Design equation for paper machine press sections

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Design Equation for Paper Machine Press Sections

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Water removal in the press section of paper, board, and pulp machines has an important influence on machine efficiency and cost. A press section design equation, based on the decreasing permeability model of wet pressing, is described. It is used to predict the effects of changes in operation, equipment and furnish on water removal in a press nip. The equation accounts for operating parameters such as nip load, machine speed, basis weight and web temperature. The two furnish-dependent coefficients can be determined by pressing handsheets. Several examples from studies on commercial and pilot machines are used to illustrate the method and demonstrate its accuracy.

L'essorage à la section des presses de machines à papier à carton et à pâte a une influence importante sur l'efficacité et les coûts d'opération des machines. Une équation de conception de section des presses, établie sur le modèle de perméabilité décroissante du pressage humide, est décrite. Elle est utilisée pour prédire les effets des changements de conditions d'opération d'équipement et de composition de fabrication, sur l'essorage à la pince d'une presse. L'équation tient compte des paramètres d'opération tel que le chargement de pince, la vitesse de la machine, le grammage, et la température de la feuille. Les deux coefficients qui dépendent de la composition de fabrication peuvent être déterminés en pressant des formettes. Plusieurs exemples d'études sur des machines commerciales et des machines pilotes sont utilisés pour illustrer la méthode et en démontrer l'exactitude.

INTRODUCTION

This paper describes a practical approach to calculate the water removed by a press nip in a paper machine. The method is based on a simple, non-linear equation derived from a fundamental understanding of water flow from a porous structure in a typical press nip. It accounts for the characteristics of the pulp and operating parameters such as machine speed, nip load, basis weight and temperature. A brief outline of the theoretical basis of the equation is given below.

The concept for the decreasing permeability (DP) model of wet pressing is based on the basic principles of flow through a porous media. For any material the flow rate is governed by the pressure applied and the resistance to flow as described by the simple equation below:

$$\text{flow rate} = \frac{\text{pressure}}{\text{resistance}} \tag{1}$$

In pressing, flow rate decreases with time of applied pressure. Thus, either the applied pressure must decrease or the flow resistance must increase.

In an early picture of pressing, proposed by Wahlstrom in 1960, decreasing flow rate (drainage) is due to decreasing pressure. This is based on the concept that two parallel pressures exist: a network pressure and a hydraulic pressure [1]. The network pressure is the load supported by the fibre network; the hydraulic pressure is that applied to water. In this picture, only hydraulic pressure contributes to dewatering. As dewatering proceeds, hydraulic pressure decreases, and network pressure increases. Network pressure does not contribute to water removal, hence the hydraulic pressure in the above equation decreases.

Later, Wahlstrom recognized that the compressibility of the fibre was controlled by water within the fibre wall and proposed a qualitative model [2]. The DP model of wet pressing is based on this point of view that increasing resistance rather than decreasing pressure accounts for diminishing water removal in pressing. The model concept is that, in the moisture range of normal wet pressing, although more pressure is being applied upon fibres as water between fibres is expelled, this pressure is also causing dewatering. It squeezes water out from lumens and cell walls. The barrier to water removal is therefore a very high resistance to flow, rather than diminished pressure. This fact has considerable consequences in the mathematical modelling of the dewatering process, simplifying it to allow pressing to be modelled as flow through a permeable medium.

It is possible in some extreme cases, usually outside the range of commercial wet pressing, for fibres to carry pressure than cannot contribute to water removal. The DP model can account for this [3], but it has been found that a simplified form, omitting the pressure term, was applicable in all the cases tested over a lengthy period [4–6].

The DP model equation is a simple function of press operating parameters and two dewatering coefficients that are furnish dependent [3]. The form of the equation has

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been found to be consistent with dewatering data for pressing of commercial newsprint, market pulp, and fine paper machines [4]. For lightweight webs (<100 g/m^2), an additional term is required to account for rewet [5].

The coefficients for a particular furnish can be obtained by fitting the DP model equation to data from laboratory pressed handsheets [6]. The agreement between the model predictions and measurements on commercial board and newsprint machines has been shown to be within the measurement accuracy of approximately 1% for press sections where the nip loads increase in successive nips. The model can accommodate single- or double-felted nips, multilayer products, and can account for the effect of basis weight and web temperature.

The purpose of this report is to present the DP model in a simple form for use in design and optimization of press sections. Representative values for the two furnish dependent coefficients obtained to date are given, along with several examples of applications.

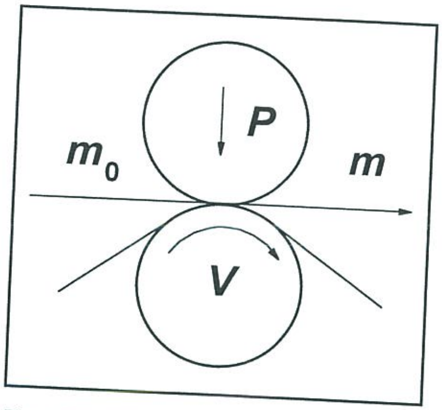


Fig. 1. The DP model determines the moisture ratio leaving the press nip, *m*, from the entering moisture ratio, *m*$_0$, the nip load, *P*, and the machine speed, *V*.

THEORY

The DP model of wet pressing gives the moisture ratio of the paper leaving the press nip, *m*, as a function of press operating parameters and the dewatering characteristics of the furnish (Fig. 1).

$$m = m_0\left(1+\frac{Anm_0^n I}{\upsilon W^2}\right)^{-1/n} + \frac{R}{W} \qquad (2)$$

where

m = outgoing moisture ratio

$= \dfrac{\text{mass of water}}{\text{mass of dry fibre}}$

m_0 = ingoing moisture ratio

I = press impulse (kPa·s)

$= \left(\dfrac{\text{press load}}{\text{speed}}\dfrac{(\text{kN/m})}{(\text{m/s})}\right)$

W = basis weight (kg/m^2)

υ = kinematic viscosity (m^2/s)

n = compressibility factor

A = specific permeability (g/m)

R = rewetting factor (kg/m^2)

This equation can be derived from either the Kozeny-Carman equation [3] or Darcy's law (Appendix I). The effect of web temperature on dewatering is embodied in the kinematic viscosity. The rewetting term is based on the Sweet equation [5].

DETERMINATION OF COEFFICIENTS

The furnish-dependent coefficients can be determined by pressing handsheets on a single-felted, two-roll press (Fig. 2). This requires 1 kg (oven-dry basis) of pulp preferably collected from the couch or couch trim of the paper or board machine. Sixty standard circular handsheets with a basis weight of 130 g/m^2 are prepared and couched to nominal moisture ratios of 1.5, 2.0, 3.0 and 4.5. This high basis weight is used for all grades to minimize the effect of rewet on the laboratory press. A press speed of 100 m/min is commonly used for ease of pressing and handling of the laboratory handsheets. At this speed, press nip loads of 10, 30, 50, 150 and 350 kN/m give press impulses of 6, 18, 30, 90 and 210 kPa·s.

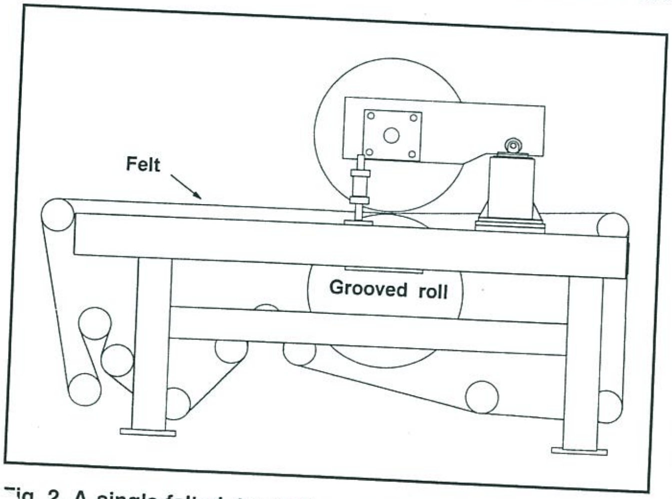
With the press running, each handsheet is dropped on the felt. Immediately after passing through the nip, the press is stopped and the handsheet peeled from the granite roll and weighed. Each handsheet is subsequently oven dried to measure bone-dry basis weight. The moisture at each condition is the average of three handsheets.

A nonlinear least squares procedure is used to fit Eq. (2) (without the rewet term) to the handsheet measurements to yield the compressibility (*n*) and the specific permeability (*A*) of the furnish (Fig. 3).

APPLICATION

The DP model equation can be used to predict the moisture of the web after the press by specifying the operating conditions of the press (speed, load, ingoing moisture ratio and web temperature) and the dewatering characteristics of the web (compressibility factor, *n*, and specific permeability, *A*).

Coefficients have been determined for newsprint, market pulp and fine paper by fitting the model equation to survey data from Canadian machines [4] (Table I). The specific permeability of market pulp, *A*, is an order of magnitude greater than that for newsprint or bond, which probably reflects the more aggressive nature of market pulp felts [7,8]. These coefficients should be used to give an initial estimate of water removal as a function of operating conditions for machines making these grades. For more accurate calculations with a specific furnish, the coefficients can be determined from measurements of handsheets on a laboratory press as described in the previous section. A list of coefficients for particular furnishes, shown in Table II, illustrates the range of possible values for specific permeability, *A*, and the compressibility factor, *n*. These coefficients give model predictions



ig. 2. A single-felted, two-roll press is used to dewater hand- ieets for the determination of the two model coefficients that are furnish dependent.

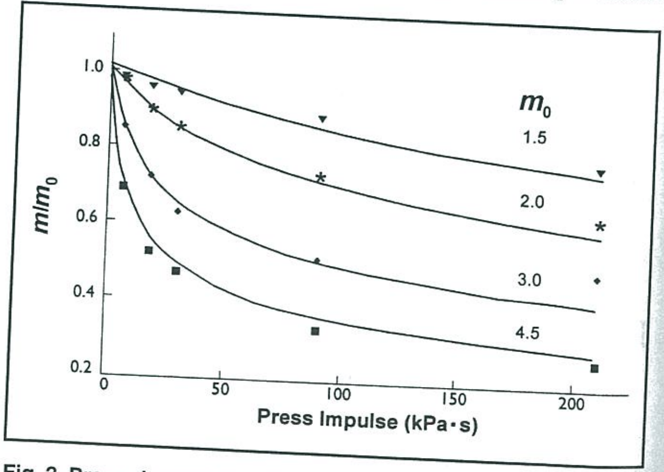


Fig. 3. Press dewatering of handsheets made from the filler furnish of a linerboard [6]. Lines are a fit of DP model, at the nominal values of initial moisture, to determine the compressibility coefficient (*n*) and the specific permeability coefficient (*A*).

TABLE I
COEFFICIENTS FOR THE DECREASING PERMEABILITY MODEL (CANADIAN INDUSTRY AVERAGES)

Furnish	*A*[1] g/m × 10^{-12}	*n*	Source	Reference
Newsprint	7.5	3.28	1986 Canadian industry survey	[4]
Market pulp	232.3	3.55	1986 Canadian industry survey	[4]
Bond	9.8	4.03	1986 Canadian industry survey	[4]

1. Assuming web temperature of 45°C.

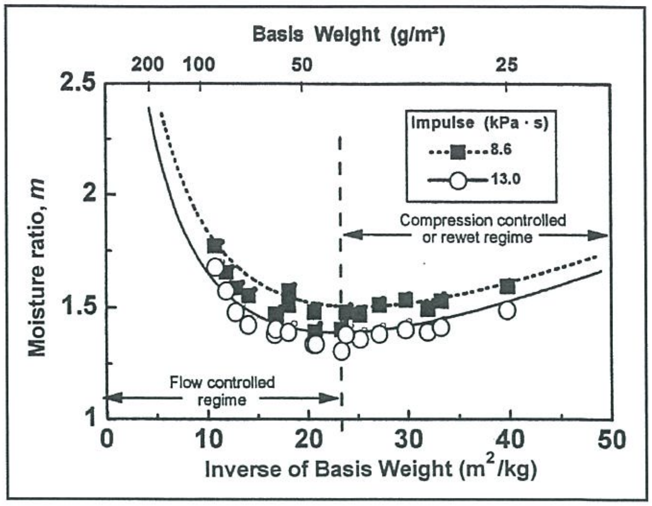


Fig. 4. The moisture after the second press on a pilot paper machine is linear with the inverse of basis weight for basis weights less than 100 g/m^2 because of rewet [5].

within 1% of the measured web solids after the presses on the corresponding commercial machine.

Rewet is a constant and independent of basis weight. For webs with a basis weight greater than 100 g/m^2, the moisture ratio after the press is controlled primarily by drainage resistance. Below 100 g/m^2, rewet has a significant effect and plotting the moisture ratio after the press against the inverse of basis weight gives a linear relationship for measurements on a pilot paper machine, as shown in Fig. 4 [5]. Because the amount of rewet is difficult to measure in the laboratory, it is determined either by fitting Eq. (2) to pressing data over a range of basis weight as shown in Fig. 4 or, more simply, by taking the difference between the value measured on the machine and amount of water removed as predicted by the model (Table III).

The specific permeability of the newsprint furnishes increased from the survey data in Table I to the high brightness newsprint in Table II to the pilot machine trials in Table III. The high brightness newsprint contained a significant portion of kraft which increased pressability and, consequently, the specific permeability, *A*. The pilot machine trials used paper that was dried then reslushed which gives higher dryness values after pressing. This is reflected in the higher value for specific permeability, particularly the "newsprint", which was a groundwood, chemical pulp furnish.

For machines with more than one press nip, the moisture leaving the last nip can be calculated by applying Eq. (2) in steps. The moisture leaving the first press becomes that entering the second press and so on (Fig. 5). However, because dewatering strongly depends on press impulse and is largely independent of the shape of the pressure pulse, for grades where rewet can be neglected, such as those with basis weights greater than 100 g/m^2, the impulses from individual nips can simply be added together. In effect, the entire press section behaves like a single nip. Although the nonlinear form of Eq. (1) suggests that this approach is not possible, the additivity of nip impulses can be proven mathematically (Appendix II). This simplification can be used only when the temperature is the same in each nip, all nips are either single- or double-felted, and rewet is negligible.

A web in a double-felted nip dewaters like two webs with one half the basis weight. Effectively, double-felting increases the specific permeability by a factor of four because of the basis weight squared term in the denominator of Eq. (2) [6]. The water removal by a double-felted nip can be calculated by multiplying the specific permeability by four and using the full basis weight of the sheet, *W*.

Some board grades are made of several layers of different furnishes. A first-order estimate of water removal can be made by determining the water removal of each component separately and then taking the weighted average. For a two-component board, where the furnishes have equal compressibility factors, the specific

TABLE II
COEFFICIENTS FOR THE DECREASING PERMEABILITY MODEL (SPECIFIC FURNISHES)

Furnish	*A* g/m × 10^{-12}	*n*	*R* g/m^2	Source	Reference
High-brightness newsprint	18.4	2.42	3	laboratory-pressed handsheets (contains kraft)	
Filled high-brightness newsprint	15.3	2.76	3	laboratory-pressed handsheets (contains kraft)	
Corrugating medium	6.75	5.12	–	Semichemical-laboratory-pressed handsheets	[6]
Corrugating medium	5.29	5.87	–	OCC[1] laboratory-pressed handsheets	[6]
Corrugating medium	7.85	5.28	–	Mixture of SC[2] and OCC[1] handsheets	[6]
Linerboard	16	3.75	–	filler-laboratory-pressed handsheets	[6]
Brown liner	17.3	3.89	–	laboratory-pressed handsheets	[6]
White liner	35.4	3.51	–	laboratory-pressed handsheets	[6]

1. Old corrugated containers
2. Semichemical pulp

TABLE III
COEFFICIENTS FOR THE DECREASING PERMEABILITY MODEL (PILOT MACHINE TRIALS) – RESLUSHED PULP

Furnish	*A* g/m × 10^{-12}	*n*	*R* g/m^2	Source	Reference
Newsprint	39.8	3.41	23	fit to pilot paper machine data	[5]
TMP Newsprint	21.2 ± 4.0	3.35 ± 0.23	9	Trial #1 – laboratory-pressed handsheets	this study
TMP Newsprint	23.2 ± 2.0	3.29 ± 0.22	9	Trial #2 – laboratory-pressed handsheets	this study

TABLE IV
SAMPLE CALCULATIONS WITH THE DP MODEL (CORRUGATING-MEDIUM MACHINE)

Change	Machine Speed (m/min)	Basis Weight (g/m²)	Web Temperature (°C)	Press Loads (kN/m)			Total Press Impulse (kPa•s)	Solids (%)
				First	Second	Third		
–	800	120	50	100	150	–	18.75	39.2
Double basis weight	800	**240**	50	100	150	–	18.75	33.2
Increase 2nd press load	800	240	50	100	**200**	–	22.5	34
Reduce speed	**600**	240	50	100	200	–	30	35.2
Install third press + double-felted	800	240	50	100	150	**200**	33.75	37.9
Increase web temperature	800	240	**80**	100	150	200	33.75	39.8
Install shoe press	800	240	50	100	200	**1000**	97.5	41.3

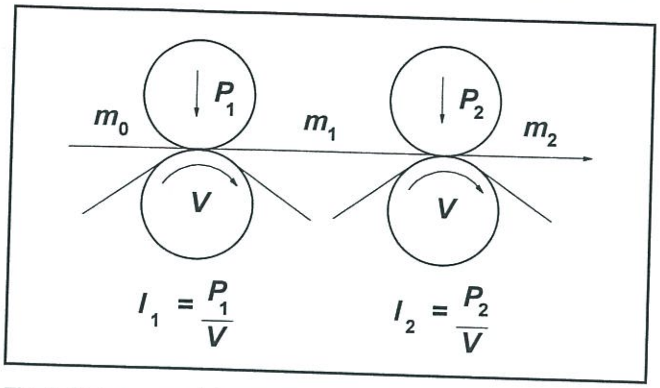


Fig. 5. For a press with two nips, the moisture leaving the first nip, m_1, becomes the moisture entering the second nip.

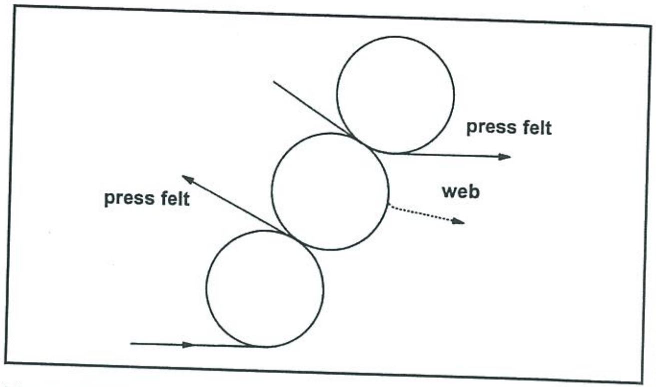


Fig. 6. Three-roll, inclined-press section on a corrugating-medium machine.

permeability is:

$$A = \frac{A_1 A_2 (W_1 + W_2)}{A_1 W_2 + A_2 W_1} \qquad (3)$$

where

A_1 = specific permeability for furnish 1 (g/m)
A_2 = specific permeability for furnish 2 (g/m)
W_1 = basis weight of layer 1 (kg/m²)
W_2 = basis weight of layer 2 (kg/m²)

PRACTICAL EXAMPLES

Heavy-Weight Grades (>100 g/m²)

The following is an example of how Eq. (2) is used to determine the water removal on a commercial machine. Consider a corrugating-medium machine with a three-roll inclined press as shown in Fig. 6. The couch moisture ratio is 4.0 (20% web solids content). The machine speed is 800 m/min and the first and second press nips are loaded to 100 and 150 kN/m. This gives a press impulse of 7.5 kPa•s in the first nip and 11.25 kPa•s in the second nip. Assume that the web temperature is 50°C in both nips so that the impulses can be combined to give a total impulse of 18.75 kPa•s. At this temperature, the kinematic viscosity is 5.5×10^{-7} m²/s. For a basis weight of 0.12 kg/m² (oven-dry basis), the effect of rewetting is negligible and for this calculation R will be set to zero. For this demonstration, we will use the coefficients for a mixture of OCC and semichemical pulp from Table II ($A = 7.85 \times 10^{-12}$ g/m and $n = 5.28$).

Substituting these numbers into Eq. (2) gives the moisture ratio leaving the press section:

$$m_2 = 4.0 \times \left(1 + \frac{7.85\times10^{-12} \times 5.28 \times 4.0^{5.28} \times 18.75}{5.5\times10^{-7} \times 0.12^2}\right)^{-1/5.28} = 1.55$$

The moisture ratio can be converted into a web solids value:

$$S = \frac{100}{m+1} \qquad (4)$$

For this condition, the web solids is 39.2%.

The effect of different operating conditions on the web solids leaving the press section can also be examined. For example, the model predicts that doubling the basis weight to 0.24 kg/m² (oven-dry basis) would reduce the web solids from 39.2 to 33.2% (Table IV).

The model can be employed to determine how to improve upon this diminished water removal (Table IV). Possibilities include increased loading of the existing press, lower speed, a new double-felted first press (Fig. 7), higher web temperature, or a new shoe press in the third press position (Fig. 8). The model calculations for double-felting are implemented by multiplying the specific permeability by four. Increasing the web temperature improves water removal by lowering the kinematic viscosity (υ). Some typical examples are shown in Table IV. These calculations indicate that to achieve a pressed web solids greater than 39% at a basis weight of 0.24 kg/m² (oven-dry basis) requires an additional press nip. If this additional nip was lightly loaded, a higher web temperature would also be required.

Lightweight Grades (<100 g/m²)

For lightweight grades (<100 g/m²), rewetting becomes significant and the R/W term in Eq. (2) is necessary. The following example with a shoe press shows how the rewetting term is evaluated and how the model can be used to predict shoe press operation.

The trials were conducted on Paprican's pilot paper machine with a 100% TMP newsprint made from reslushed paper to evaluate the dewatering with a shoe press at different loadings and sheet temperatures. Paper samples, collected after the couch just before and after the trials, were used to prepare handsheets to determine the coefficients, as described previously. The two sets of coefficients (Table III) are similar, which indicates that this method is reliable and consistent.

These coefficients were used to predict the solids after the third press on a pilot paper machine with the press configuration shown in Fig. 8. The operating conditions and the measured and predicted solids are in shown Table V. During these trials, the water removal was measured after the shoe press for three nip loads (400, 700, 1000 kN/m) and two web temperatures separated by 4.8°C by applying a steam shower.

The predicted solids after the third press are higher than the measured solids by a constant amount (Fig. 9). This offset can be interpreted as 9.0 g/m² of rewetting.

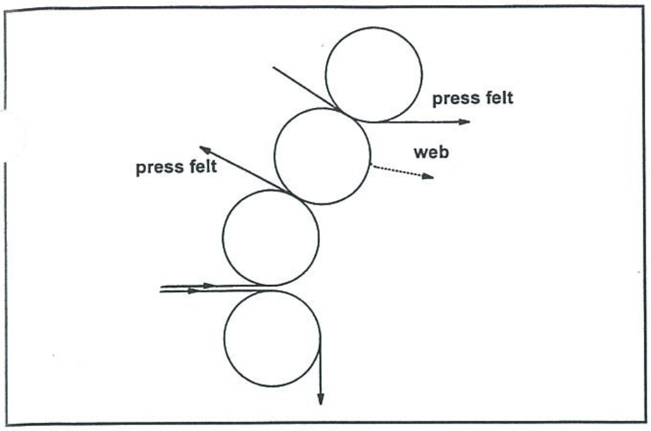


Fig. 7. Original press with the addition of a first, double-felted nip.

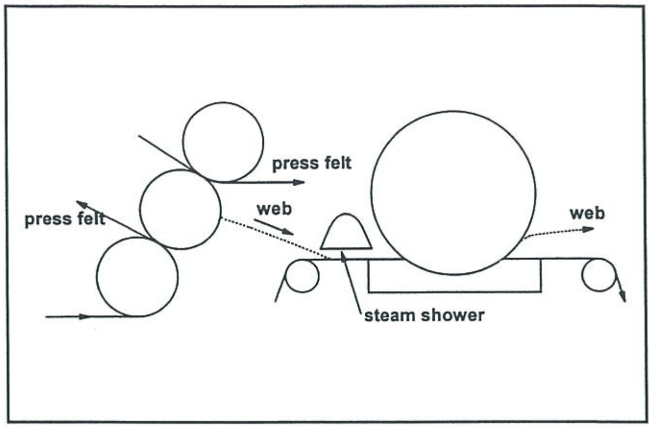


Fig. 8. Original press with the addition of a third, shoe press.

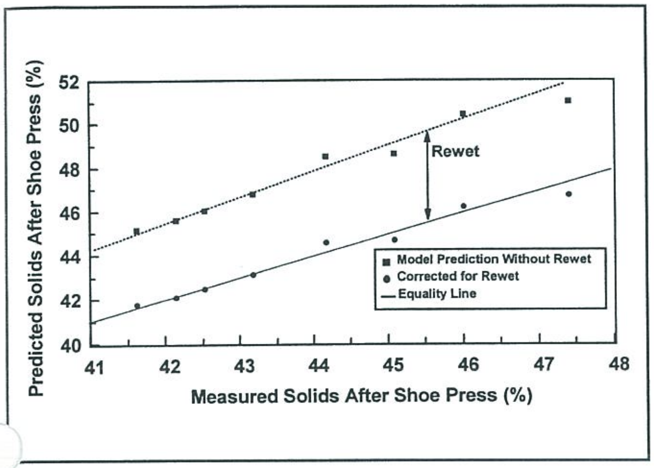


Fig. 9. Measured solids after the shoe press on the pilot paper machine are equal to predicted solids for 9.0 g/m^2 of rewetting.

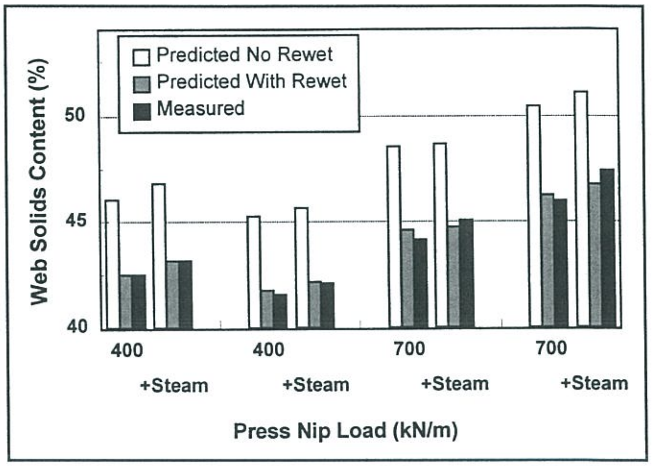


Fig. 10. Measured solids after the shoe press on the pilot paper machine are on average 3.8% greater than predicted solids without the rewet term.

TABLE V
SHOE PRESS TRIALS AND SIMULATION RESULTS. REWETTING WAS ESTIMATED AS THE AVERAGE DIFFERENCE BETWEEN ALL MEASUREMENTS AND CORRESPONDING SIMULATIONS

					Solids				Solids Gain with Steam Shower	
					Measured		Predicted			
Speed (m/min)	Nip Load (kN/m)	Steam Shower	Average Temperature (°C)	Basis weight oven-dry (g/m²)	In (%)	Out (%)	No Rewetting (%)	With Rewetting (%)	Measured (%)	Predicted (%)
760	400	Off	32.5	49.3	37.5	42.5	46.1	42.5	0.6	0.6
760	400	On	38.0	49.0	37.9	43.2	46.8	43.2		
760	400	Off	31.0	49.8	35.8	41.6	45.2	41.8	0.5	0.6
760	400	On	36.5	49.8	35.1	42.2	45.7	42.2		
760	700	Off	31.5	49.8	35.4	44.2	48.5	44.6	0.9	0.3
760	700	On	34.5	50.3	34.6	45.1	48.7	44.7		
760	1000	Off	30.5	50.7	35.3	46.0	50.5	46.2	1.4	0.6
760	1000	On	35.5	50.7	34.9	47.4	51.1	46.8		

Using a rewet of 9.0 g/m^2 in Eq. (2) for the shoe press gives an average prediction error of 0.5% for all the loading and temperature conditions (Table V). Rewetting reduces the solids by 3.8% on average and has a strong effect on the press efficiency, as shown in Fig. 10.

SUMMARY

The DP model provides a simple, practical design equation for calculating the moisture ratio of a web after one or more press nips. The model requires the ingoing moisture ratio, the nip load, press speed, web temperature and basis weight. The two furnish dependent coefficients can be determined by laboratory pressing of handsheets. Multiple single-felted nips and double-felted nips can be accounted for. The model predictions have been shown in previous work to be within the measurement accuracy of the moisture content of the web.

APPENDIX I

Derivation of the Decreasing Permeability Model of Wet Pressing from Darcy's Law

Using Darcy's law, the water flow through the fibre mat can be expressed as:

$$v = \frac{kp}{\mu l} \tag{5}$$

where

v = average flow velocity, m/s
k = permeability, m^2
p = pressure applied to fibre mat, Pa
l = mat thickness, m
μ = viscosity of water, Pa·s

Assume that the permeability, k, and mat thickness, l, are a nonlinear function of the moisture ratio, m, of the mat.

$$k = \mathrm{B}m^{\mathrm{b}} \tag{6}$$

$$l = \mathrm{C}Wm^{\mathrm{c}} \tag{7}$$

where

m = moisture ratio of the mat after pressing
W = basis weight (kg/m^2)

and B, C, b, c are constants.

This implies that:

$$k = k_0\left(\frac{m}{m_0}\right)^{\mathrm{b}} \tag{8}$$

$$l = l_0\left(\frac{m}{m_0}\right)^{\mathrm{c}} \tag{9}$$

where

m_0 = moisture ratio of the mat before pressing
k_0 = permeability before pressing
l_0 = mat thickness before pressing

Substituting Eqs. (8) and (9) into Darcy's law gives:

$$v = \frac{p}{\mu}\frac{k_0}{l_0}\left(\frac{m}{m_0}\right)^{(\mathrm{b-c})} \tag{10}$$

From continuity:

$$v = \frac{W}{\rho}\frac{\mathrm{d}m}{\mathrm{d}t} \tag{11}$$

where

ρ = density of water, kg/m^3

Combining Eqs. (10) and (11) gives:

$$\frac{\mathrm{d}m}{m^{\mathrm{b-c}}} = \frac{\rho}{W\mu}\frac{k_0}{l_0}\frac{1}{m_0^{\mathrm{b-c}}}p\mathrm{d}t \tag{12}$$

Integrating:

$$\int_{m_0}^{m}\frac{\mathrm{d}m}{m^{\mathrm{b-c}}} = \frac{\rho}{W\mu}\frac{k_0}{l_0}\frac{1}{m_0^{\mathrm{b-c}}}\int_0^t p\mathrm{d}t \tag{13}$$

The press impulse, I, is defined as:

$$I = \frac{P}{V} = \int_0^t p\mathrm{d}t \tag{14}$$

where

P = line load of press, kN/m
V = machine speed, m/s

Substituting Eq. (14) into (13) and rearranging gives the DP pressing model equation:

$$m = m_0\left(1 + \frac{Anm_0^n I}{\upsilon W^2}\right)^{-1/n} \tag{15}$$

where

$\upsilon = \dfrac{\mu}{\rho}$ is the kinematic viscosity

The two furnish-dependent factors are:

$n = \mathrm{b} - \mathrm{c} - 1$, compressibility factor

$A = \dfrac{B}{C}$, specific permeability, g/m

For lightweight grades [5], an additional term can be added to the model to account for rewetting: R = rewet, kg/m^2

$$m = m_0\left(1 + \frac{Anm_0^n I}{\upsilon W^2}\right)^{-1/n} + \frac{R}{W} \tag{16}$$

APPENDIX II
Proof that Press Impulses are Additive

When rewet is negligible, such as for grades with basis weights greater than 100 g/m^2, the press impulses are additive. Consider two press nips in series as shown in Fig. 5. From the DP model equation, the moisture ratios are:

$$m_1 = m_0\left(1 + \frac{Anm_0^n I_1}{\upsilon W^2}\right)^{-1/n} \tag{17}$$

$$m_2 = m_1\left(1 + \frac{Anm_1^n I_2}{\upsilon W^2}\right)^{-1/n} \tag{18}$$

where

m_1 = moisture ratio after first press
m_2 = moisture ratio after second press
I_1 = first press impulse (kPa·s)
I_2 = second press impulse (kPa·s)

Substituting m_1 from Eq. (17) into Eq. (18) gives:

$$m_2 = m_0\left(1 + \frac{Anm_0^n I_1}{\upsilon W^2}\right)^{-1/n} \times\left[1 + \frac{Anm_0^n I_2}{\upsilon W^2}\left(1 + \frac{Anm_0^n I_1}{\upsilon W^2}\right)^{-1}\right]^{-1/n} \tag{19}$$

After simplification:

$$m_2 = m_0\left[1 + \frac{Anm_0^n\,(I_1 + I_2)}{\upsilon W^2}\right]^{-1/n} \tag{20}$$

which demonstrates that individual press impulses can be added together.

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