

COMPUTATIONAL MODELLING OF PAPER DRYING MACHINES

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Abstract

A mathematical model for the drying of paper on commercial machines is applied to two paper machines and the results are compared with actual production data, with an emphasis on minimising drying energy consumption. The model predicts the specific steam consumption (SSC: $\text{kg}_{\text{steam}}/\text{kg}_{\text{paper}}$) of the paper machine with a 91% correlation on the basis of machine data monitored over a three year period and also demonstrates that 65% of the moisture evaporation occurs in the free draw.

A series of simulations were performed to demonstrate the effect of the paper sheet condition on drying, specifically initial moisture content, sheet thickness, sheet basis weight and initial temperature. A second set of calculations was carried out to examine the effect of drying conditions, namely cylinder temperatures, pocket air temperatures and pocket air humidity, on achievable machine speed and specific steam consumption. The results showed how lower cylinder temperatures, higher pocket ventilation temperatures and higher pocket absolute humidity will all lead to more efficient drying operation as measured by a decreased SSC.

Two scenarios were considered from a machine design perspective. One simulation investigated the optimal geometrical arrangement of the two rows of drying cylinders, whilst maintaining a constant total sheet length within the dryer section. A second execution of the computational model was to investigate the effect of converting an initial dryer sub-section from double-felting to single-felting in a bid to improve heat transfer, drying rate and also runnability in this critical wet section. The simulation predicted that this would lead to a production increase of almost 20 m/min from a nominal machine speed of 880 m/min.

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1. Introduction

Previous work (1,2,3,4) described the development of a theoretical model to describe paper drying and conducted tests and a literature review to obtain the appropriate physical properties for paper and transfer

coefficients representative of the paper machine. The theoretical model output was checked against actual paper machine data for Australian Newsprint Mills, Boyer, No. 3 paper machine (PM3) for which both moisture content data and energy consumption information are available, and found to be consistent.

A number of investigators have developed mathematical models of the paper drying process. Nissan (5,6,7) together with Han (8,9,10), and Corte (11,12) were the pioneers in defining the paper drying process and their work set the scene for subsequent model development. Whilst limited by the use of analog computer solution Depoy's (13) model and experimental tests provided the evidence for industry to make the change from the traditional absorbent felts to open weave synthetic fabrics in the dryer section of the paper machine. Lee and Hinds (14,15,16) were successful in developing a computational framework built upon comprehensive mass and energy equations which described the drying process and obtained reasonable correlations to describe the liquid, vapour and thermal transport coefficients. However, their physical data were determined for 600 g/m² linerboard rather than the 50 g/m² newsprint of interest in this current study. More recently Harmann and Schulz (17) and Ramaswamy (18) have put forward comprehensive and plausible descriptions of the convective drying of paper with the latter concentrating on the production of 0.45mm linerboard.

Nederveen et al (19) summarised the work of a number of drying investigators and provided a summary of the current direction of drying research. Nederveen et al suggested there was considerable scope for further experimental work to describe quantitatively all phenomena related to evaporation within the paper machine, noting the degree of conflict between authors concerning the percentage of evaporation occurring in the free draw of the paper machine as opposed to that occurring whilst the sheet is in contact with the hot cylinder surface. Some authors quote a figure of 10% of total moisture evaporation occurring in the free draw whilst others claim 40%.

The application of this model in calculating drying rate within the paper sheet has been extended to describe the energy consumption associated with given drying conditions. The detail of the current model makes it possible to ascertain the implications of changes in energy input to various parts of the dryer section. For known values of energy consumption the drying efficiency can be calculated and used as the basis for comparisons between different machine operating conditions and configurations. With this framework in place it is then desirable to run a series of calculations to develop practical correlations which relate drying performance to operating parameters. These trends will prove extremely useful in establishing the optimal energy efficient control strategy for operating the dryer section of the paper machine with minimisation of the SSC and maximisation of achievable production rate as broad objectives. The other useful function of the mathematical model is its ability to forecast the effect of configuration changes to the dryer section. Several examples of the modelling ability to assist with design related issues are presented in this paper on the basis of the development of a detailed model described previously (1,2,3,4) in terms of evaluation of sheet properties by laboratory testing, their incorporation into a finite difference computation and evaluation by comparison with full scale machine data.

2. Review of computational model

A mathematical model has been developed previously (1,2,3,4) to describe the paper drying process. The model is centred around the consideration of the paper sheet as a porous, hygroscopic material which releases moisture to the surroundings via the mechanisms of liquid capillary flow, diffusional vapour flow and bulk vapour flow as a consequence of the total pressure gradient across the sheet thickness. Liquid flow within the paper sheet occurs due to the capillary pressure differentials created by the non-uniform pore structure of the paper sheet and is controlled by Darcy's law. Vapour flow by diffusion is driven by the vapour concentration gradient which primarily occurs due to the non-uniform temperature distribution across the sheet (Fick's law). The third major mechanism for moisture removal from the

sheet is that of bulk vapour flow which differs from the diffusion term in that the flow is pressure driven rather than concentration driven and Darcy's law applies. Given that the pressure within the dryer hood is close to atmospheric, this phenomenon therefore occurs if the paper sheet temperature exceeds 100°C.

Mass and energy balances are established for an element of paper of thickness, dy , as shown in **Figure 1**, where a typical slice contains fibres and pores in the ratio $(1 - \epsilon) : \epsilon$. ϵ is the porosity with the pore volume divided between liquid water and water vapour in the ratio $S : (1-S)$, and S is the degree of fractional saturation. This leads to the defining differential equations for mass and heat transfer balances in the sheet:

$$\frac{\partial M}{\partial t} = \frac{\rho_L \kappa_L}{\mu_L} \frac{\partial^2 P_L}{\partial y^2} \frac{dy}{b_{wt}} + D_v \frac{\partial^2 \rho_v}{\partial y^2} \frac{dy}{b_{wt}} \left[+ \frac{\rho_v \kappa_v}{\mu_v} \frac{\partial^2 P_v}{\partial y^2} \frac{dy}{b_{wt}} \right] \quad (1)$$

$$\frac{\partial CT}{\partial t} = k \frac{\partial^2 T}{\partial y^2} + \frac{\rho_L \kappa_L}{\mu_L} H_L \frac{\partial^2 P_L}{\partial y^2} + D_v (H_v + Q_s) \frac{\partial^2 \rho_v}{\partial y^2} \left[+ \frac{\rho_v \kappa_v}{\mu_v} (H_v + Q_s) \frac{\partial^2 P_v}{\partial y^2} \right]. \quad (2)$$

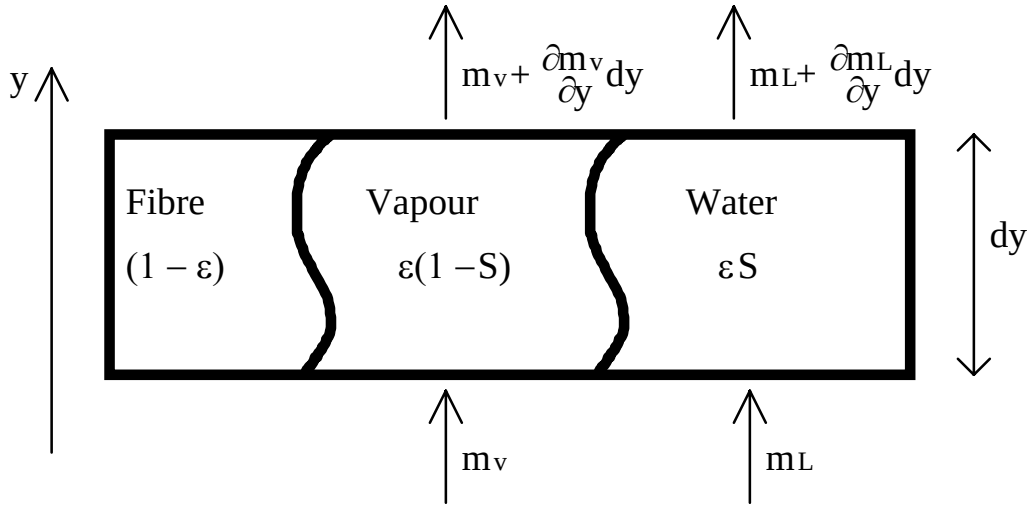


FIGURE 1
Shows mass transfers through an element of the paper sheet

M is the sheet moisture content $[\text{kg}_{\text{water}}/\text{kg}_{\text{fibre}}]$, ρ is density, κ is the sheet permeability (intrinsic), μ is viscosity, P is the internal pressure, y is the dimension perpendicular to the plane of the sheet, D is the diffusion coefficient, C is the combined specific heat capacity of paper slice, Q_s the heat of sorption, H_{fg} the heat of vaporisation for water, H is enthalpy, b_{wt} is the dry basis weight of paper sheet $[\text{kg}/\text{m}^2]$, t is time and the subscripts L and v refer to liquid and vapour phases respectively. The parentheses $[]$ indicate that the bulk flow term is included only when the internal web pressure exceeds atmospheric.

At the heated drying cylinder surface the temperature boundary condition relates the heat transfer through the interface to the heat conduction at the paper surface. The other three mass transfer boundary conditions (liquid diffusion, vapour diffusion and bulk vapour flow) are consistent with a zero mass flux

across the impermeable cylinder surface. At the open side of the sheet the surface convection heat transfer is equated to the heat conduction through the sheet. In a similar fashion the vapour diffusion flow at the open air interface is related to the external vapour density gradient by the surface mass transfer coefficient. The final two boundary conditions at this interface are derived on the premise that the surface offers no resistance to the pressure driven flows of liquid and vapour.

Reardon (1) and Reardon, Davis and Doe (2) detail the development and definition of the physical parameters which are required by the model. These include pore size distribution, permeability, sorptive characteristics, thermal conductivity, specific heat capacity, density, diffusion coefficients and shrinkage characteristics as well as heat and mass transfer coefficients at the interfaces.

The heat and mass transfer boundary conditions are a key part of the computational model. During the process of single-sided hot surface drying the paper sheet sees an impermeable heated surface on one face and is exposed to a body of conditioned air on the other face. **Figure 2** shows the physical situation schematically where T_{air} is the air temperature within dryer hood, ϕ the air relative humidity within dryer hood, T_c the temperature of hot drying surface, h_c the contact heat transfer coefficient, h_s the open surface heat transfer coefficient, and, h_m the surface transfer coefficient.

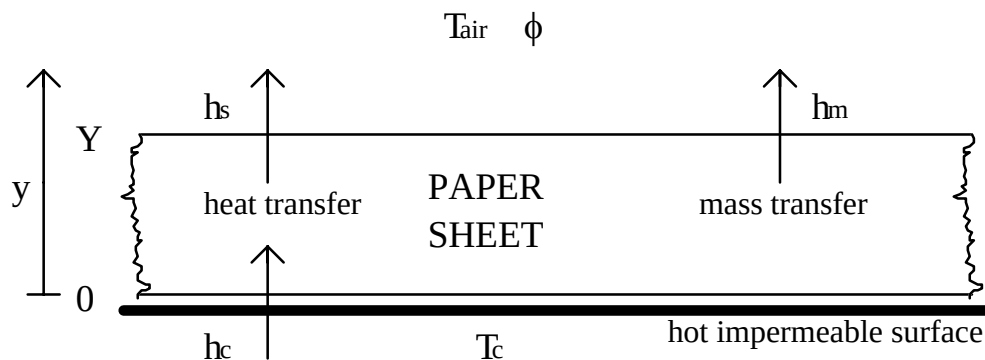


FIGURE 2
Illustrates boundary conditions and transfer coefficients

The temperature boundary condition relates the heat transfer through the interface to the heat conduction at the paper surface. The liquid and vapour mass boundary conditions are consistent with a zero mass flux across the impermeable cylinder surface. At the open surface the heat conduction term is equated to the surface convection heat transfer through the surface heat transfer coefficient h_s . In a similar fashion the vapour diffusion flow at the open air interface is related to the external vapour density gradient by the surface mass transfer coefficient, h_m . The final two boundary conditions are derived on the premise that the surface offers no resistance to the pressure driven flows of liquid and vapour.

As part of the model it is necessary to introduce time dependent boundary conditions, which change in a regular pattern as the sheet makes its way through the dryer section. The surface relations vary as a function of the sheet's location within the dryer section in accordance with **Figure 3** (for a double-felted dryer section).

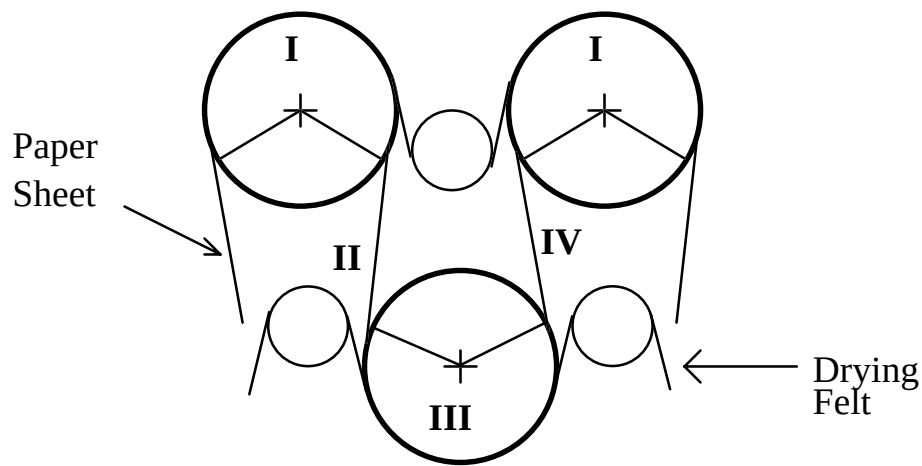


FIGURE 3
Four boundary condition regions for each drying cylinder pair in the double felted region of the dryer section

Section **I** is identical to the configuration for hot surface drying as described earlier. The surface mass transfer coefficient applied here must take account of the restricting nature of the adjacent felt. In section **II** both sides of the sheet are open to the local air flows. There is no heating supplied and the sheet cools quickly due to the dual-sided evaporation. There is no felt in contact with the sheet so evaporation occurs unimpeded. Section **III** is the reverse of **I**; the sheet is heated from its 'top' side whilst moisture removal can occur through the dryer felt on the 'bottom' side. Section **IV** is identical to **II**.

The cyclic changes of surface transfer coefficients are essentially the same for both single and double felted parts of the dryer section. The general pattern of boundary conditions is the same but in the case of double felted drying sections the surface heat and mass transfer coefficients must be modified for the absence of the dryer felt during the free draw.

3. Dryer section energy balance

The energy flows into and out of the dryer section are characterised by four major streams; paper fibre, steam, air, and water which enters with the paper and leaves with the exhaust air. There is also the provision for a term which expresses heat loss by radiation and natural convection from the dryer hood to the machine room. These flows are represented schematically in **Figure 4** showing the dryer hood shown as the structural framework which encloses the entire drying region which includes the dryer cylinders, the ventilation system, the dryer fabrics and the paper sheet itself which enters with a moisture content of around $1.4 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$ and leaves with $0.1 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$. The dryer hood operates under slight negative gauge pressure. The air vented by the exhaust fans is a combination of air from the supply fans (60-80%), *pocket ventilation (p.v.) air*, and *infiltration air* (20-40%). The pocket ventilation air is so named because the duct outlets direct the drying air into the dryer pockets formed by the cylinders, the dryer fabric and the paper sheet. The infiltration air leaks into the dryer hood through various access door openings and reduces the average air temperature and absolute humidity within the dryer hood. As these are counteracting effects in drying terms there will be an optimal infiltration rate which aids energy efficient drying. From this overall description an energy balance can be developed which enables the heat loss and dryer efficiency to be calculated. The variables used in the dryer hood energy balance are

defined in **Table 1**, where the terms M_{in} and M_{out} refer to the paper sheet moisture content ($\text{kg}_{\text{water}}/\text{kg}_{\text{fibre}}$) at the inlet and outlet of the dryer section respectively. The variables w_{pv} , w_{leak} and w_{exh} refer to the absolute humidity of the pocket ventilation, leakage and exhaust air flows. The $m_{\text{ }}$ terms are mass flow rates (kg/s).

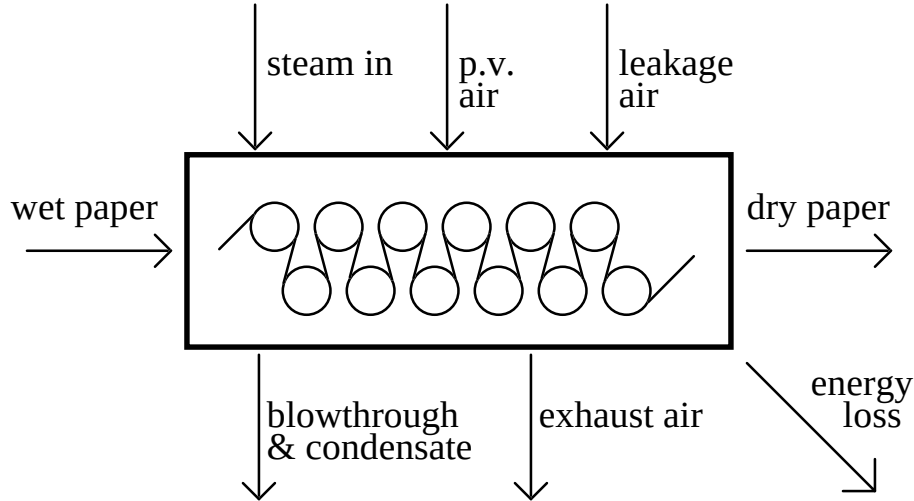


FIGURE 4
Energy flows through the dryer section of the paper machine

Equating energy into the dryer system with energy out of the system produces the defining relation :

$$m_f c_{pf} (T_{f_{out}} - T_{f_{in}}) + m_s (h_{s_{out}} - h_{s_{in}}) + c_{p_{air}} (m_{exh} T_{exh} - m_{pv} T_{pv} - m_{leak} T_{leak}) + m_f c_{pw} (M_{out} T_{f_{out}} - M_{in} T_{f_{in}}) + (w_{exh} m_{exh} h_{g_{exh}} - w_{pv} m_{pv} h_{g_{pv}} - w_{leak} m_{leak} h_{g_{leak}}) + Q_{loss} = 0, \quad (3)$$

where the c_p terms represent the specific heat at constant pressure for the subscripted components, h is the enthalpy of water/steam as a function of temperature and phase and Q_{loss} is the rate of heat loss from the dryer hood into the machine room. Of the four distinct streams within the dryer section it can be said that the steam and dry paper fibre exhibit constant mass flow so that mass flow rate in equals mass flow rate out, whilst the water and air flows interact with contributions from a number of sources. The relevant mass flow equations relating this interaction are, for water,

$$M_{in} m_f + w_{leak} m_{leak} + w_{pv} m_{pv} = M_{out} m_f + w_{exh} m_{exh}, \quad (4)$$

and for air,
$$m_{leak} + m_{pv} = m_{exh}, \quad (5)$$

Equation 5 allows the mass flow of the infiltration (leakage) air into the hood to be quantified using measurements of the hood air supply and exhaust flow rates. The knowledge of machine operating speed, basis weight and trim (machine width) implies a value for fibre mass flow and equation 4 then is able to determine paper sheet moisture loss and consequently sheet moisture content at the dryer inlet. This is a very useful calculation as the initial moisture content is a quantity which is rarely measured and yet clearly has a first order effect on all drying rate estimates.

TABLE 1
Definition of energy balance variables

Stream	Mass Flow	Temperature
paper fibre in	m_f	$T_{f_{in}}$
paper fibre out	m_f	$T_{f_{out}}$
steam in	m_s	$T_{s_{in}}$
condensate out	m_s	$T_{s_{out}}$
p.v. air in	m_{pv}	T_{pv}
leakage air in	m_{leak}	T_{leak}
exhaust air out	m_{exh}	T_{exh}
water in	$M_{in}.m_f$	$T_{f_{in}}$
	$w_{leak}.m_{leak}$	T_{leak}
	$w_{pv}.m_{pv}$	T_{pv}
water out	$M_{out}.m_f$	$T_{f_{out}}$
	$w_{exh}.m_{exh}$	T_{exh}

A sample calculation for the ANM PM3 machine provides an indication of the applicability of the equations and the magnitude of the flows. At a machine speed of 1050 m/min, manufacturing newsprint of basis weight 48.8 g/m² and final moisture content of 8.9%, the measured air flows were $m_{pv} = 41.0$ kg/s, and $m_{exh} = 73.7$ kg/s. The infiltration air flow must therefore be $m_{leak} = 32.7$ kg/s, and the *hood balance*, which is defined as the ratio of conditioned air input to total exhaust air, is 56%. Using the air condition data, namely that the machine room absolute humidity is $w_{leak} = 0.015$ kg/kg, the inlet pocket ventilation air is at $w_{pv} = 0.03$ kg/kg, and the exhaust air has a moisture content of $w_{exh} = 0.11$ kg/kg. The quantity of water evaporated from the sheet is $(M_{in} - M_{out}).m_f = 6.39$ kg/s. This corresponds to an initial moisture content of 1.32 kg_{water}/kg_{fibre} (57% wet basis).

The calculation can be extended to equation 1 to assess the energy loss from the dryer hood to the machine room. Given the temperatures, $T_{f_{out}} = 80^\circ\text{C}$, $T_{f_{in}} = 50^\circ\text{C}$, $T_{exh} = 75^\circ\text{C}$, $T_{pv} = 40^\circ\text{C}$, $T_{leak} = 25^\circ\text{C}$, the steam enthalpies, $h_{s_{out}} = 690$ kJ/kg, $h_{s_{in}} = 2771$ kJ/kg, the specific heats, $cp_f = 1.34$ kJ/kg $^\circ\text{C}$, $cp_a = 1.005$ kJ/kg $^\circ\text{C}$ and a dryer section steam consumption of 9.44 kg/s, the energy loss is $Q_{loss} = 660$ kW. The distribution between both input and output energy flows is shown in **Figure 5**. Q_{loss} is identified by the arrow.

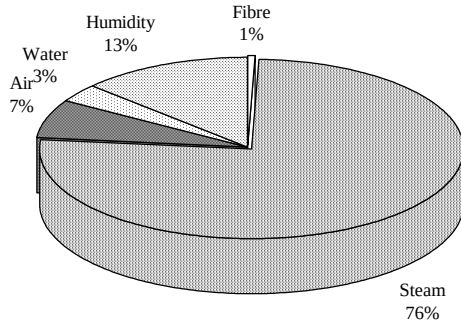


FIGURE 5a
Input energy flows

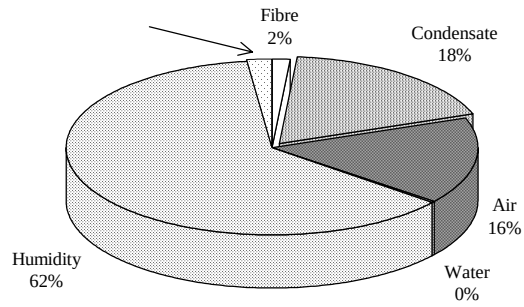


FIGURE 5b
Output energy flows

The efficiency of the dryer section can be appraised in terms of the ratio of moisture evaporation from sheet to the steam energy expended :

$$\eta = \frac{m_f (M_{in} - M_{out})(h_{g_{exh}} - c_{p_w} T_{in})}{m_s (h_{S_{in}} - h_{S_{out}})} = 81\% . \quad (6)$$

In the paper industry it is more common to quote the specific steam consumption (SSC) on either a per unit paper produced or per unit water evaporated basis. Given these definitions the figures are :

$$SSC_{water} = \frac{m_s}{m_f (M_{in} - M_{out})} = 1.5 \frac{kg_{steam}}{kg_{water\ evap}} , \quad (7)$$

and,

$$SSC_{paper(reel)} = \frac{m_s}{m_f (1 + M_{out})} = 1.7 \frac{kg_{steam}}{kg_{paper}} . \quad (8)$$

Although SSC_{paper} is more frequently quoted, SSC_{water} is more useful because it normalises the effect of initial moisture content and allows dryer sections to be compared equitably. When comparing these values with other paper mills caution is required as the steam consumption may only include drying cylinder steam or it may include all steam used by a machine from former to the calender roll stack at the end of the machine rather than the steam use of the complete dryer section alone.

4. Comparison of ANM machines with other industry energy data and computational model

(i) Achieved specific steam consumption

A comprehensive survey of Canadian newsprint machine dryer section energy use by Pikulik and Sayegh (20) showed that SSC_{paper} varied from 1.2 kg/kg to 3 kg/kg with a mean of 2 kg_{steam}/kg_{paper}. The parameter SSC_{water} exhibited a range of 1 kg/kg to 2.2 kg/kg with an average value of 1.5 kg_{steam}/kg_{water}. Comparison of the ANM machine dryer data with these values shows them to be in the lower half of the respective ranges, and equal to or below the mean values of the Canadian study. This may be due in part to the fact that the 1993 ANM data were obtained five years after Pikulik and Sayegh conducted their study. General modernisation of installed paper-making equipment throughout the Canadian industry during this time would probably lead to a modest reduction in the specific steam consumption from those figures quoted in 1988. The TAPPI Technical Information Sheet TIS-0404-15 (21) presents data summarising paper machine drying rate for approximately 70 different newsprint paper machines. The results are given in terms of water evaporation per unit of cylinder drying surface (kg_{water}/h/m²), which is calculated in accordance with TAPPI Technical Information Sheet TIS-0404-07 (22), against steam temperature. This quantity is a measure of dryer section effectiveness as opposed to energy efficiency. For a given dryer section size it ranks the ability of a machine to evaporate moisture in the dryer section for a given peak steam temperature in the drying cylinders. The specific drying rate figure for the PM3 machine is 15.7 kg_{water}/h/m² for 48.8 g/m² newsprint produced at 1050 m/min with a peak steam pressure of 130kPag (124°C). For the ANM PM2 machine producing 48.8 g/m² newsprint at 880 m/min with a peak steam pressure of 110kPag (122°C) the evaporation per unit of cylinder drying surface is 14.3 kg_{water}/h/m². The TIS-0404-15 results are used to generate **Figure 6** which includes reference marks to distinguish the ANM machine operating points. The line through the middle of the data points is a best fit line which represents the average drying rate per unit of drying cylinder surface for each steam temperature. Data points situated above this, such as the ANM PM2 and PM3 operating points, represent above average dryer section performance. One of the key reasons for the range of values is that some paper machines may not be operating at the dryer's full potential because machine speed is limited by other sections of the paper machine, the press or forming section for example. Variations in dryer configuration, such as single versus double-felted runs, and pocket ventilation rates will also affect these values.

(ii) Steam consumption predictions

Historical steam consumption data over the period from September 1990 to November 1992 of typical paper machine operating parameters were recorded to compare the model forecasts of steam consumption against actual machine results. Since the machine data were logged over a relatively long period of time (2 years) there are variations in the machine drying characteristics which will manifest themselves in the form of scatter on the summary graphs. These perturbations are due to a number of factors including pulp variation, machine runability, local drying effects, internal drying cylinder scale build-up, inlet moisture content variation, soiling of drying fabrics over operational life and local pocket ventilation settings. **Figure 7** demonstrates the trends indicated by both theoretical and actual machine data with respect to specific steam consumption variation with basis weight. The relationship between machine specific steam consumption and the model prediction can be expressed through the linear regression calculation of equation 9,

$$SSC_{\text{machine}} = 0.91 \times SSC_{\text{model}} + 0.123, \quad (9)$$

where the data have a regression coefficient of 0.78. The mild scatter in the data occurs for the reasons described previously which are changes in machine operation which are not able to be monitored or quantified in a straightforward manner. Given these factors the correlation observed is a good reinforcement of the realistic behaviour of the computational model.

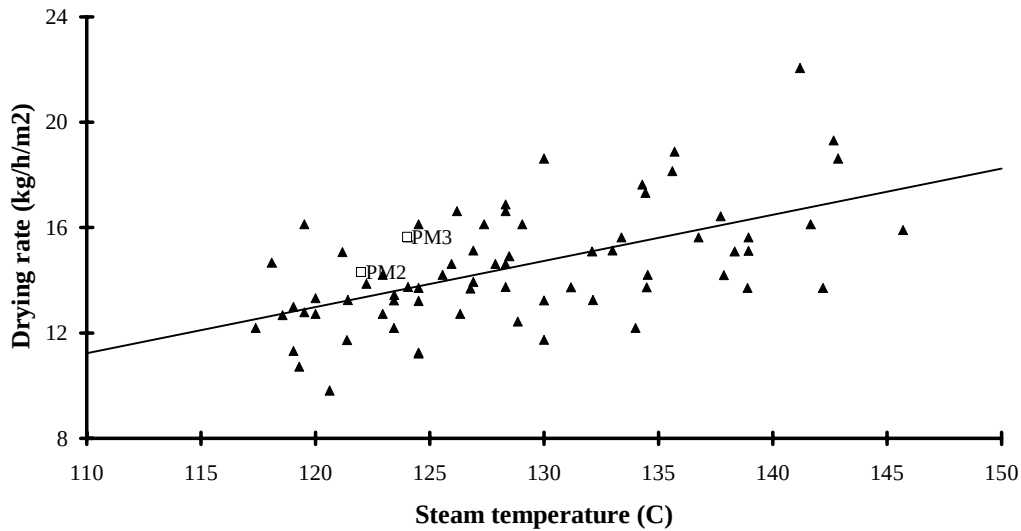


FIGURE 6
Paper machine drying rate data (TAPPI TIS 0404-15, 1986)

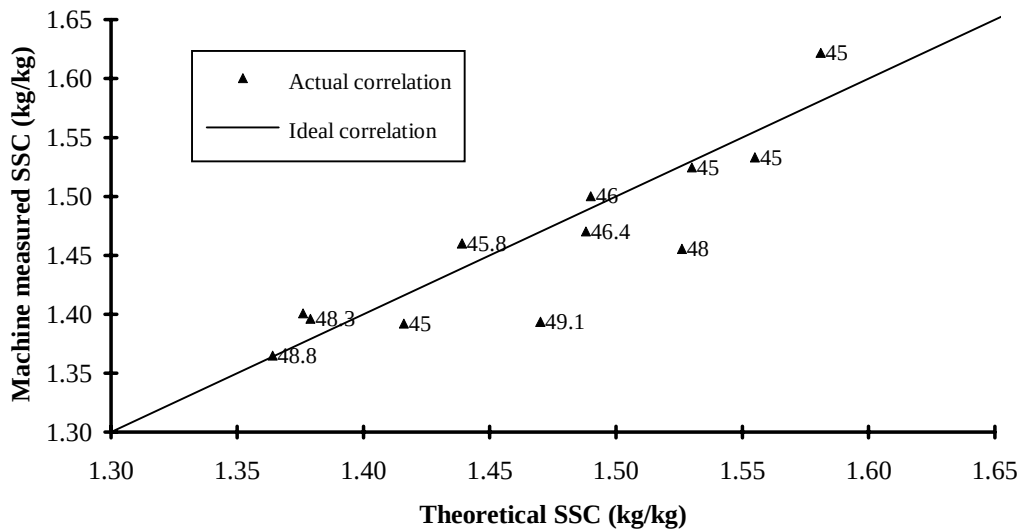


FIGURE 7
Comparison between machine measured specific steam consumption (SSC) data and model prediction of SSC for a number of monitored paper machine operating conditions between (1990-1992). The sheet basis weight (g/m²) is shown with each data point.

5. Exploring the computational model predictions - dryer section operating conditions

(i) Nominal machine conditions

In analysing the range of paper sheet and paper machine parameters it is necessary to establish a base-case from which changes in specific parameters can be assessed. The key paper sheet conditions and their nominal standard (base-case) values are,

- inlet moisture content - $1.38 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$ (58% wet basis)
- sheet caliper - $70 \mu\text{m}$
- dry basis weight - 44.4 g/m^2 (0% moisture, equivalent to a nominal basis weight of 48.8 g/m^2 at the reel)
- inlet temperature - 50°C

Paper machine control conditions which can be infinitely varied by the model and their standard values for each of the five dryer sub-sections are listed below for PM3.

- dryer cylinder temperatures - 95°C , 110°C , 116°C , 122°C , and 120°C
- dryer pocket temperatures - 55°C , 65°C , 78°C , 80°C , and 85°C
- dryer pocket humidity - 65%, 65%, 55%, 52%, and 30%
- machine speed - 1050 m/min
- no. of drying cylinders - 48

The core function of the model is to predict the variation with time of the moisture content of a slice of paper as it progresses through the paper machine dryer section. Comparing actual machine moisture content values with the model prediction showed the forecast moisture change during drying to cylinder No. 38 on PM3 to be 2% (dry basis) less than actual and 0.1% (dry basis) more than actual by the exit from the drying cylinder. On PM2 no intermediate measurement was possible but the overall moisture change between dryer inlet and exit differed only by 0.2% (dry basis) between theoretical and actual. Together with the specific steam consumption comparison in Section 4 (ii), these results present evidence that the mathematical model is a reliable forecast tool for paper drying.

Analysis of the drying behaviour on PM3 shows that whilst the free draw accounts for 30% of the dryer section length, 65% of the moisture evaporation occurs in these zones between cylinders. The remaining 35% of the drying occurs from the sheet whilst it is in contact with the heated cylinder. This represents an overall calculation, as the relative drying rates will vary between sub-sections depending upon local temperatures and whether single or double-felting is employed. By comparison Nederveen et al (19) quotes the degree of variation between authors concerning the percentage of evaporation occurring in the free draw of the paper machine as opposed to that occurring whilst the sheet is in contact with the hot cylinder surface where some authors quote a figure of 10% whilst others claim 40%. The figure of 35% emerging from this study falls within the published range, but is of course extremely dependent upon the paper machine design geometry.

The key production data of interest from any analysis are the achievable machine speed for a given set of conditions and the resultant specific steam consumption (SSC). The SSC represents the mass ratio of drying steam used for each unit of paper produced by the machine, the paper industry's measure of dryer energy efficiency. The achievable machine speed for a given set of drying conditions and initial conditions is that speed which brings the paper sheet to a fixed final moisture content, taken as 9% (wet

basis) or $0.10 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$ for the paper machine under study, immediately after the final drying cylinder.

(ii) Effect of paper sheet properties

This first parametric analysis assumes the standard paper sheet inlet and dryer section control conditions are maintained at nominal values and calculates the achievable operating speed and the required energy input in terms of specific steam consumption [$\text{kg}_{\text{steam}}/\text{kg}_{\text{paper}}$] under the constant drying conditions defined earlier. This calculation is done for four sets of conditions by varying in turn each of the paper sheet initial conditions - initial moisture content, caliper, basis weight, initial temperature - in each case over its likely operational range. This gives rise to the graphs presented in.

The *moisture content* of the paper sheet leaving the press section is a first order parameter in controlling achievable drying rate for a given set of drying conditions. The moisture content is directly representative of the drying load - the quantity of water to be evaporated in the dryer section. Water that is not removed mechanically in the press section must be removed at added cost in the dryer section. The *cost* of extra dryer inlet moisture for given operating conditions is a decrease in production speed and an increase in dryer energy consumption. **Figure 8** demonstrates that *under constant drying conditions* an increased initial moisture content will lead to a decrease in production speed and an almost linear increase in steam consumption per unit of dry paper produced. About the base-case of $1.38 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$, it can be shown that a 10% increase in initial moisture content will lead to an 8.6% reduction in machine speed and an 8.5% increase in specific steam consumption. These data highlight the importance of an efficient press section.

It is quite understandable that the specific steam consumption shows an almost linear relationship with initial moisture content. An increment in initial moisture content brings about a proportional increase in the quantity of water to be evaporated. The evaporation of more water per unit mass of dry fibre will result in the use of a proportional increase in the amount of steam per unit mass of dry fibre. The computational model, however, also ensures that the required heat transfer can actually be achieved as will be discussed later.

The paper sheet *caliper* is a parameter which varies for different paper grades depending upon the desired basis weight and porosity of the final product. For a fixed basis weight, which is specific to paper grade, the effect of caliper on drying is to alter the diffusion and permeability paths through which vapour and liquid moisture must pass to reach the sheet surface and in so doing dry the paper sheet. The sheet dry caliper which has been assumed for the 'standard dry sheet' is $70\mu\text{m}$. The effect of changing this value on drying rate and specific steam consumption, under the fixed drying conditions defined earlier, is illustrated in Figure 8. For a constant sheet basis weight, increasing the sheet caliper makes the sheet more bulky, increases the amount of void space and increases the distance moisture must travel to exit the sheet. An increase in caliper also decreases the thermal conductance of the sheet and results in a lower average temperature through the sheet. Consequently this change is accompanied by a reduction in achievable drying rate for constant operating conditions. Hence the paper machine speed must be lowered in order to dry the sheet and this sees additional steam used per unit of reel-dry paper produced. Figure 8 demonstrates that about the base-case of $L_{\text{init}} = 70\mu\text{m}$, it can be shown that a 10% increase in sheet caliper will lead to a 2.8% reduction in machine speed and a 2.4% increase in specific steam consumption. These data show that whilst sheet caliper is a significant parameter in controlling drying it is less dominant than the initial moisture content of the paper sheet. During actual paper machine operation the sheet caliper is governed by the grade of paper and basis weight.

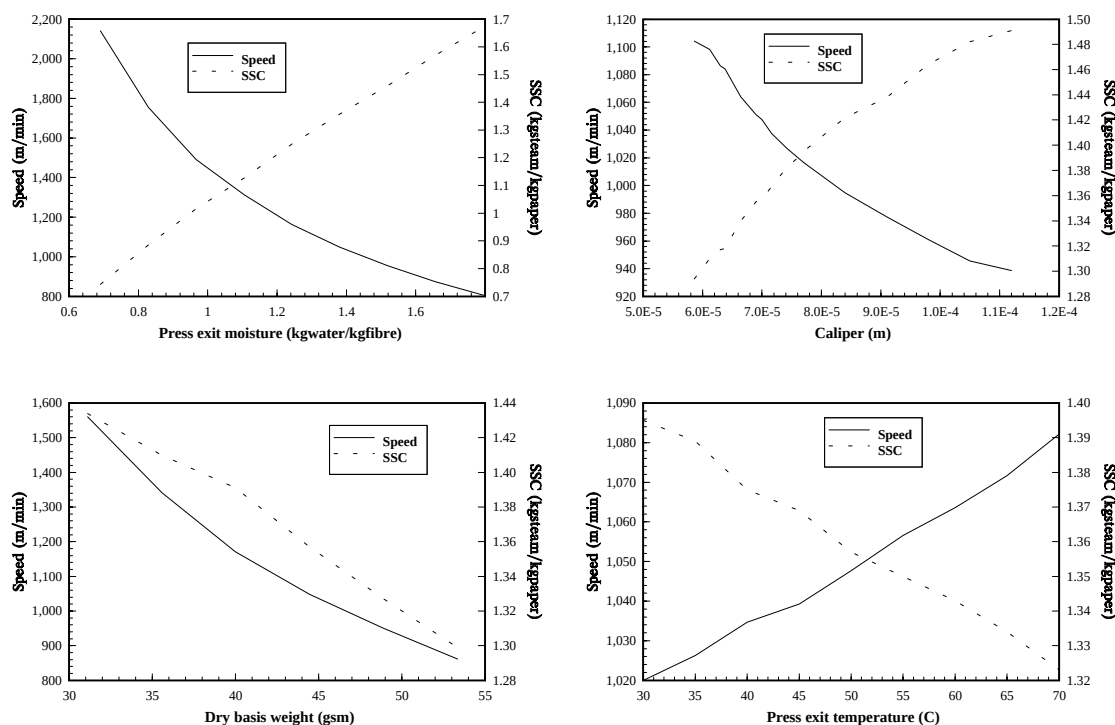


FIGURE 8
Variation of paper sheet drying rate and dryer steam consumption with initial moisture content, sheet caliper, basis weight and initial temperature

The paper sheet *basis weight* is the key parameter which identifies each product. Telephone directory paper is 36-40 g/m², newsprint is 45-49 g/m² and higher quality paper suitable for four colour offset printing is produced in the 52-55 g/m² range. Variation in the sheet basis weight changes the fibre density per square metre. For the same initial moisture content the quantity of water per square metre of paper will change directly with the basis weight. This change will be accompanied by a proportional change in production rate for a given set of conditions. The predicted change to drying rate and specific steam consumption resulting from a variation in sheet basis weight is shown in Figure 8. About the base-case of $b_{wt} = 44.5 \times 10^{-3}$ kg/m², it can be shown that a 10% increase in sheet basis weight will lead to a 9.7% reduction in machine speed and a 2.0% decrease in specific steam consumption. These data show that basis weight is almost inversely proportional to machine speed. This is understandable as increasing basis weight means a corresponding increase in the water removal requirement for a fixed initial moisture content. The decreasing SSC with increasing basis weight is a more interesting phenomenon. This suggests that drying heavier sheets at slower speeds is a more efficient means of drying a quantity of newsprint. The analysis predicts this relationship because the variation in basis weight is done at constant sheet caliper. This increase in basis weight whilst maintaining constant sheet thickness means that the fibre and water matrix is much more densely packed and the dewatering path is therefore much shorter than in a more bulky sheet. The shorter dewatering path reduces the overall resistance to moisture movement within the sheet and allows moisture to evacuate much more easily.

The paper sheet *initial temperature* is determined by the pressing operation prior to the dryer section. Most press sections include a *steambox* which passes a stream of live steam over the wet web to heat the sheet. High temperatures in the press section lower the water viscosity and assist the process of

mechanical dewatering. Thus a high initial temperature is often associated with a lower initial moisture content entering the dryer section. In isolation the initial sheet temperature is likely to affect drying rates to a limited degree due to the lack of substantial thermal mass of a given area of paper. About the base-case of $T_{init} = 50^{\circ}\text{C}$, it can be shown that a 5°C increase in initial temperature will lead to a 0.8% increase in achievable machine speed and a 0.7% decrease in specific steam consumption. This demonstrates that the overall drying process is relatively insensitive to this parameter. This occurs because the relatively light basis weight paper sheet has very little thermal storage. Increasing the sheet initial temperature is a very small energy input in the overall dryer energy balance, representing just 5% of the total energy input into the dryer section.

(iii) Effect of machine drying conditions

The controllable drying conditions investigated are cylinder steam temperature which is controlled by the steam pressure for the given dryer sub-section, pocket air temperature which is controlled by the steam flow through the air heating coils, and pocket air humidity which is governed by the quantity of dry air circulated through the dryer hood for a given evaporation rate. The outcome of these calculations is significant because they demonstrate how the dryer section energy efficiency is influenced by changes in operating conditions.

On a paper machine the cylinder steam temperature, pocket air temperature and pocket air humidity are varied in each of the five sub-sections which constitute the overall dryer section. Thus, each of these five groups of 6-16 drying cylinders expose the paper sheet to the same nominal drying conditions. When investigating a change in one of these three parameters it is therefore necessary to acknowledge that each parameter is set at a different value depending upon the position within the dryer section. Hence, for the purposes of analysis a *change* in one of the three controlling parameters means that the value in *each* of the five sub-sections changes by a corresponding amount.

The *cylinder steam temperatures* are controlled by the pressure of the steam input into the cylinders. The steam pressure relates to a specific saturation temperature. The magnitude of heat transfer coefficients from steam to the cylinder itself and through the cast iron cylinder shell governs the surface temperature to which the paper sheet is exposed. The nominal steam temperatures for the five dryer sub-sections are : 95°C , 110°C , 116°C , 122°C , and 120°C . These values have been varied over the range $\pm 10^{\circ}\text{C}$ in the computation and the achievable machine speed, as limited by drying capacity, and the resultant specific steam consumption are calculated. This is done by iterating the drying model with different machine speeds to determine the speed which will bring the sheet to a moisture content of 9% or $0.10 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$ at the exit from the final drying cylinder. As an example, a change of $\Delta T_{\text{cyl}} = +5^{\circ}\text{C}$ in the cylinder steam temperatures leads to the following sub-section temperatures : 100°C , 115°C , 121°C , 127°C , and 125°C .

The results of these calculations are presented in **Figure 9**, and demonstrate that the dryer section operates more efficiently at lower cylinder temperatures, although this will naturally slow production speeds. For example, a 10°C increase in all cylinder temperatures leads to a 34% increase in drying speed and a 3.5% increase in specific steam consumption. This demonstrates that drying capacity is particularly sensitive to the cylinder steam temperature. The practical limitation may come in the form of pressure rating of the cylinders or the paper sheet attaching to the cylinders if the contact temperature is too high.

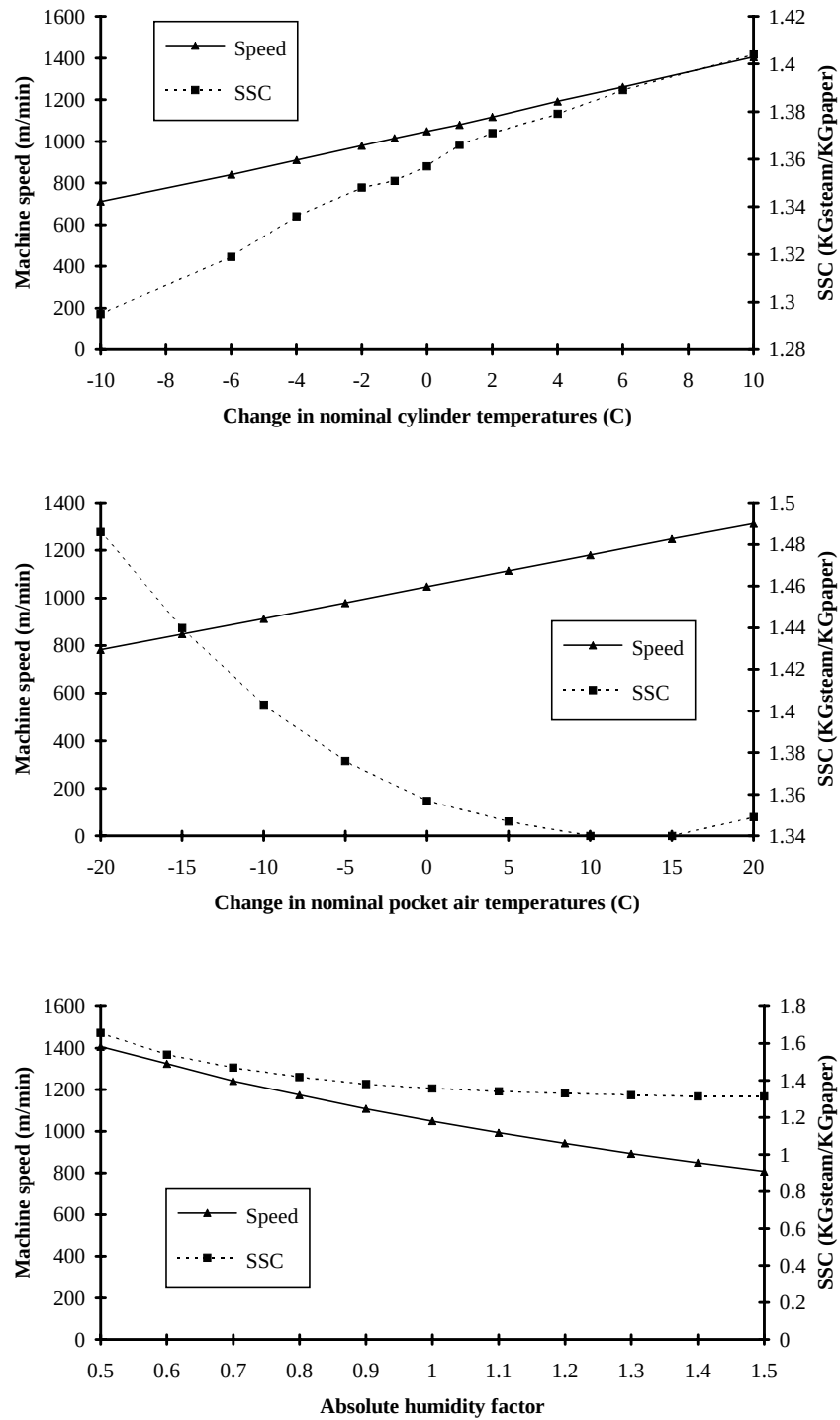


FIGURE 9
Variation of machine drying rate and dryer steam consumption with changes in cylinder steam temperature and pocket air temperature and absolute humidity

The *pocket ventilation air temperatures* throughout the dryer section are controlled by the pressure of the steam fed to the heat transfer coils which heat the incoming air. The amount of steam controls the temperature of air input into the dryer hood and consequently the temperature of the mixed drying air adjacent to the paper sheet in the dryer pockets. The nominal temperatures of the drying air for the five dryer sub-sections are : 55°C, 65°C, 78°C, 80°C, and 85°C. In the following calculations these values are varied over the range $\pm 20^\circ\text{C}$ and the achievable machine speed, as limited by drying capacity, and the resultant specific steam consumption are calculated. Again this is done by iterating the drying model with different machine speeds to determine the speed which will bring the sheet to a moisture content of 9% or $0.10 \text{ kg}_{\text{water}}/\text{kg}_{\text{fibre}}$ at the exit from the final drying cylinder. As an example, a change of pocket air temperature $\Delta T_{\text{pock}} = +10^\circ\text{C}$ in the pocket air temperatures leads to the following sub-section temperatures : 65°C, 75°C, 88°C, 90°C, and 95°C.

The results demonstrate that the dryer section operates most efficiently when the pocket air temperatures throughout the whole dryer section are all increased by 11°C . This change leads to a 1.4% decrease in specific steam consumption and a 14% increase in drying speed. This demonstrates that better drying performance can be achieved without compromising production speed through increasing the temperature of the pocket ventilation air. Practical limitations may arise from the ability of the hood to minimise infiltration air from the machine room which dilutes the conditioned air input into the dryer section and lowers the temperature in the drying pockets or the maximum heat transfer available from the heat transfer coils at the given air flow.

The *pocket air humidity* is controlled by the volume of air injected into the dryer hood for a given drying (evaporation) rate. The air flow is controlled by both the supply and exhaust fans. The hood is maintained at a slight negative pressure by ensuring the capacity of the exhaust fans exceeds that of the supply fans. Air is supplied into individual pockets through the double-felted parts of the dryer section, and by more general ducting arrangements in the single-felted parts at the wet end. The nominal pocket relative humidity values for the five dryer sub-sections are : 65%, 65%, 55%, 52%, and 30%. In terms of absolute humidity these values may be represented as : 0.0697, 0.1186, 0.1927, 0.1994, and, 0.1282 $\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$. These absolute humidity values were varied in the model over the range $\pm 50\%$ and the achievable machine speed, as limited by drying capacity, and the resultant specific steam consumption are calculated. As an example, a change of +25% to the absolute humidity of the pocket air, or $W_{\text{factor}} = 1.25$, leads to the following values : 0.0871, 0.1483, 0.2409, 0.2493, and, 0.1603 $\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$.

The results demonstrate that the dryer section operates more efficiently at higher humidities, although this comes at the expense of drying capacity. For example, a 20% increase in all pocket absolute humidities leads to a 10.2% decrease in drying speed and a 2% decrease in specific steam consumption. It is noted that above a 40% increase in absolute humidity there are no significant further gains in energy efficiency. Practical limitations to changes in the pocket humidity may come in the form of local condensation caused by increases in humidity or where low humidities may require larger air flows which exceed either the supply fan capacity or the stability limit for the paper sheet which is exposed to this air movement.

6. Exploring the computational model predictions - overall dryer design

The theoretical drying model is intended to assist with optimising the dryer section performance both in terms of operational settings as well as hardware configuration. The previous section discussed the control strategy application whilst the ensuing examples will demonstrate the model relevance in examining the effects of major structural changes to the dryers on either of the ANM machines. Whilst it

would not be economic to redesign an entire paper machine dryer section in terms of cylinder locations and length of the open draws simply from the viewpoint of energy efficiency, it is of interest to assess the current configuration from this perspective. This provides an opportunity to demonstrate the capability of the model and compare it with the design tools employed by the paper machine original manufacturer in the 1960s when the machine was built and during subsequent modifications.

The PM3 dryer section has 48 drying cylinders, the first twelve cylinders composing two single-felted dryer sub-sections whilst the remaining three sub-sections are double-felted drying runs. The typical sheet wrap per drying cylinder is 2.968m whilst most of the free draws are 1.159m long. These figures vary marginally at the changeover between sub-sections. An interesting theoretical consideration lies in the question of the optimal balance between cylinder wrap and open draw for a dryer section. The length of cylinder wrap governs the amount of heat which can be input into the paper sheet to provide energy for the evaporation of moisture. The open draw offers a considerably higher mass transfer coefficient where the evaporating moisture is not impeded by the close contact of the drying fabric. Thus an excessively large cylinder wrap will maintain a hot sheet which cannot freely vent moisture whilst an excessive amount of free draw will allow the sheet temperature to drop dramatically so that insufficient energy remains for further evaporation after an initial period in the free draw.

The ANM PM3 machine has a 70% : 30% split between cylinder wrap and free draw length throughout its dryer section. To analyse the suitability of this mix a series of calculations were devised whereby the total length of paper run throughout the dryer section (200.039m) was held constant and the balance between cylinder wrap and free draw varied. The balance was changed by adding/subtracting a fixed incremental distance to each of the 48 lengths of cylinder wrap throughout the dryer section and subtracting/adding the same distance to the 48 free draw lengths throughout the dryer section. For each of these dryer section geometries the paper sheet speed required to bring the sheet to standard dryness, 8.9% or 0.0988 kgwater/kgfibre was calculated. Constant drying conditions such as cylinder temperature and dryer pocket air temperature and humidity were used throughout all calculations.

The results presented in **Figure 10** show the variation of paper machine speed with a variable referred to as *offset*, which is defined as the incremental length added to the cylinder wrap components of the dryer section. Thus a positive value for *offset* means that the cylinder wrap is being increased and the free draw decreased. Similarly a negative value for *offset* means that each free draw section has been lengthened whilst reducing the contact with the heated cylinder to maintain the overall length constant. The results show that the optimal value for *offset* is +0.1m. This implies that cylinder wraps would be increased to 3.07m and the free draws reduced to 1.06m. Given this change the achievable machine speed under constant drying conditions would increase by 0.5% to 1055 m/min. This is a modest performance increase and demonstrates that the initial design of the dryer section geometry of this paper machine was well-founded. However, the calculation very succinctly emphasises the usefulness of the computer-based model for resolving a wide range of performance issues related to dryer section operation.

The ANM PM2 machine is about 10 years older than the wider PM3 and generally runs at 880 m/min when producing 48.8 g/m² newsprint. In order to improve the runnability of the paper sheet through the dryer section as well as drying capacity one proposal that has been considered is to revise the initial single-felted dryer sub-section. All drying cylinders in PM2 (and PM3) are 1.52m (5') diameter. The cylinder-sheet contact area could be increased by installing larger diameter cylinders. 2.13m (7') cylinders are available and could be retrofitted as the upper cylinder row in the wet single-felted region. The number of cylinders would be reduced in this case from twelve to ten - corresponding to five 2.13m cylinders along the upper row. Consequently, the change in achievable drying rate for a given set of drying conditions will be influenced by the new balance between cylinder wrap and open draw in the wet end sub-section and also the reduction in cylinder number. A diagram of the proposed arrangement and the key dimensional variables is presented in **Figure 11**. The diagram defines the variables *s*,

representing the offset distance between upper cylinders, D and d , being the diameters of the upper and lower cylinders respectively, L , the vertical distance between upper and lower cylinder centres, and θ , the angle of contact arc between paper and the heated cylinder in excess of 180° . The geometrical relationship between the parameters is,

$$D + d = 2L \sin \theta + (D + s) \cos \theta. \quad (10)$$

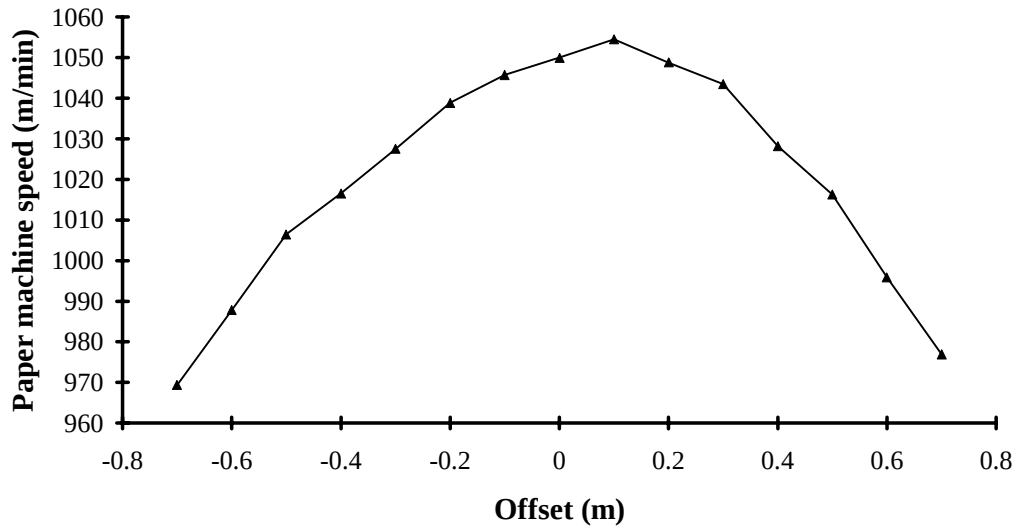


FIGURE 10
Attainable operating speed on PM3 with cylinder wraps increased by *offset* and free draws reduced by *offset*

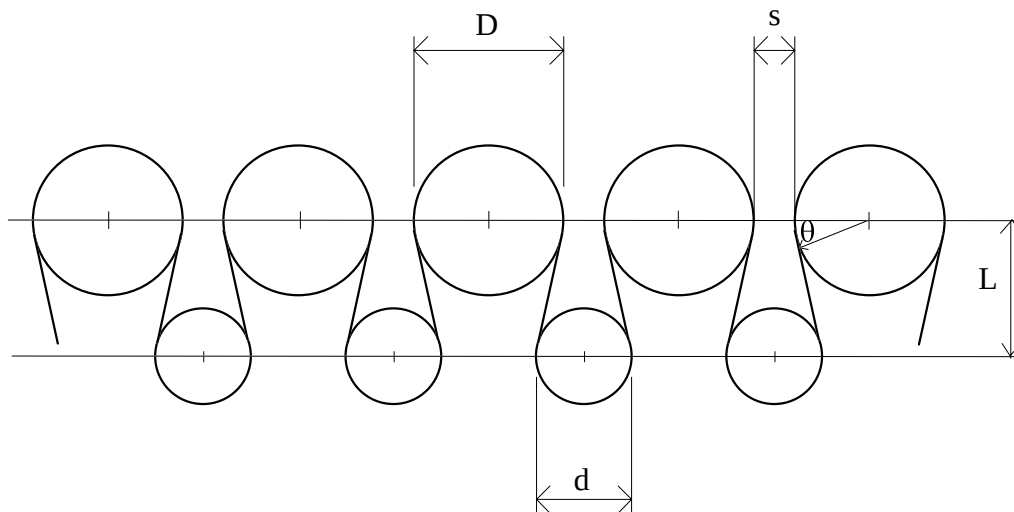


FIGURE 11
Diagram of potential PM2 single-felted drying run with 2.13m diameter upper cylinders

As mentioned earlier D is to be set to 2.13m. The horizontal separation distance s is typically 0.45m on most paper machines and it appears impractical to reduce the clearance below this value. The lower cylinder diameter d may be either 0.45m if new turning rolls are specified or 1.52m if the existing cylinders are re-used in this location - note that this option would retain the flexibility to put some heat into the lower cylinders even though they are insulated from the paper sheet by the drying felt. Thus, given the vertical separation L equation 10 can be solved for θ . Then the contact arc and free draw can be determined from,

$$\text{cylinder wrap} = \frac{D}{2}(\pi + 2\theta), \text{ (top cylinder), and,} \quad (11)$$

$$\text{free draw} = \left(L - \frac{D+d}{2} \sin \theta \right) / \cos \theta. \quad (12)$$

With these relations for cylinder wrap and free draw as functions of L the computational model was set up to predict achievable machine speed under the new drying configuration for varying values of vertical separation between upper and lower rolls. The results are presented in **Figure 12** both for the case of $d=0.45\text{m}$ and $d=1.52\text{m}$ and show clearly that selecting the lower cylinder with the 1.52m diameter gives considerably more drying capacity than the smaller 0.45m diameter turning roll would. This is partly because of the increased overall dryer section run which leads to a longer residence time for mass transfer to occur, but primarily because the larger lower roll promotes a greater contact angle on the upper heated roll and this allows more heat to be transferred into the sheet.

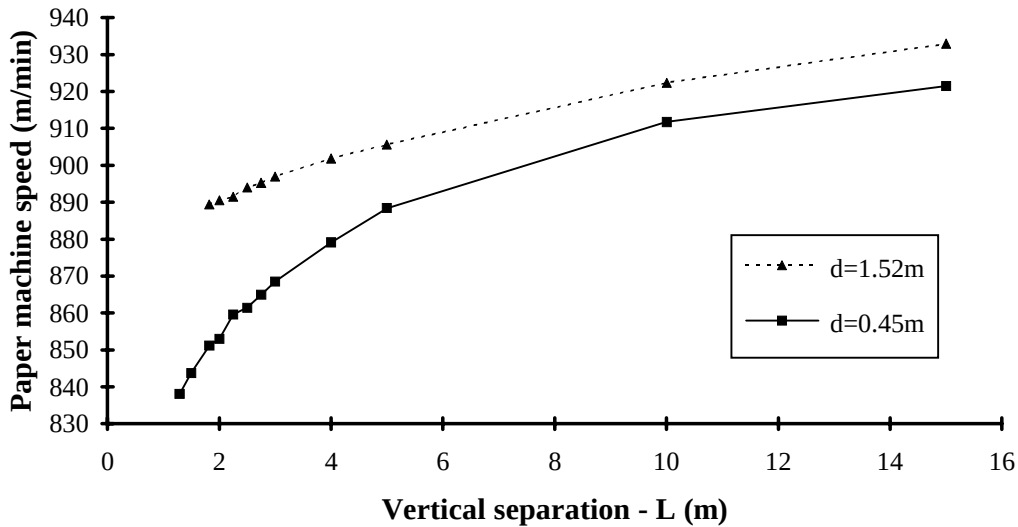


FIGURE 12
Paper machine production for a number of potential paper machine geometries

The selection of the optimal L is limited by physical considerations. This distance must be greater than the sum of the radii of upper and lower cylinders, 1.825m and 1.29m for the case of the large and small lower rolls respectively. The maximum distance is limited primarily by space considerations and the allowable increase in unsupported sheet length. It is unlikely that an L value beyond 3m would be considered. Comparing the results for $L=3\text{m}$ shows a machine speed of 897 m/min for the 1.52m lower cylinder case and 868 m/min 0.45m case. These values should be compared with the achievable speed

under the existing geometry which is 880 m/min. On this basis the new values represent a 2.2% increase and a 1.4% decrease in production rate respectively. The potential 2.2% improvement may not be considered sufficient to justify the rebuild unless other factors such as improved paper sheet runnability were taken into account. It should be emphasised that the preceding calculations have assumed constant drying conditions. The new dryer section geometries considered may allow more intense drying conditions to be employed beyond those currently used in which case these effects should be factored into a future calculation.

7. Conclusion

Earlier work (Reardon, 1995 and Reardon, Davis and Doe, 1996, 1997, 1997) has researched drying variables and developed a theoretical foundation for modelling the drying of paper on actual production machines. The model has been applied to two ANM paper machines and the calculations presented demonstrate the breadth of the model application.

In terms of predicting specific steam consumption of the paper machine a 91% correlation between observed machine drying performance and that predicted by the computational model was obtained. This was a comparison of the computed estimates and actual machine data moisture content monitored over a three year period. Subtle changes in the machine characteristics over such a long timeframe are invisible to the model and have led to the small distortions between the forecast and actual values. The model also predicts that 65% of moisture evaporation occurs in the free draw for ANM PM3.

A series of simulations were performed to demonstrate the effect of the paper sheet condition on drying, specifically initial moisture content, sheet thickness, sheet basis weight and initial temperature. The results showed that the sheet moisture content at entry to the dryer section is the most dominant parameter in setting achievable SSC targets. Temperature at inlet has minimal effect on drying efficiency due to the limited thermal storage capacity of the paper sheet. In general it was found to be more efficient, on a per kg of dry paper basis, to dry dense sheets than highly porous sheets due to the shorter dewatering paths encountered.

A second set of calculations was carried out to examine the effect of drying conditions, namely, cylinder temperatures, pocket air temperatures and pocket air humidity, on achievable machine speed and specific steam consumption. The results showed how lower cylinder temperatures, higher pocket ventilation temperatures and higher pocket absolute humidity will all lead to more efficient drying operation as measured by a decreased SSC. For a fixed absolute humidity level and unchanged cylinder temperature there is an optimum profile of pocket air temperatures throughout the dryer section which minimises SSC at a value of $1.34 \text{ kg}_{\text{steam}}/\text{kg}_{\text{paper}}$. Low absolute humidities and increased cylinder temperatures dramatically increase achievable machine speed, but at the significant expense of SSC.

Two scenarios were considered from a machine design perspective. The first simulation showed the optimal geometrical arrangement of the two rows of drying cylinders, whilst maintaining a constant total sheet length within the dryer section, to be an extension of each cylinder wrap by 10cm (and corresponding 10cm decrease in each free draw), which would lead to a 5 m/min speed increase under constant conditions. This is relatively small and suggests that ANM PM3 was well designed in this regard.

The second design simulation was that of PM2's potential conversion to an initial dryer sub-section with seven foot diameter cylinders, in a bid to improve heat transfer and hence drying rate and also improve runnability in this critical wet section. The simulation predicted that this would lead to a production

increase of almost 20 m/min, just over 2% which suggests the project would not be feasible on the basis of increased drying rate alone but would need to be co-justified by other factors.

The flexibility of the computational model is such that the effect on drying rates and specific energy consumption can be predicted in response to a change in any of the physical sheet properties, drying conditions or machine design. The model is therefore a valuable design support tool for the paper manufacturer in the areas of planning, operational control, trouble-shooting and benchmarking.

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Acknowledgement

This investigation has been made possible through the support and cooperation of Australian Newsprint Mills Limited, Boyer, Australia.

Received: November 11, 1997

Accepted: September 30, 1998

This paper was accepted for abstracting and publication in the September issue of *TAPPI JOURNAL*.