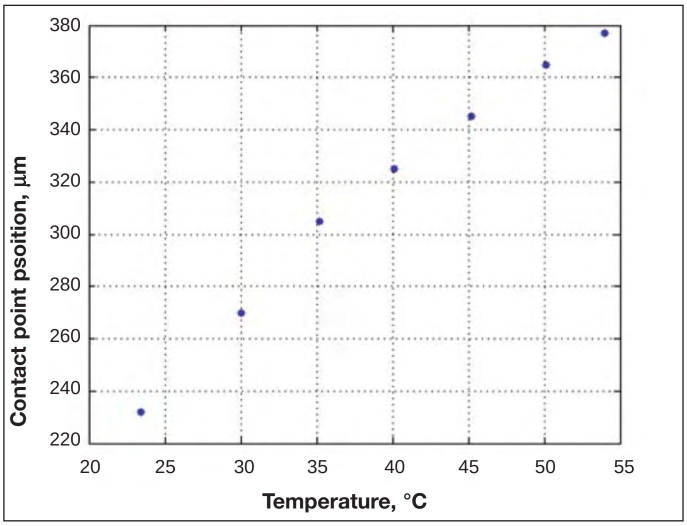


**Fig. 7** **Contact point position between discs, given by the LVDT gauge, as a function of the temperature of the flowing water in the refiner case. Contact point positions were settled at a net power consumption of 7 kW, constant for every temperature. At the beginning of the trial, flowing water and refiner case were at the thermal equilibrium; the temperature rise rate is 0.5 °C/minute.**

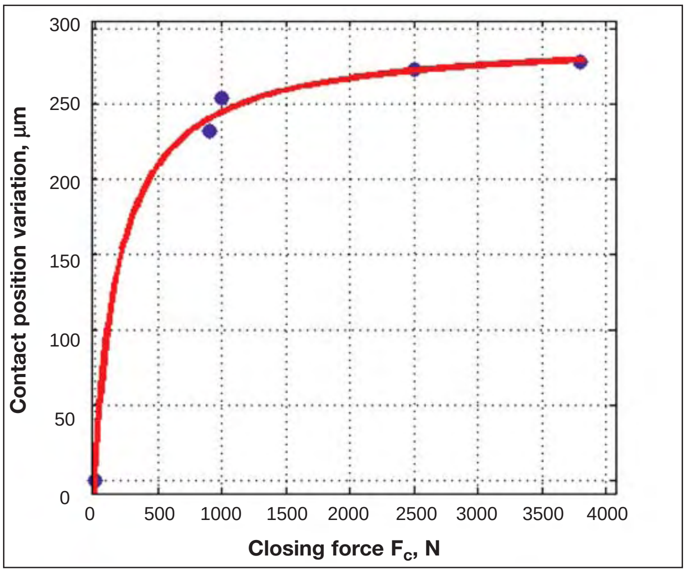


**Fig. 8** **Contact position variation versus the net closing force $F_C$ is drawn. Experimental points and their homographic regression are shown.**

is different from iron-fibres friction coefficient. Moreover, from a practical point of view, we have a limit on the power consumption when water is flowing. Hence the same operation point, at which gap clearance should be measured with water instead of pulp suspension circulating in the refiner, cannot be achieved in terms of closing force applied on discs.

Finally, the influence of the normal net closing force and of the pulp suspension temperature must be evaluated separately.

## EXPERIMENTAL RESULTS

### Thermal expansion

The influence of temperature on contact point position has been firstly considered in a range from 24 to 55°C. During the experimental session, water was circulating and the refiner motor was connected. Due to turbulences inside the refiner, the temperature continuously increased. Every 5°C, discs were put in contact. Contact between discs was revealed by a rapid increase in absorbed power. Hence, the contact point was determined, for a net power consumption of 7 kW at all temperatures.

Linear regression of the experimental points reported in Figure 7 gives a thermal correction of +4.7 µm/°C. This kind of thermal correction has classically been used to take into account temperature variations in the flowing suspension (*13,14,15*).

To check the application of this correction technique at the beginning of the refining trial, we measured contact position with

**Table 1**
**Contact point position between discs, given by the LVDT gauge, is reported as a function of the time elapsed from the beginning of the refining trial. Contact positions were settled for a net power consumption of 7 kW. At the beginning, flowing water and refiner case were not at thermal equilibrium. The rate of temperature increase was: 0.7 °C/minute.**

| Time elapsed min | Contact position µm | Actual temp. °C | Thermal correction µm/°C | Time elapsed min | Contact position µm | Actual temp. °C | Thermal correction µm/°C |
|---|---|---|---|---|---|---|---|
| 2 | 1018 | 28 | | 9 | 1066 | 33.2 | 9.3 |
| 3 | 1030 | 29 | 12 | 10 | 1072 | 33.8 | 9.3 |
| 4 | 1035 | 29.6 | 10.6 | 11 | 1076 | 34.5 | 9.0 |
| 5 | 1040 | 30.3 | 9.6 | 12 | 1082 | 35.1 | 9.0 |
| 6 | 1049 | 31 | 10.3 | 13 | 1086 | 35.8 | 8.7 |
| 7 | 1053 | 31.7 | 9.5 | 14 | 1091 | 36.4 | 8.7 |
| 8 | 1060 | 32.3 | 9.6 | 15 | 1094 | 37.1 | 8.5 |

an independently imposed water temperature time profile. (The profile used corresponded to the profile we observed in practice in the pulp during a refining trial.) From Table 1, it is obvious that the thermal correction coefficient is not constant versus time and depends on the time elapsed from the beginning of the trial, on the actual temperature (hence of the heating rate) and on the temperature difference between the refiner temperature and the flowing water at the beginning of the trial.

For this reason, no equation is proposed to describe the influence of temperature on contact position. Instead, experimental measurement of contact position for a water temperature time profile equal to observed time profile of the pulp temperature during a refining trial is suggested.

Then, variation of the disc contact position, due to temperature rise, can be taken into account by the following formal relationship:

$$\Delta CP_T(t,T_0,T) = f_T(t,T) \quad [1]$$

where $t$, $T_0$, $T$, $\Delta CP_T$ and $f$ represent the time elapsed, the temperature of the refiner at the beginning of trial, the actual temperature of the flowing water, the contact point position with respect to the contact point before the trial and a generic function, respectively. The general form of the function $f_T$ is not known. Indeed our experiments show that $\Delta CP_T$ must be evaluated individually for each refiner and for each rate of temperature increase.

### Closing force

The contact position was measured at several forces FC ranging from 0 to 3800 N.

**Table 2.**
**Influence of the pressure inside the refiner case on the contact position. Figures 7 and 8 apply to determine the corrected contact position.**

| Flow rate $m^3$/h | Inlet pressure bar | Outlet pressure bar | Temperature °C | Fc N | Contact position, µm | Corrected contact position, µm |
|---|---|---|---|---|---|---|
| 9.6 | 2.08 | 3.08 | 30.2 | 3100 | 379 | 379 |
| 5.0 | 2.31 | 3.35 | 31.7 | 3500 | 387 | 379.5 |

Net power consumption depends on the applied closing force and in this study a closing force of 3800 N corresponds to a net power of about 7 kW, which, as discussed earlier, could not be exceeded for the potential damage to discs.

Contact position variation, as a function of the closing force, was measured with the refiner motor connected and with water flowing in the refiner case. Contact position for $F_C$=0 is determined as the position at which the first bruising occurs. The contact point changed with respect to the closing force, showing an asymptotic behaviour for high values of the closing forces $F_C$ (Fig. 8).

A simplified form of a homographic function has been used to fit this curve:

$$f_F(F_C) = \frac{a\,F_C}{F_C + d} \qquad [2]$$

where $F_C$, $a$ and $d$ represents the closing force and the coefficients of the homographic function respectively.

The asymptote of $\Delta CP_{F_C}$ when $F_C$ approached large values, is equal to a.

The proposed homographic equation has no physical significance and merely describes the asymptotic behaviour of the experimental curve, empirically.

These measurements appear to be consistent with the gap clearance distribution shown in Figure 3.

Hence, the variation of the contact position can be expressed by the following relationship:

$$\Delta CP_{F_C}(F_C, F_{C0}) = \frac{ad(F_C - F_{C0})}{(F_C + d)(F_{C0} + d)} \qquad [3]$$

where $\Delta CP_{F_C}$ is the variation (µm) with reference to the contact position measured at a closing force $F_{C0}$ (Newton).

The asymptotic behaviour can be explained by the observed out-of-tram behaviour: as discs are forced against each other, the contact surface increases and the serration force needed to produce additional deformation arises continuously.

Moreover, since a net closing force $F_C$ of about 2000 N is enough to produce correction of the parallelism error between discs, it can be supposed that during refining, the discs are operating parallel to each other.

### Influence of pressure in the refiner case

The contact position was measured for two different outlet pressures. Variations in the outlet pressure were obtained by altering the refiner flow rate. In Table 2, flow rate, inlet and outlet pressure, net closing force $F_C$, contact position and the corrected contact position (taking into account the temperature and net closing force) are shown. The pressure variation considered in Table 2 is larger than the usual pressure variation during a refining trial.

## DISCUSSION

### A new protocol for gap clearance measurements

Two functioning parameters must be taken into account for effective correction of the contact point measurement. These two parameters are the time profile of the flowing suspension temperature and the closing force.

Equations 1 and 3 provide relationships between the contact position variations and changes in temperature the force $F_C$, respectively. We propose a correction relationship as follows :

$$CP(t, T_0, T, F_C, F_{C0}) = CP_0 + \Delta CP_T + \Delta CP_{F_C} \qquad [4]$$

Where $CP_0$ represents the contact position measured at a temperature $T_0$ and at a closing force $F_{C0}$. Introducing Eq.1 and Eq.3 into Eq.4 leads to the following expression:

$$CP(t, T, T_0, F_C, F_{C0}) = CP_0 + f_T(t, T_0, T) + \frac{ad(F_C - F_{C0})}{(F_C + d)(F_{C0} + d)} \qquad [5]$$

The contact point correction due to the closing force (which commonly is varied between 3000 and 9000 [N]) is almost constant during any one refining trial, being virtually at its asymptotic value. (Fig. 8)

Hence, the practical consequence of Eq.5 is that the real gap clearance is much larger than the measured values presented in the literature. To avoid further discrepancies we propose a new protocol for gap clearance measurements:

1. measurement of the contact point position $CP_0$, for an empty and stopped refiner, at a temperature $T_0$ and at a closing force $F_{C0}$;
2. characterisation of thermal expansion effects on the contact position;
3. characterisation of the influence of the net serration force on the contact point position.

(Of course in the case of a measurement with a proximity gauge, only steps 1 and 3 have to be carried out)

### Case study

In Figure 9 an example of gap clearance measurement during a refining trial is shown. The proposed protocol was applied to achieve these corrected values. Plates with a grinding angle of +5°/-5° were used to refine mixed softwood bleached kraft pulp. The trial was performed with a constant SEL of 1.30 W/m and a final specific energy of 210 kWh/t. Bleached mixed softwood kraft pulp was used. The initial approaching of discs and the moving away at the end of the trial are noticeable.

The gap clearances in Figure 9 are much larger than gaps generally presented in the literature, and it is our contention that gap clearances of around 20 µm, commonly proposed for high specific refining energy, vastly underestimate the real value. The following analysis of the stresses involved in the gap supports our contention.

In Table 3, a comparison between normal closing force and gap clearance for two refining tests is shown. The two refining trials have been carried out at two different total power consumptions and they were run with the same bleached kraft mixed softwood pulp. Data have been taken at the beginning of the process, so that fibre suspensions are exactly the same.

We stress that net closing force does not exceed 6000 N at the beginning of the refining tests.

Where conventions of the hydromechanic theory apply (*8*) the inter-crossing bar area $A_{IC}$ is computable with the following expression:

$$A_{IC} = \xi\pi\left(R_{out}^2 - R_{in}^2\right)^{-3} \qquad [6]$$

and for the discs used in this trial this expression is =$14.34 \cdot 10^{-3}$ m$^2$ . ($R_{in}$, $R_{out}$ and ξ represents the inner and the outer radius of the refining disc (Fig. 5) and the

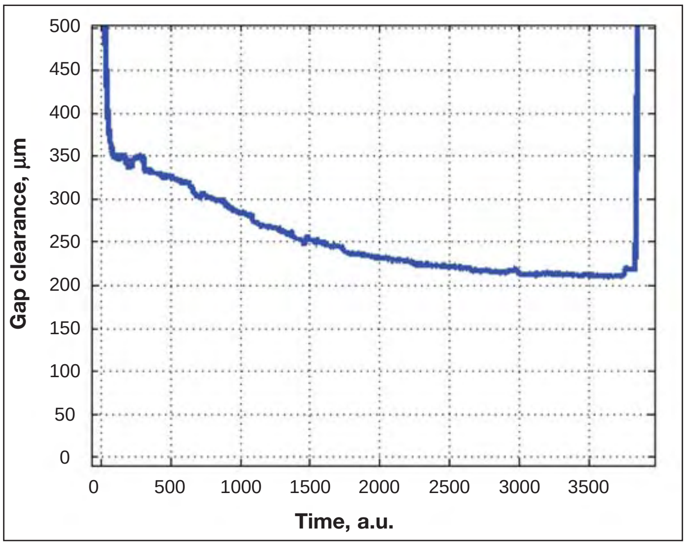


**Fig. 9 Corrected gap clearance evolution during a refining trial.**

**Table 3**
**Gap clearance and net closing force $F_C$ are compared at the beginning of the refining trial for two different total powers.**

| Total power [kW] | Gap clearance [µm] | $F_C$ [N] |
|---|---|---|
| 28 | 350 | 5600 |
| 22 | 385 | 3000 |

inter-crossing bar area fraction, respectively)

Hietanen and Ebeling (*22*) have pointed out that fibres may be considered as flocs and consequently, just a fraction of the inter-crossing area is covered by fibres. Kerekes et al. (*23*) have studied this fraction and they assume that only about 25% of the total inter-crossing area is covered by fibres. Using this figure, the pressure on the fibrous structure, for a net closing force of 5600 N, is:

$$P_S = \frac{F_C}{0.25 A_{IC}} = 15.6 \times 10^5 \quad Pa \qquad [7]$$

meaning that the mean pressure on fibrous structure does not exceed 20 x $10^5$ Pa for the case considered here.

As Kerekes et al. have pointed out (*23*) and Amiri et al. have shown experimentally (*21*), as stress is increased on a pulp pad the strain approaches a constant level at about 0.25 MPa and further increases in stress do not induce any additional strain. This strain would be equivalent, for a kraft pulp pad close to those arising in the bar gap, in terms of number of fibres, consistency and strain rate, to about 0.4-0.5 mm for a pressure pulse of 0.25 MPa ((*21*) - Fig.8). This result is consistent with the magnitude of our corrected gap clearance in terms of the thickness of the pulp pad.

Further evidence of the validity of our measurement protocol is that the gap clearance sizes we measured are in good agreement with Radoslavova's measurements (*19*).

## CONCLUSION

Several parameters can affect the gap clearance measurement in low-consistency refining.

The results showed that two parameters must be taken into account for an effective correction of gap measurement. In addition to the well known temperature dependence, the effect of the closing force must be considered due to the presence of an out-of–tram lack of parallelism between discs. An incorrect account and/or no account of the closing force effect may produce errors of the same magnitude as the measured gap clearance. Furthermore, temperature and closing force effects must be evaluated separately. As a result of these observations, a new protocol for gap clearance measurements has been proposed, and its practical application described.

Consequences of the application of the new protocol on the absolute value of the measured gap clearance were discussed. A larger gap clearance is implied compared to the previous reported values in the literature, and these larger magnitudes are shown to be consistent with other indirect predictions of the pulp behaviour in a disc refiner.

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