Development of a mechanical model of the doctor blade-press roll tribosystem with the aim to optimize the cleaning performance: numerical predictions and first experimental verification

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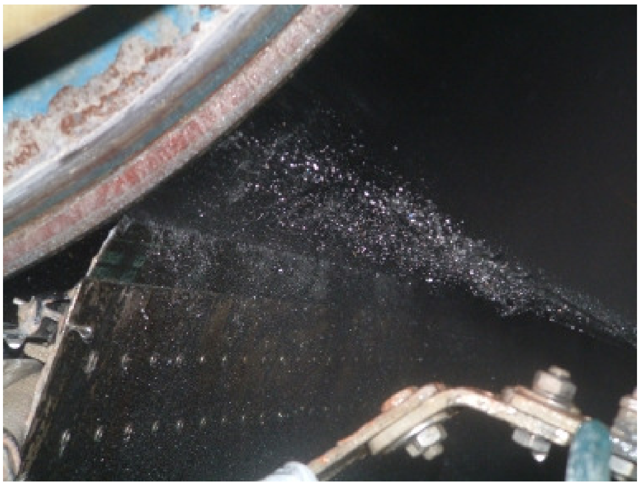
Abstract: In the paper production, doctor (scraping) blades are placed in contact with press rolls during wet pressing so as to purge the surface of the rolls from processing water, contamination, and stickies. The contact is achieved by mounting the blade on a holder, which is tilted around a rotation axis until the blade tip contacts with the roll. The contact force is determined by the supply pressure of the air forced through the tube that is placed at the bottom of the holder. Due to contact, the blade wears off and needs to be replaced periodically. Our aim is to optimize the cleaning performance of the system by modelling the tribological contact between doctor blade and press roll, in order to achieve an optimum cleaning performance, thus increasing the blade lifetime and reducing energy consumption. The model is susceptible to an inextensive numerical evaluation, as compared to that of a more advanced modelling approach, e.g in terms of a full finite-element analysis of the beam deflection. A first comparison with experimental findings is encouraging.

Key words: Paper industry, doctor blade, hydrodynamic lubrication, wear

1. INTRODUCTION

Modern papermaking factories are divided in four main sections, namely the forming section, the press section, the drying section and the calender section. Through these sections, the paper pulp is processed until a homogeneous paper sheet is produced. [1]

In the present paper, we focus on the wet pressing section, where the paper pulp gradually reduces its water content by passing between series of rolls and by being pressed against them. As the paper pulp passes over the press roll and moves to the next one (1), a certain amount of water containing contamination particles remains on the roll's surface. In order to keep its surface clean from particles and avoid contamination of the continuously flowing pulp, a scraping blade –known as doctor blade– is pressed against the roll's surface. [2-4] The blade contact force against the roll is determined by the air pressure applied to a polymer hose. A large pressure flow causes a higher contact pressure at the blade tip, which improves the cleaning performance at expenses of higher energy consumption and an increased wear rate of the blade.



1 Press section of a paper machine. The doctor blade keeps the press roll surface clean from contaminations and splash water.

Due to the interest of the industry to save energy costs and an increasing pressure of lawmakers to reduce the immense energy consumption at paper mills, [5] there is great potential for energy saving if a more efficient cleaning strategy could be achieved. The large number of subsequent rolls used in the press section and their large dimensions provide room for improvement in order to reduce energy costs, avoid pollution and increase profit. According to the International Energy Agency,[6] the pulp, paper and printing industry was in 2004 the fourth largest industrial consumer of energy with a share of 5.7% of the total industry energy use. The estimated total electricity consumption in a newsprint paper machine is 590 kWh/t.[7] Most of this electricity consumption (31%) occurs in the press section.[8]

In a recent study, Holmberg et al.[9] have drawn the attention of the tribological community to the problematic of friction losses in paper machines. In their comprehensive analysis, they calculate that 32 % of the electrical energy and 9.6 % of the total energy used in paper machines is consumed to overcome friction, thus quantifying the potential room for improvement. According to their study, friction losses could be reduced by 11% in the short term just by applying state-of-the-art tribological solutions, and up to 23.6 % in the mid and long term.

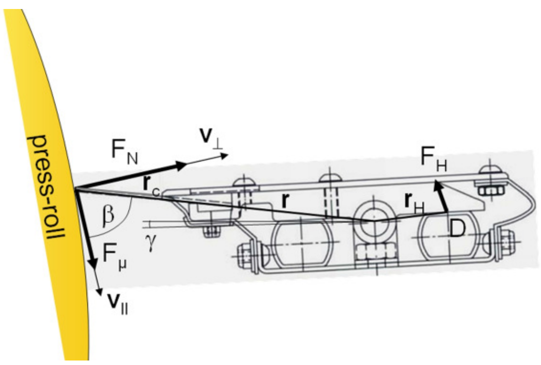
Nowadays the optimum process parameters set at the doctor blade – press roll tribosystem are based on the accumulated experience during years. The aim of this work is to develop a comprehensive model of the tribosystem in order to optimise the cleaning performance of doctor blades through a systematic and scientific approach

2. NOTATION

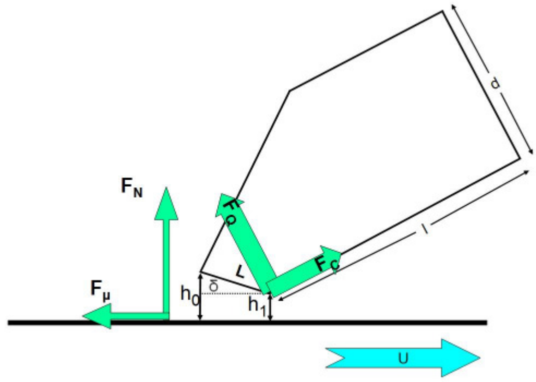
In what follows, a list of the symbols and variables used in the paper is provided (see also 2).

$\mathbf{R}_{FC}$: Reaction force acting on the blade tip
$\mathbf{F}_{Q}$: Force perpendicular to the blade tip
$\mathbf{F}_{C}$: Force parallel to the blade tip
$\mathbf{F}_{\mu}$: Friction force
$\mathbf{F}_{N}$: Normal force
$\mathbf{v}_{M}$: Roll speed vector at the contact point, whose components are $v_{\parallel}$ and $v_{\perp}$
$\mathbf{R}_{FA}$: Reaction force acting on the rotating axis
$\mathbf{M}_{C}$: Torque acting on the blade holder orientated out of the plane
$\mathbf{r}_{C}$: Vector that links the end of the holder with the blade tip
$\mathbf{r}_{C0}$: Initial position of $\mathbf{r}_{c0}$ before rotation
$\mathbf{F}_{H}$: Force per unit length of the pressurized hose
$\mathbf{r}_{H}$: Vector that links the rotation axis with the center of the hose
p_{H}: Pressure of the hose
E_{H}: Young's Modulus of the hose
L_{0}: Perimeter length of the *undeformed* (relaxed) hose

L_H: Perimeter length of the *deformed* (relaxed) hose
d_H: Height of the *deformed* (compressed) hose
a_H: Length where $\mathbf{F}_H$ acts on the part of the *deformed* (compressed) hose attached to the plate
t: Thickness of hose wall (constant)
$\mathbf{r}$: Vector that links the rotation axis with the blade tip
$\mathbf{x}$: Displacement of the blade due to bending
$\mathbf{R}_x$: Displacement of the hose arm due to pressure changes
$\Delta\gamma$: Rotation angle of the holder due to bending of the blade
β: Angle between the tangent to the mill and the blade
μ: Coefficient of friction
E: Young's Modulus of the doctor blade
I: Second moment of inertia of the doctor blade
d: Thickness of the doctor blade
l: Free length of the doctor blade $l = |\mathbf{r}_C|$
U: Sliding speed at the surface of the press roll
δ: Opening angle at the blade tip due to bending
η: Viscosity of the lubricating fluid
L: Contact length of the doctor blade
h_0: Gap height at fluid intake
h_1: Gap height at fluid outtake
So: Sommerfeld number
K: Convergence ratio
W: Blade width in the out-of-plane direction
α: Angle of the blade tip
H: Hardness of the doctor blade
k: Archard wear coefficient
k_D: Archard dimension wear coefficient
ΔV: Removed wear volume



(a)



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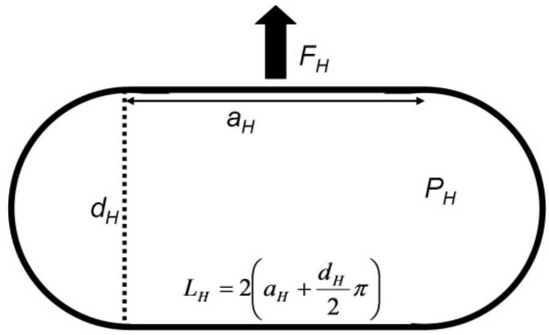


(c)

2 (a) Schematic representation of the doctor blade and its holder. (b) Detail of the doctor blade tip. (c) Detail of the pressurized hose.

3. MODELLING

3.1. Modelling Approach

The modelling approach is based on the assumption that an optimum cleaning performance can be achieved by forcing the doctor blade to operate under "weak" hydrodynamic conditions. In this case, friction and wear are minimised, while an optimum cleaning performance is guarantied as long as the film thickness between the doctor blade and the press roll is kept small, where its minimum value should undergo the estimated minimum particle diameter; for further discussion we refer to Ref. 10.

In a recent model proposed by the authors,[10] the doctor blade is considered as a pad bearing sliding over the roll surface. Assuming equilibrium conditions between hydrodynamic and contact forces, a non-dimensional group involving the key parameters was obtained. Its optimum value can be calculated by imposing the onset of hydrodynamic sliding conditions.

In the present work, a mechanical model governing the deflection of the blade yields a relationship between the linear contact force at its tip and the imposed air pressure. The change of the blade tip due to wear is taken into account by applying a geometrical wear model. Under these assumptions, the influence of the process parameters on the cleaning performance can be systematically analysed.

The stationary mode, of primary interest here, is valid only under operating conditions that can be viewed as quasi-static and rendered invalid within relatively short time intervals where forced oscillations, induced e.g. by surface irregularities, have a crucial impact on the movement of the blade tip. [11,12]

3.2. Hydrodynamic Model

A thorough description of the hydrodynamic model is found in Ref. 10. In what follows, only the most salient features are described for the sake of completeness.

The doctor blade is considered as a one dimensional beam, whose deflection is governed by the Euler-Bernoulli elastic beam theory

$$F_Q = \frac{Ed^3\delta}{6l^2}, \tag{1}$$

where E is the Young's Modulus of the blade, l and d are the blade length and thickness and δ is the opening angle,

$$\frac{h_0 - h_1}{L} = \sin\delta \sim \delta. \tag{2}$$

Imposing equilibrium conditions at the blade tip between hydrodynamic and contact forces, the following relationship is obtained

$$F_Q = F_N \cos\beta, \tag{3}$$

where β is the positioning angle of the blade (blade angle).

The normal load F_N: can be calculated analytically for a pad bearing using the Reynolds equation [13]

$$F_N = \frac{6U\eta L^2}{h_1^2} So, \tag{4}$$

where U denotes the sliding velocity, η the viscosity, L the contact length and h_1 the minimum film thickness, i.e. the gap height at fluid discharge. So is the Sommerfeld number for the lubricated wedge flow and hence a function of the convergence ratio

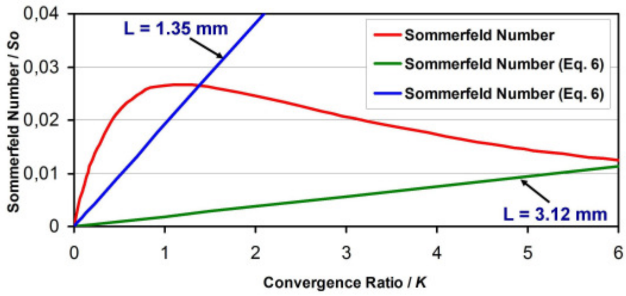
$$K = \frac{h_0 - h_1}{h_1} \tag{5}$$

solely: $So = So(\mathrm{K})$.

Upon substituting eq. (1) and eq. (4) into eq. (3), a linear further relationship between So and K is established:

$$So(K) = \frac{h_1^3}{36U\eta L^3} \frac{Ed^3}{l^2\cos\beta} K. \tag{6}$$

From this relationship one determines a unique value of K (3).



3 Relationship between the Sommerfeld Number *So* and the convergence ratio *K*, for two different contact lengths *L*.

An optimum cleaning performance is achieved for a small gap h_1 and small converging ratios ($h_0 \sim h_1$), i.e. when $K \rightarrow 0$ in eq. (6). By this means, the following condition for a non-dimensional group involving the key parameter is obtained:

$$\frac{h_1^3}{36U\eta L^3} \frac{Ed^3}{l^2\cos\beta} = \frac{1}{12}. \tag{7}$$

3.3. Geometrical changes due to wear

During the paper production, doctor blades need to be replaced periodically due to wear. During the wear process, the geometry of the blade changes, which modifies the contact conditions at the tip. Based on purely geometrical relations, the actual blade length l and its contact length L (i.e. at a certain point of time) can be calculated for a given wear volume ΔV. [10]

$$L = \sqrt{\frac{2\Delta V \sin\alpha}{W \sin\beta \sin(\pi - \alpha - \beta)}}, \tag{8}$$

$$l = \sqrt{\frac{2\Delta V(\cot\alpha + \cot\beta)}{W}}, \tag{9}$$

where W is the blade width in the out of plane direction.

The removed wear volume at every differential increment dV can be simply imposed or derived from the operational parameters by using a wear law, such as the one proposed by Archard [14]:

$$dV = k\frac{F_N U}{H}dt = k_D F_N U dt, \tag{10}$$

where k_D is a dimension wear coefficient to be fitted to experimental results, F_N is the normal load, U is the sliding speed, H the material hardness, and dt is the differential time increment.

3.4. Mechanical Model

The hydrodynamic model and the relationship between the geometrical key quantities at the blade tip, which were recalled in the previous sections, rely in the fact that the contact force at the blade tip is known. However, in a paper mill, the only parameter readily available to the operator is the air pressure applied to the polymer hose. In this section, a simple mechanical model aims to link both physical quantities.

The doctor blade is assumed to be a non-compressible one dimensional beam connected to a fixed holder. The holder is free to rotate around an axis in order to contact the press roll. The contact force depends on the air pressure flowing through a hose placed below the holder.

The reaction force at the blade tip can be decomposed in two components, one component perpendicular $\mathbf{F}_Q$ and one component parallel $\mathbf{F}_C$ to the blade tip contact line:

$$\mathbf{R}_{FC} = -(\mathbf{F}_Q + \mathbf{F}_C). \tag{11}$$

The friction force F_μ between the blade and the roll is given as

$$\mathbf{F}_\mu = \mu\mathbf{F}_N \times \frac{\mathbf{v}_M \times \mathbf{F}_N}{|\mathbf{v}_M \times \mathbf{F}_N|} = \mu F_N \hat{\mathbf{v}}_{\parallel}, \tag{12}$$

where $v_{\parallel}$ is a unit vector tangent to the roll at the contact point and F_N and F_μ are given by

$$\mathbf{F}_N = \mathbf{F}_{Q\perp} + \mathbf{F}_{C\perp}, \tag{13}$$

$$\mathbf{F}_\mu = \mathbf{F}_{Q\parallel} + \mathbf{F}_{C\parallel}. \tag{14}$$

The momentum at the blade holder $\mathbf{M}_C$ is given by:

$$\mathbf{M}_C = \mathbf{r}_C \times \mathbf{R}_{FC}. \tag{15}$$

We assume that the forces and torques acting on the blade holder are equal in magnitude and with opposite sign to those acting on the blade. Thereby, the following balance applies

$$\mathbf{R}_{FA} + \mathbf{F}_H - \mathbf{R}_{FC} = 0. \tag{16}$$

By imposing conservation of momentum at the rotation axis

$$\mathbf{M}_A = \mathbf{r}_H \times \mathbf{F}_H - \mathbf{r} \times \mathbf{R}_{FC} - \mathbf{M}_C = 0 \tag{17}$$

so that

$$\mathbf{r}_H \times \mathbf{F}_H = \mathbf{r} \times \mathbf{R}_{FC} + \mathbf{M}_C. \tag{18}$$

We aim to relate the contact force at the blade tip with the force imparted by the pressure hose. Based on the follow relation

$$\mathbf{F}_N + \mathbf{F}_\mu = \mathbf{F}_Q + \mathbf{F}_C \tag{19}$$

and substituting and combining eq. (11) and (12) we obtain that the reaction force at the blade tip is

$$\mathbf{R}_{FC} = -\left(F_N \hat{\mathbf{v}}_\perp + \mu F_N \hat{\mathbf{v}}_\parallel\right) \quad (20)$$

and the related momentum

$$\mathbf{M}_C = -\mathbf{r}_c \times \left(F_N \hat{\mathbf{v}}_\perp + \mu F_N \hat{\mathbf{v}}_\parallel\right). \quad (21)$$

Substituting the latter two equations in the balance of momentum (eq. 18) we finally obtain a relation between the force imparted by the pressure hose $\mathbf{F}_H$ and the normal load at the blade tip $\mathbf{F}_N$

$$\mathbf{r}_H \times \mathbf{F}_H = -(\mathbf{r} + \mathbf{r}_c) \times \left(F_N \hat{\mathbf{v}}_\perp + \mu F_N \hat{\mathbf{v}}_\parallel\right). \quad (22)$$

So far, bending of the doctor blade upon contact with the roll has been neglected in the mechanical model. In the conventional leading-order approximation, the deflection angle at the blade tip is given by

$$\alpha = \arctan\left(\frac{F_Q l^2}{2EI}\right). \quad (23)$$

According to this angle, the displacement of the blade is

$$\mathbf{r}_C = \mathbf{r}_{C0} + \mathbf{x} \quad (24)$$

with

$$x = \frac{F_Q l^3}{3EI} \hat{\mathbf{F}}_Q. \quad (25)$$

Given a rotation γ, the relation between $\mathbf{F}_N$ and $\mathbf{F}_H$ becomes:

$$(\mathbf{r}_H R_x(\Delta\gamma)) \times \mathbf{F}_H = \\ -((\mathbf{r} + \mathbf{r}_{C0} + \mathbf{x}) R_x(\Delta\gamma)) \times \left(F_N \mathbf{v}_\perp(\Delta\gamma) + \mu F_N \mathbf{v}_\parallel(\Delta\gamma)\right), \quad (26)$$

which according to eq. (9) can be updated for any wear rate.

In a refined mechanical model, the elasticity of the pressure hose can be included readily. Thus, the necessary supply pressure can be calculated from the required force component F_Q or F_Q according to

$$p_H = E_H t \left(\frac{\pi}{L_0} - \frac{1}{d_H}\right)\left(1 + \sqrt{1 + \frac{4 F_H d_H L_0}{E_H t (d_H \pi - L_0)^2}}\right) \quad (27)$$

In the rather simple but, for the present purposes, sufficiently accurate model proposed here, the hose is regarded as an elastic membrane with vanishing stiffness. Under these assumptions, one readily infers the relationship (27) between the supplied air pressure p_H, the actually arising plate distance d_H, and the reaction force F_H acting on the hose, where $F_H = p_H a_H$ from Figure 2(c). It is seen that $\pi \cdot d_H - L_0$ cannot become negative as the hose wall is elastically stretched. In view of a suitable evaluation of (27) in an advanced future analysis, it is noted that (27) can be conveniently cast in a relationship between three non-dimensional groups: $p_H \cdot L_0/(E_H \cdot t)$ as function of d_H/L_0 and $F_H/(E_H \cdot t)$.

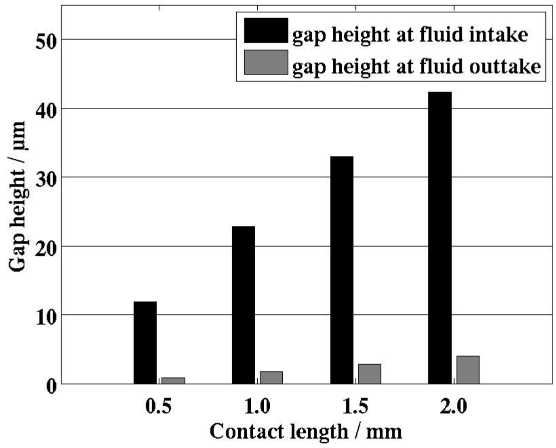
4. RESULTS

The proposed model is applied in order to calculate the film thickness, when typical operational parameters are applied (Table 1).

Table 1 Reference case parameters

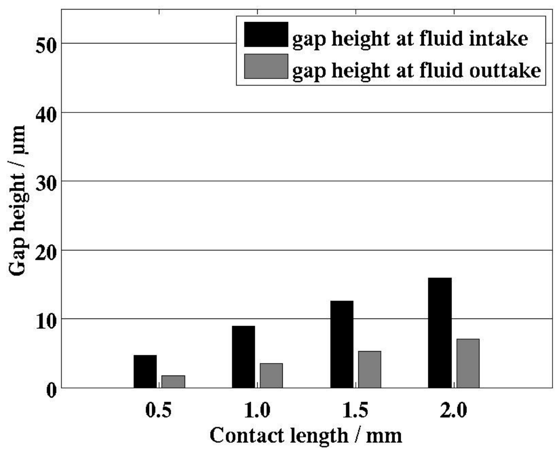
Parameter	Value
l	40 mm
d	1.5 mm
E	25 MPa
F_N	225 N/m
F_H	1600 N/m

The results show the gap height at fluid intake and at fluid outtake for four different contact lengths L, namely 0.5, 1.0, 1.5 and 2.0 mm (4). For a rather new doctor blade (L = 0.5 mm), the value of h_0 and h_1 is small and a satisfactory cleaning performance can be expected. As the blade tip wears off, the cleaning performance degrades and for a severely worn doctor blade tip, the water film both at flow intake and outtake becomes thicker.



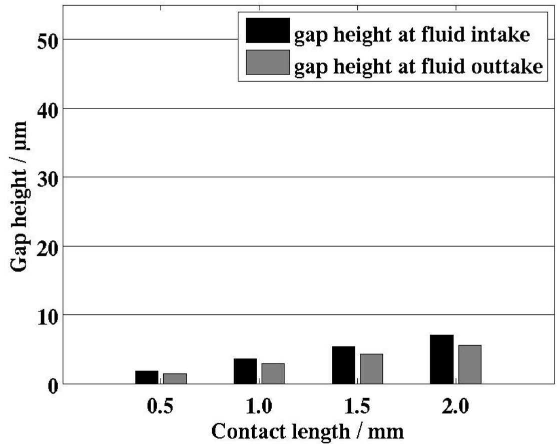
4 Gap height at fluid intake h_0 and at fluid outtake h_1 for the parameters shown in Table 1.

If the free length of the doctor blade *l* is shortened up to 20 mm (Figure 5), the model predicts an improvement of the cleaning performance for all values of *L*.



5 Gap height at fluid intake h_0 and at fluid outtake h_1 for a doctor blade with a free length of 20 mm.

Instead of shortening the blade length, an even better cleaning performance can be achieved by increasing the blade thickness *d* up to 4.5 mm (Figure 6).

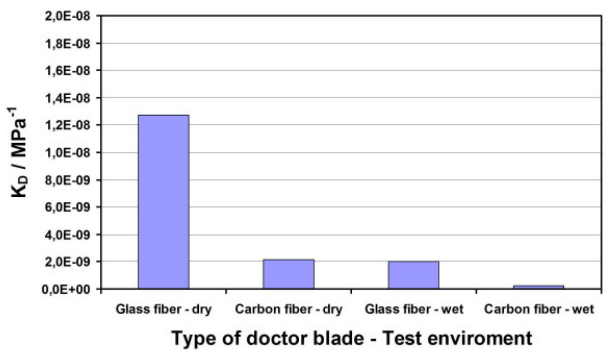


6 Gap height at fluid intake h_0 and at fluid outtake h_1 for a doctor blade with a thickness of 4.5 mm.

5. EXPERIMENTAL

Dry and water-lubricated tribological model tests were performed on a pin-on-disc tribometer. The pin was replaced by doctor blade samples with a width of 8 mm. During the tests, the blade was pressed against a 100Cr6 steel disc with a constant normal load F_N of 5 N, a blade angle β of 28° and a sliding velocity of 16 m/s.

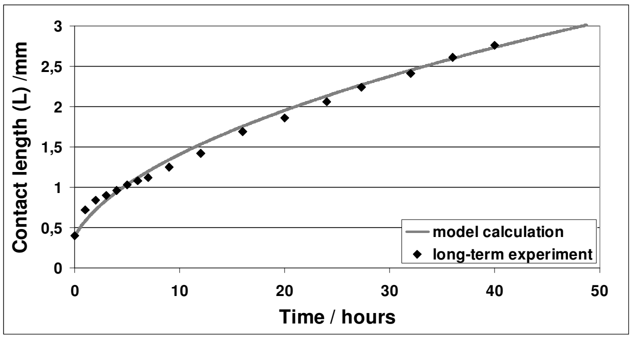
During the tests, wear was measured as the vertical displacement of the blade. Afterwards, the Archard wear coefficient k_d was calculated from the measured wear rate. The results show higher wear rates for glass fiber reinforced plastic blades when compared to carbon fiber reinforced polymer blades (Figure 7). In both cases, wear was more severe under dry contact conditions.



7 Archard wear coefficient k_D for carbon fiber and glass fiber blades tested under dry and water lubricated conditions

Additional tests were performed using a scale paper mill component test, which was designed to performed tests on doctor blades with a width of 190 mm. A selected carbon fiber reinforced polymer blade slid against a steel mill with 0.7 m radius with a sliding velocity of 20 m/s and a contact force of 95 N. The latter value was set in order to have the same contact force per unit length as in the pin-on-disc tests. The blade angle was set in this case to 30°.

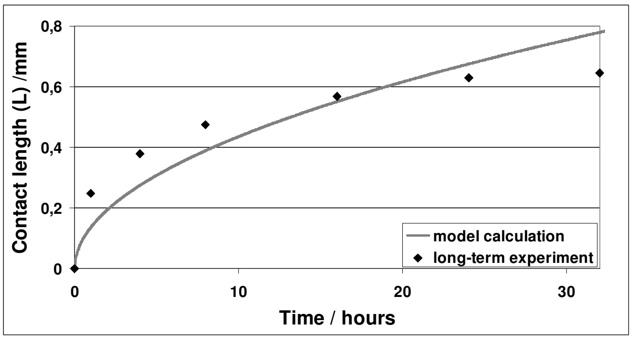
The test was interrupted regularly in order to measure the contact length of the doctor blade. The results obtained under dry contact conditions, are shown in 8.



8 Evolution of the contact length *L* as a function of time under dry contact conditions. The dots are measured via a component test and the line is the prediction of the model.

The dots are the measurements obtained in the component test, whereas the line is the prediction of the geometrical wear model using the Archard wear coefficient measured with the pin-on-disc test.

Analogously, the results obtained for the water-lubricated test are shown in Figure 9. The water was sprayed using four water nozzles in order to obtain a homogeneously distributed water film along the blade. As it can be observed, the contact length of the blade increased significantly slower in comparison to dry contact conditions. Additionally, when the blade reached a contact length of about 0.6 mm after 24 hours test, the contact length stagnated and no further wear could be measured. This means that after this point, the blade slid under hydrodynamic conditions.



9 Evolution of the contact length *L* as a function of time under water-lubricated conditions. The dots are measured via a component test and the line is the prediction of the model.

These results show the feasibility of the model to predict the contact length as a function of time. Even if some process parameters, such as the blade angle or the sliding speed differ from the model test, the predictions of the mechanical model are remarkable, provided that the Archard wear coefficient is obtained using independent experiments under similar wear conditions.

6. CONCLUSIONS

A mathematical model for describing the cleaning performance and the lifetime of the doctor blade – press roll tribosystem was presented.

The approach relied on a recently developed hydrodynamic model, which links in a non-dimensional group the most relevant operational parameters during wet pressing. Changes of the blade tip due to wear were taken into account by a simple wear model based on Archard. A mechanical model linked the contact force at the blade tip with the force of the pressure hose, which is the actual parameter controlled by operators.

The model allows a systematic analysis of the cleaning performance of the doctor blade as a function of the process parameters. Thicker and shorter blades reduce the gap height between the blade tip and the press roll, consequently improving the cleaning performance.

The building blocks of the model can be used independently in order to focus on particular phenomena. For instance, the geometrical wear model was successfully applied to predict the result of a component test, by fitting the Archard wear coefficient using model tests. Also, feeding the dependence of the supply pressure p_H on the effective gap height d_H as provided by (27) into a more advanced model would enhance the accuracy of the predictions.

7. ACKNOWLEDGEMENTS

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