Modeling multicylinder paper drying-validation of a new simulation program

BJÖRN WILHELMSSON, STIG STENSTRÖM, LARS NILSSON, RIKARD KROOK, HÅKAN PERSSON, AND ROLAND WIMMERSTEDT

ABSTRACT

A mathematical model was developed for the drying of paper in a multicylinder drying section. The model is based on the unsteady state, one-dimensional heat conduction equation, which is applied to both the cylinder shell and the paper web. No internal mass transfer phenomena were modeled explicitly. Great emphasis was placed on finding the proper heat and mass transfer coefficients that are integral parts of the boundary conditions. Based on the mathematical model, a simulation program was developed. In order to verify the simulation output nine different industrial paper dryers were surveyed. These produced different paper grades: newsprint, fine paper, fluting, and paperboard. During a survey, temperatures and moisture contents of both paper and drying air as well as the temperature of the cylinder surface were measured. Seven of the nine cases involved steady-state production, whereas in the remaining two cases the basis weight and machine speed were altered considerably. The model applied just as well to lighter paper grades such as newsprint as to heavier grades such as paperboard. The data predicted by the program compared favorably with the measured data in all nine cases.

ONE OF THE LAST STAGES IN the papermaking process is the drying of the continuous paper web. The most common way to dry paper is to employ a multicylinder drying section, in which a combination of contact and convective drying is used. The web passes large rotating cast iron cylinders which are heated from the inside by condensing steam. Not only is the drying section a critical sector in the paper production, but it is also an energy user of gargantuan measures. It is estimated that about two-thirds of the total energy required in papermaking is used to dry the paper *(1)*. These two facts act as incentives to the present work.

Computer simulation of the drying section has proved itself to be a versatile and useful tool, e.g., for optimizing the production and for obtaining a better understanding of the complex interaction of the process parameters. A recent review of the literature on the modeling of paper drying *(2)* shows that at least 20 models exist, ranging widely in complexity, from simple ones that use many empirical correlations, to models of great intricacy and elaboration. It is notable that none of these models includes a detailed study of the influence of the dryer fabric on the drying process.

This article presents a new simulation model which is based partly on fundamental theory of heat and mass transfer and partly on empirical results. Emphasis is placed on tuning the model to the actual process and above all on comparisons of simulation output and measured paper mill data.

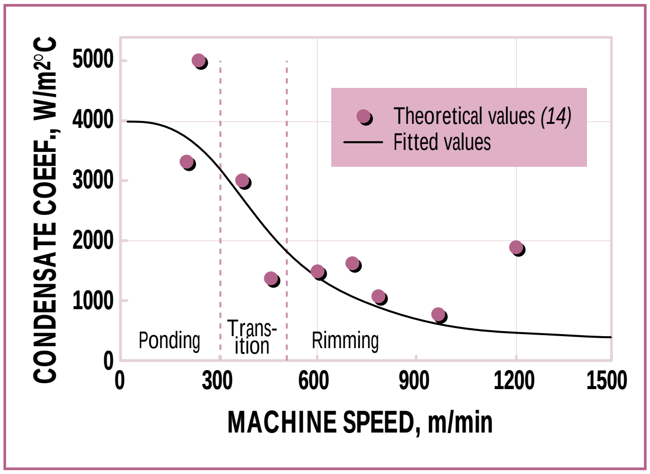
MATHEMATICAL MODEL

In this model all transport processes in the paper web are represented by a lumped parameter, viz., the apparent thermal conductivity, which accounts for both conduction and evaporation/condensation phenomena within the web. The lumped parameter approach has been found to yield very good results, while at the same time reducing the computational time significantly as compared with a case where coupled mass and heat transfer equations have to be solved simultaneously. Since no internal mass transfer phenomena are considered in the model, evaporation takes place only at the surface(s) of the paper web.

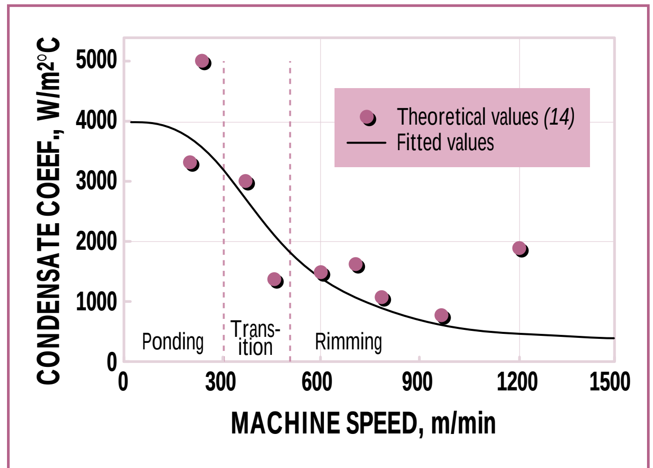
The mathematical basis of the model is the equation for unsteady state heat conduction, Eq. 1. It is applied to both the cylinder shell and the paper web with appropriate boundary conditions. The heat transfer is considered to be one-dimensional and perpendicular to the paper web (in the *z*-direction). The equation is solved subject to six boundary conditions. A full description of the model is found in *(3)*, the following is a rather condensed version:

$$\partial T/\partial t = (k/\rho c_p)\, \partial^2 T/\partial z^2 \quad (1)$$

The boundary condition at the paper-air interface is given by Eq. 2, which states that heat used for evaporation of water is either conducted to the surface or convected from the ambient air. A corrected convective heat transfer coefficient, h_{pa}^*, is employed since drying involves simultaneous heat and mass transfer



1. The fitted condensate coefficients versus machine speed. The theoretical values have been calculated for a 2-mm thick laminar film according to Appel and Hong (14). The approximate transition region between ponding and rimming for 1.5-m diameter cylinder is indicated.



2. The fitted contact coefficient intercepts versus basis weight

	Machine A	Machine B	Machine C	Machine D	Machine E
Paper grade	Fine paper	Fluting	Paperboard	Newsprint	Fine paper
Basis weight (moisture free), g/m²	77	133	213	See Table II	See Table III
Machine speed, m/min	708	600	454	See Table II	See Table III
Number of cylinders	37	59	84	36	20
Single-tier configuration	1-6	1-10	—-	1-36	1-8
Condensate coefficient, W/m²°C	1650	1500	1400	1900	3300
Contact coeff., intercept, W/m²°C	500	300	400	500	1400

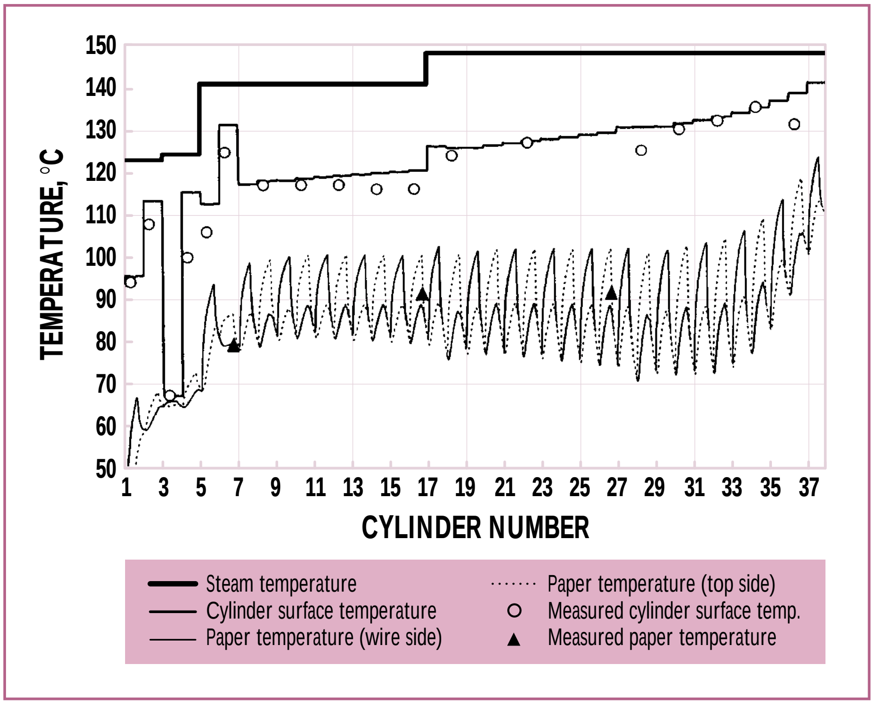
I. Some key data for the five drying sections.

(4). Standard Nusselt correlations for parallel flow past a flat plate *(4)* was used to obtain the uncorrected coefficient, h_{pa}. The mass rate of flow, $\dot{m}_{pa}$, is calculated using the Stefan Eq. 3. The equation contains the parameter $K_{G,pa}$, which is the coefficient for mass transfer from the paper surface to the ambient air. It is obtained from the corresponding heat transfer coefficient, h_{pa}, by the Chilton-Colburn analogy *(5)* between heat and mass transfer. Above the critical moisture content the partial vapor pressure at the paper surface, P_p, is a function of temperature only. Below this limit the pressure is given by a desorption isotherm *(6)*:

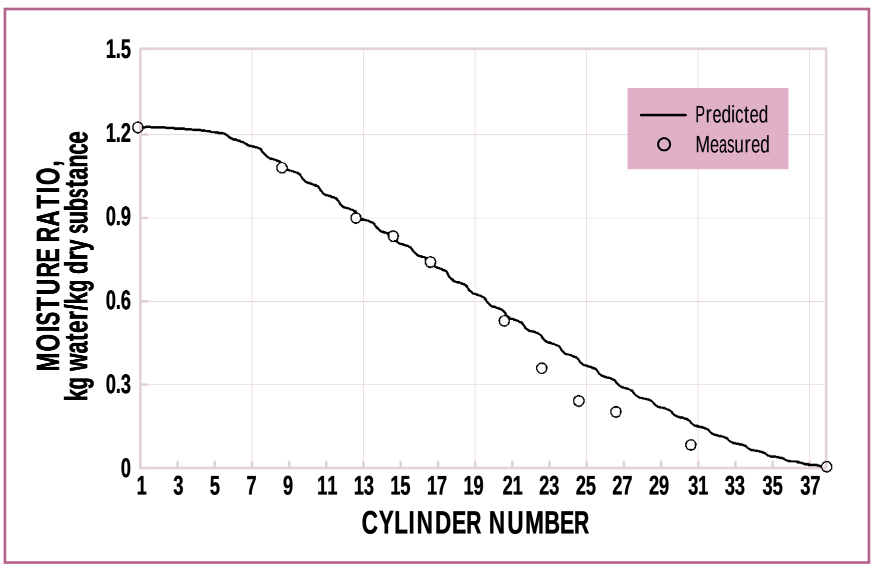
[SEE PAGE 167 FOR EQ. 2]

$$\dot{m}_{pa}/A = [K_{G,pa} M_w P_{tot}/RT] \ln [(P_{tot} - p_a)/(P_{tot} - p_p)] \; (T \text{ in Kelvin}) \qquad (3)$$

Experimental studies *(7)* have shown that the fabric reduces the size of the mass transfer coefficient by 30–50%. The model takes this into account by introducing a new parameter, called the fabric reduction factor, *FRF*. The reduced mass transfer coefficient, $K_{G,pfa}$, is obtained from



3. Comparison between predicted and measured temperatures for Machine A



4. Comparison between predicted and measured sheet moisture content for Machine A

Eq. 4. It is then inserted in Eq. 3 to yield the reduced mass rate of flow, $\dot{m}_{pfa}$. Computations, based on the experimental results in *(7)*, indicate that the corrected heat transfer coefficient, h_{pfa}^*, is approximately unaffected by the fabric, Eq. 5. The final expression for the boundary condition at the paper surface when it is covered by a dryer fabric is given by Eq. 6:

$$K_{G,pfa} = K_{G,pa}\,(100 - FRF) \quad (4)$$

$$h_{pfa}^* = h_{pa}^* \quad (5)$$

[SEE PAGE 167 FOR EQ. 6]

The boundary condition at the cylinder-paper interface is governed by Eq. 7, where h_{cp} is generally referred to as the contact heat transfer coefficient. Equation 8 reflects the moisture dependence of the contact coefficient. The intercept, $h_{cp}(0)$ at $u = 0$, should be in the interval 200–500 W/m²°C. The intercept of the contact coefficient is the first of two fitting parameters used to tune the model. The subject is further elaborated in the section entitled "Tuning of the model."

[SEE PAGE 167 FOR EQ. 7]

$$h_{cp}(u) = h_{cp}(0) + 955u \quad (8)$$

At the cylinder-air interface, the boundary condition is given in Eq. 9. Only convective heat transfer is considered, radiation effects having been neglected. The heat transfer coefficient is obtained from Nusselt correlations for parallel flow past a flat plate *(4)*.

[SEE PAGE 167 FOR EQ. 9]

The fifth boundary condition, Eq. 10, is applicable when the fabric is sandwiched between the cylinder and the paper in a single-tier configuration. A value of 300 W/m²°C was found to provide good agreement between the predicted and the measured cylinder surface temperatures on several different paper machines.

[SEE PAGE 167 FOR EQ. 10]

The heat transfer from the steam through the condensate layer to the inner surface of the cylinder is governed by Eq. 11, which constitutes the sixth boundary condition. The heat transfer coefficient h_{sc}, commonly known as the condensate coefficient, is the second fitting parameter of the model. It is further elaborated in the section entitled "Tuning of the model."

[SEE PAGE 167 FOR EQ. 11]

The apparent thermal conductivity of the paper represents all heat transfer processes in the paper web. The model employs Eq. 12 which was reported in *(8)*. k_{dry} is the value at u = 0; it has been assigned a value of 0.08 W/m°C in all simulations.

$$k_p(u) = (k_{dry} + u \times k_w) / (1 + u) \quad (12)$$

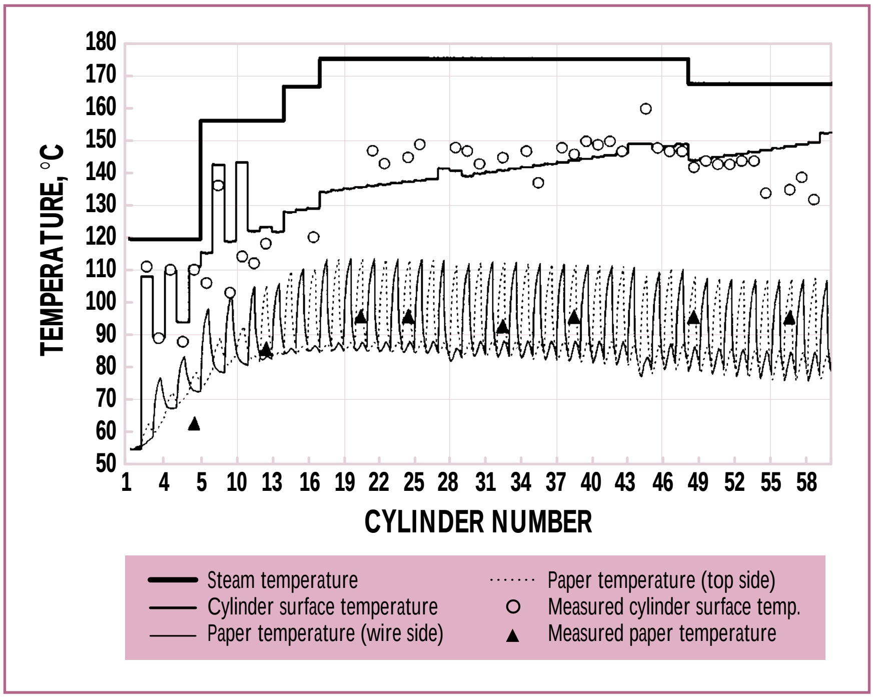
In order to take the shrinkage in the *z*-direction of the paper into account, the expression for the paper thickness in Eq. 13 is a function of the moisture content. This equation was reported to yield reasonable agreement with experimental observations *(8, 9)*:

$$d_p(u) = G_{dry}[(1/\rho_{dry}) + (u/\rho_w)] \quad (13)$$

SIMULATION PROGRAM

The partial differential Eq. 1 is solved numerically by an implicit finite difference method. Since only one-dimensional heat conduction is considered, both the continuous paper web and the cylinder shell can be split up into small elements. By following the step-by-step progression of such a small element in the machine direction, it is possible to simulate the entire dryer section of the paper machine. During this procedure, it is necessary to keep track of the position of the element so that the appropriate boundary conditions can be applied.

The simulation program runs under MS Windows and was developed using the Borland Pascal compiler. Full use has been made of the graphical interface supported by Windows. The user has a large degree of freedom to vary parameters such as the machine geometry and the operating conditions. The program offers options, e.g., pocket ventilation, single-tier configuration, and vacuum rolls. The simulation output is contained in three plot files and one report file. The plot files are intended to be imported into a spreadsheet program such as MS Excel or similar. The execution time for a 40-cylinder machine is around 5 min using an IBM compatible 486 66 MHz computer.

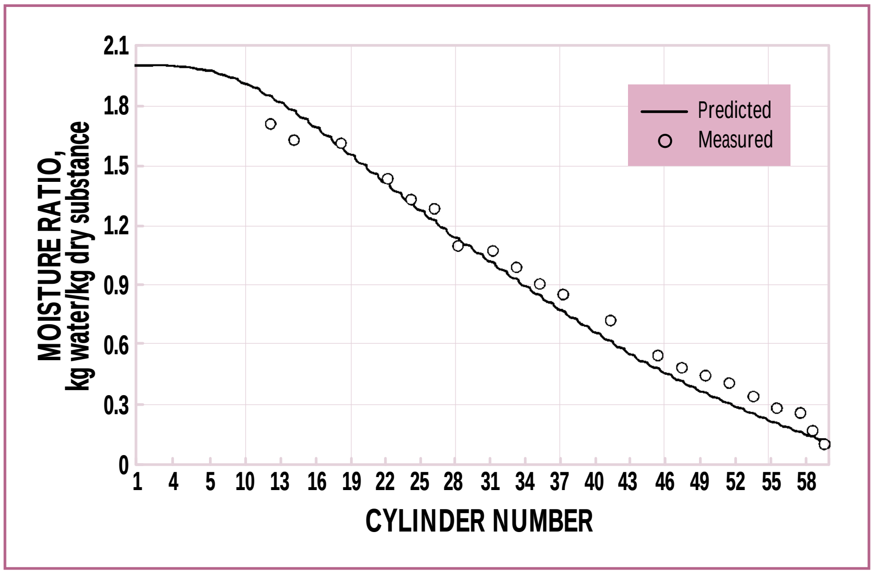


5. Comparison between predicted and measured temperatures for Machine B

EXPERIMENTAL

In order to establish the reliability of the output of the simulation program, comparisons must be made between calculated data and data actually measured in industrial paper dryers. Thus far, nine drying section surveys have been performed. These have concerned paper machines of a wide variety of characteristics. The data are compiled in *(10)*, along with detailed accounts of both the measuring instruments and the results, together with comments. An English version, dealing with only three of the machines, is presented in *(11)*. It was decided that the surveys should be limited to the paper web and its immediate surroundings. Thus, the heat recovery system and the intricacies of the steam and condensate system were not included. It was also decided that parameters concerning paper quality, such as degree of beating and filler content, should not be included either. In each of the surveys, the following variables were measured:

- Paper web moisture content
- Paper web surface temperature
- Moisture content of the air in the pockets or in the exhaust air



6. Comparison between predicted and measured sheet moisture content for Machine B

- Dry air temperature in the pockets or in the exhaust air
- Cylinder surface temperature.

Additional information such as machine speed, steam pressures, basis weight, etc., were usually taken from the process computers at the mills. In the following, brief descriptions of the measuring instruments that were employed are presented. They are presented in greater detail in *(10)*.

The moisture content of the paper web was measured with a NDC 100 T instrument from NDC Systems, USA. It is a portable back scatter instrument with a radioactive source (low-level gamma-rays), which measures the total basis weight of the web. An IR-instrument, type M400-A from Linear Laboratories, was used for measuring the paper surface temperature. It measures IR-radiation in the 8–14 µm spectral range, in which the emissivity of paper is independent of moisture content *(12)*. A dew point meter, type DP3-D-B/C from MBW Electronics, was employed for the measurements of the air humidity in the pockets. Air was extracted from inside the hood—through an electrically heated hose so as to avoid condensation—to the instrument, that was placed outside the hood. The dry temperature of the air was measured by a Pt-100 resistance thermometer, type I-400 from Rotronic AG.

The instruments were all fastened to the end of a 2.4-m long galvanized iron tube that was attached at variable height and angle to a small cart. The cart was placed inside the hood and the hood doors were closed. Each measurement was allowed to progress until stable values were attained for all the instruments.

The cylinder surface temperature meter employs a thin Pt-100 Kapton foil, attached to the back of a Teflon™ tape by an adhesive Kapton tape, as sensor. The Teflon tape was mounted on a spring blade in such a way that the tape, and thus the sensor, readily followed the curvature of the cylinder surface. The meter was attached to the end of a long wooden stick which could easily be held by hand. Phenomena such as frictional heat and convective losses are treated in *(13)*.

TUNING OF THE MODEL

Once the experimental data are obtained for the paper machine of interest, the simulation program has to be tuned to this particular machine. The model utilizes two of its heat transfer coefficients as fitting parameters. The two parameters are:

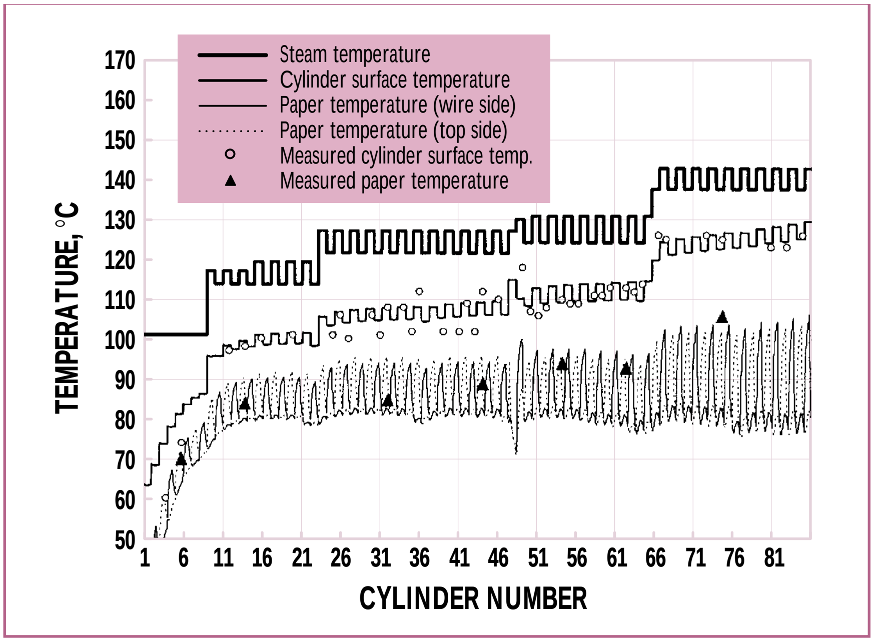
- The condensate coefficent, h_{sc}.
- The contact coefficient at zero moisture content, $h_{cp}(0)$.

The two parameters are varied until a best fit between predicted and actual paper moisture contents and cylinder surface temperatures is attained. Particularly the temperature of the cylinder surface has been found to be a very good indicator of the fit. A necessary prerequisite when fitting is that the predicted initial and final moisture contents of the paper web agree with the experimentally measured values.

Condensate coefficient

In the nine cases used for validation of the model, the condensate coefficient has been assigned values of 800–5000 W/m^2°C. Figure 1 shows the relation between the fitted condensate coefficients and machine speed. The general trend agrees fairly well with the experimental results presented in *(14–16)*. In those studies, it was found that several parameters affect the numerical value of the coefficient. As a general rule, the higher the speed of the machine, the lower the value.

The presence of spoiler bars promotes heat transfer and yields relatively high values, also for fast machines. For instance, the high value of 1900 W/m^2°C at 1200 m/min was obtained for a modern newsprint machine that has cylinders of large diameter, 1.83 m, and a state-of-the-art condensate removal system.



7. Comparison between predicted and measured temperatures for machine C

The two slowest machines are in the region in which the condensate rests in a puddle at the bottom of the cylinder and the steam condenses directly on the inner cylinder wall. This condition is characterized by very high heat transfer rates. It is called ponding, as opposed to the more common rimming condition in which a continuous film is formed inside the cylinder. The ponding, rimming and transition regions for a 1.5 m diameter cylinder are indicated in Fig. 1.

It is interesting to note that the fitted values follow a theoretical expression *(14)* for a 2-mm thick laminar film rather well. However, it must be pointed out that neither the theoretical expression nor the graph can be used for predicting exact values of the coefficient.

Contact coefficient at zero moisture content

As shown in Fig. 2, all fitted values of the contact coefficient intercept, except for two, fall between 200 and 500 W/m^2°C, which agrees fairly well with the experimentally determined interval *(17)*. The exceptions are very slow machines: 228 and 189 m/min, respectively. It is assumed that the Nusselt correlation underpredicts the convective mass transfer coefficient at low velocities. Experimental evidence for this assumption was reported by Rhodius and Göttsching *(8)*. They found that the use of the Nusselt correlation yielded too low values at velocities below about 300 m/min. In the present work, this is compensated for by increasing the contact coefficient intercept and thus the rate of heat transfer to the paper, thereby increasing the evaporation temperature and the partial vapor pressure. The relatively narrow range that the majority of the contact coefficient intercept falls within, is taken as evidence of the general applicability of Eq. 8.

SIMULATION RESULTS

Five of the nine validation cases were chosen so as to illustrate the ability of the program to simulate different paper grades within a large interval of basis weights. Certain key data are compiled in Table I. Due to the sheer amount of information, the machine geometry, the operating conditions as well as the data measured at the respective mills have not been included in the table. Complete sets of information are provided in *(10)*. At the end of the table are the fitted values of the two heat transfer coefficients used in the tuning procedure.

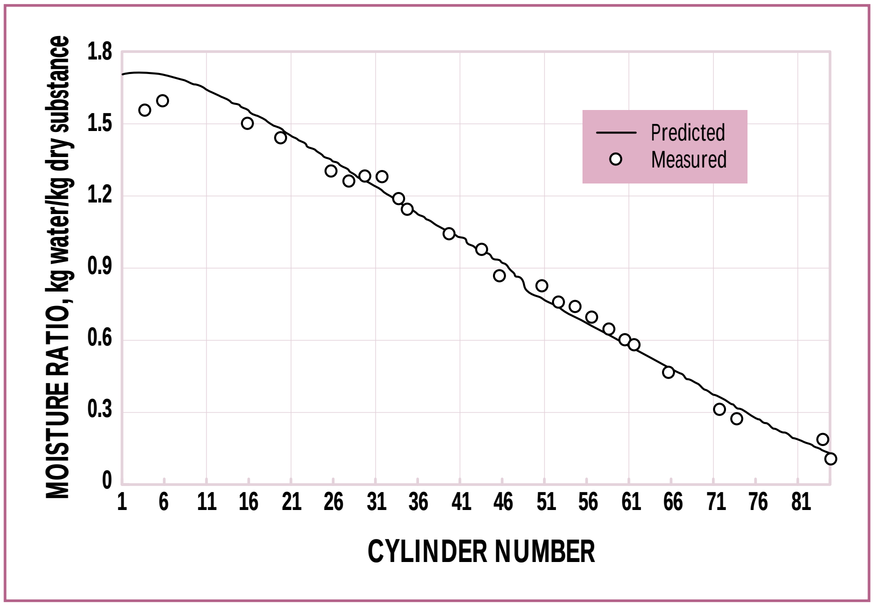
Machine A

Single-tier configuration was used on the first six cylinders of Machine A. The three cylinders for which the fabric ran between the cylinder and the web were Nos. 2, 4, and 6. As can be seen in Fig. 3, the cylinder surface temperature was overpredicted by 5–6°C for cylinders 2 and 6, whereas for cylinder 4 it was underpredicted by 15°C. Cylinder 3 was not heated at the time of the survey. The measured and the predicted increase in temperature follow each other closely in general, except for cylinders 28 and 36, for which the deviation was around 7°C.

The moisture content graph in Fig. 4 likewise shows a close correlation between the calculated and the actual values. It is possible that the slope during the constant rate period should be somewhat more steep so as to yield better agreement with the values for cylinders 22–30. Due to the fact that Machine A was a predryer followed by an in-line size press, the paper web was overdried to a final moisture content of only 0.012 kg water/kg dry substance.

Machine B

Machine B too employed the single-tier concept. The cylinder-fabric-paper combination applied to cylinders 2, 4, 6, 8, and 10. For the first four of these the agreement is excellent, as shown in Fig. 5; for cylinder 10 the deviation is 29°C. Beyond cylinder 20 the measured cylinder temperature varies between 140 and 150°C, but without increasing. The



8. Comparison between predicted and measured sheet moisture content for machine C

predicted temperatures are in the same region but increase slightly toward the dry end. The last four measured temperatures are approximately 10°C lower than the previous ones; here the agreement with the program is poor. A possible explanation for this is that the condensate removal systems of these last cylinders were working poorly, as was that of cylinder 10. The actual paper temperatures, which were taken approximately in the middle of the free draw, lie close to the half-amplitude of the calculated paper temperatures, indicating good agreement.

The agreement between the measured and the predicted moisture content data is good, as shown in Fig. 6. However, there are some peculiarities. For instance, comparing the measured values for cylinders 57, 58, and 59 reveals an unreasonably fast drying rate. Due to the construction of the machine, no values could be taken prior to cylinder 12.

Machine C

No single-tier configuration was employed in Machine C. The predicted cylinder surface temperature curve as shown in Fig. 7 has a jagged form. This is due to the top and bottom dryer cylinders being fed with different steam pressures, a strategy employed to prevent curl. The program predicted a difference of around 4°C, whereas the measured values indicated differences of 7–8°C. Apart from this, the agreement is excellent. According to the measured paper temperatures, the simulated values are a bit too low in the last third of the drying section.

The agreement in Fig. 8 must be regarded as more than acceptable, although some uncertainty exists regarding the moisture content on the first 10 cylinders. The discontinuity in the curve is explained by a 5.00-m diameter Yankee cylinder that was placed after cylinder 47.

Machine D

For Machines A, B and C it was shown that the computer program can adequately simulate the drying process for different paper grades at steady state. For Machines D and E, the focus is on more practical applications. The program being used to predict the final moisture content for changes in the production rate is an issue of principal practical interest.

The first study of a production change was performed on a modern high-speed newsprint machine. The machine is equipped with 36 cylinders, divided into 4 steam groups, and 36 vacuum rolls. The vacuum rolls were treated as extended free draws, i.e., the sequence short free draw, roll, short free draw was replaced by a single, long free draw. Single-tier configuration is employed throughout the drying section.

Changes of the basis weight and the machine speed were made according to Table II. Small changes were also made in the steam pressures and in that three more cylinders were heated under the new set of conditions. According to mill personnel, it is reasonable to assume that all other parameters remain unchanged. Using data measured at the reference operating conditions, the tuning procedure yielded the values listed in Table I. The high value of 1900 W/m^2°C for the condensate coefficient is reasonable because the machine is equipped with spoiler bars.

Simulations were performed using the new basis weight and machine speed and the fitted values of the heat transfer coefficients. Mill measurements of the final moisture content under the new set of conditions yielded a value of 0.080 kg/kg (dry basis). The program predicts 0.077 kg/kg (dry basis). To sum up, for an increased machine speed (+ 17%) and production rate (+ 8%), the program predicts the final moisture content of the sheet within 0.3% (dry basis).

Machine E

The second study of a production change involves a small machine, producing mainly fine paper of various basis weights. It consists of a predryer, a size press, and an after dryer—with only the former being studied. The 20 cylinders in the predryer constitute nine different steam groups.

Changes in the input parameters are listed in Table III. All other parameters are assumed to remain unchanged. Under the reference conditions, the steam system was operating at close to maximum capacity, which is why no changes were made in the steam pressures. In a manner similar to that employed for Machine D, the fitting parameters were determined at the reference conditions. Due to the modest machine speed, it is reasonable to assume ponding conditions in the cylinders. Thus, a value of 3300 W/m^2°C for the condensate coefficient is realistic.

Simulations were performed using the new basis weight and machine speed and the values fitted at the reference conditions. The normal value of the final moisture content of the sheet under the new set of conditions is 0.015 kg/kg (dry basis). The results of the simulation predict it to be 0.013 kg/kg (dry basis). Thus, for an increased speed (+117%) and production rate (+ 24%) the prediction of the moisture content deviates by 0.2% (dry basis).

	Reference conditions	New conditions
Basis weight, g/m^2	48.8	45.0
Machine speed, m/min	1200	1400

II. Changes in certain input data between the reference and the new set of operating conditions for Machine D

	Reference conditions	New conditions
Basis weight, g/m^2	132.0	75.6
Machine speed, m/min	189	410

III. Changes in certain input data between the reference and the new set of operating conditions for Machine E

DISCUSSION

Figure 9 shows a comparison of the TAPPI evaporation rates *(18)* as calculated for the three machines A, B, and C, respectively. It appears that the constant drying rate period applies to a larger proportion of the drying section in the case of Machine C than in the other two cases. This phenomenon is, at least partly, caused by differences in the strategies employed for increasing the steam pressure (temperature), as indicated in Figs. 3, 5, and 7. Not counting the first cylinders, which are used primarily for heating the paper to the evaporation temperature, the steam temperature in Machine C is raised from 115°C to 140°C in four steps, whereas in Machine A it is raised only once, from 142°C to 148°C. In Machine B it is raised from 157°C to 175°C in two steps and is in fact lowered then to 168°C at the end. Machine C is a good example of how, by changing the operating conditions, one can maintain a constant drying rate over a longer period of time.

Regarding the applicability of the model, it appears that the mathematical model applies equally well to light and to heavy paper grades. However, many studies compiled in *(2)* found that the heat and mass transfer resistance of the paper structure can be quite severe for thicker grades. Can both of these two findings be valid and, if so, how are they interconnected?

An analysis, similar to that in *(19)*, of the heat and mass transfer resistances involved indicates that the drying process as a whole is mainly heat transfer controlled. Simulations showed that the following two computational measures had the same effect on the production rate:

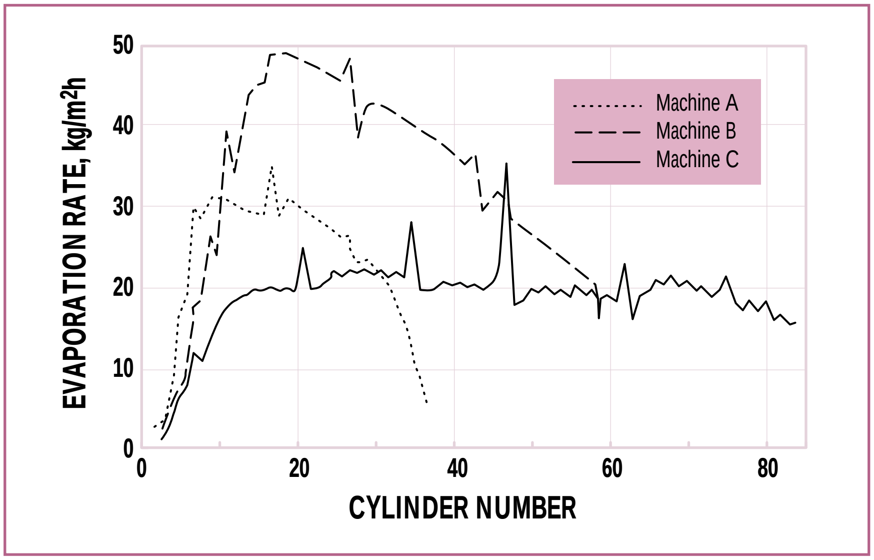
1. The contact coefficient intercept for machine A was changed from 500 to 400 W/m^2°C. This reduction in $h_{cp}(0)$ yielded only a 5% decrease in the overall heat transfer coefficient from steam to paper.
2. The external mass transfer coefficient has been varied according to Eq. 14 to reflect the internal mass transfer resistance. K_G was linearly reduced from its full value at moisture contents above 1.0 kg/kg, to 50% of its full value at zero moisture content.

$$K'_G = K_G[(1 + u)/2] \quad u < 1.0 \text{ kg/kg} \qquad (14)$$

The importance of the heat transfer resistance can also be illustrated by the following analysis. Define an effective heat transfer coefficient of the paper as:

$$h_{p,eff}(u) = k_p(u)/d_p(u) \qquad (15)$$

where the thermal conductivity is given by Eq. 12 and the thickness by Eq. 13. For a given moisture content, the insertion of effective thermal conductivity and thickness into Eq.



9. Calculated TAPPI drying rates (18) for machine A, B, C, respectively

15 indicates the internal resistance to heat transfer to be exactly three times greater for the paperboard in Machine C than for the fine paper in Machine A.

The results inferred from the reasoning above suggest the overall heat transfer rate, i. e., not only in the paper itself, to be the main limiting factor in the drying process. Furthermore, as indicated by Eq. 15, the model reflects the basis weight dependence in a logical way.

Listed below are some suggestions for future improvements and developments of the model and the simulation program.

- The internal mass transfer should be incorporated into the mathematical model. As the qualitative reasoning above shows, there is certainly a need for a more detailed understanding of the internal transfer processes. Although the agreement with measured data is good using the model in its present state, a submodel of the internal mass transfer is very valuable *(20, 21)*. With the inclusion of such a submodel, phenomena such as shrinkage and curl, caused by moisture gradients in the paper, can be accurately pedicted.
- A flowsheeting program for the steam and condensate system has been developed by Wilhelmsson. At present, only steady state calculations can be performed. This program should be extended to perform also unsteady state calculations so that the dynamic aspects of the drying section operation can be studied. Furthermore, pressure drop calculations for the tubes and siphons should be incorporated.
- Modeling of gas-fired and electrical infrared radiators—common components in the drying section—should be included in the model. They are employed primarily for drying of coated paper and for moisture profile correction, but occasionally also for increasing the drying capacity *(22)*.
- During the last decade, there has been a growing interest in so-called high intensity pressing and drying. At present, two persons in the paper drying group at our department are involved in modeling these processes *(23, 24)*. A future vision is to incorporate these models into the simulation program so that the effects on the conventional drying section can be studied.
- Impingement techniques such as the radial jet reattachment (RJR) nozzle blow *(25)* box and the impingement hood *(26)* should be incorporated into the program.

CONCLUSIONS

A mathematical model was developed for the drying of paper in a multicylinder drying section. The model is based on the unsteady state, one-dimensional heat conduction equation, which is applied to both the cylinder shell and the paper web. No internal mass transfer phenomena were modeled explicitly. A lumped parameter, the effective thermal conductivity of the paper, implicitly takes these phenomena into account to some extent.

Surveys of full-scale drying sections were performed, in which temperatures and moisture contents of both air and paper were measured. A new instrument for measuring the temperature of the cylinder surface was developed. The moisture content of the paper web was measured on-line with a new backscatter basis weight meter which employs a radioactive source.

The output from the simulation program has been favorably compared with measured data from nine different industrial paper dryers. Two parameters, the condensate coefficient and the contact coefficient at zero moisture content, are used to tune the output from the program to the measured values. Both parameters were assigned

KEYWORDS

Basis weight, bibliographies, coefficients, cylinder drying machines, dryer sections (drier sections), dryers (driers), heat transfer, machine speed, mass transfer, mathematical models, measurement, moisture content, paper grades, simulation, surveys, temperature.

physically reasonable values, confined in a rather narrow range. The model applies equally well to lighter paper grades, such as newsprint, as to heavier grades, such as paperboard. Two case studies, in which the basis weight and machine speed were altered considerably, showed the predicted and the measured data to be in excellent agreement. The presented examples indicate the potential for simulation of the multi-cylinder drying section. TJ

Wilhelmsson is application engineer with Alfa Laval Thermal AB, P.O. Box 74, 221 00 Lund, Sweden. Stenström is assistant professor, Nilsson, Krook, and Persson are graduate students and Wimmerstedt is professor, Dept. of Chemical Engineering I, Lund University, P.O. Box 124, S-221 00 Lund, Sweden.

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NOMENCLATURE

A	= area, m^2
c_p	= specific heat, J/kg°C
d	= thickness, m
FRF	= fabric reduction factor, %
h	= heat transfer coefficient, $W/m^2°C$
K_G	= mass transfer coefficient, m/s
K'_G	= reduced mass transfer coefficient, Eq. (14), m/s
k	= thermal conductivity, W/m°C
M	= molecular weight, kg/mol
m	= mass, kg
$\dot{m}$	= mass rate of flow/evaporation rate, kg/s
P	= pressure, Pa
p	= partial pressure of water vapor, Pa
R	= gas constant (= 8.314), J/mol K
T	= temperature, °C
t	= time, s
u	= moisture ratio, kg H_2O/kg dry substance
z	= space coordinate, m
l	= heat of vaporization, J/kg
r	= density, kg/m^3

EQUATIONS

$$\frac{\dot{m}_{pa}\left(T_p\right)\lambda}{A} = -k_p\left(u\right)\frac{\partial T}{\partial z}\bigg|_{z_p = d_p} + h_{pa}^{*}\left(T_a - T_{p,d_p}\right) \tag{2}$$

$$\frac{\dot{m}_{pfa}\left(T_p\right)\lambda}{A} = -k_p\left(u\right)\frac{\partial T}{\partial z}\bigg|_{z_p = d_p} + h_{pfa}^{*}\left(T_a - T_{p,d_p}\right) \tag{6}$$

$$-k_c\frac{\partial T}{\partial z}\bigg|_{z_c = d_c} = h_{cp}\left(u\right)\left(T_{c,d_c} - T_{p,0}\right) = -k_p\left(u\right)\frac{\partial T}{\partial z}\bigg|_{z_p = 0} \tag{7}$$

$$-k_c\frac{\partial T}{\partial z}\bigg|_{z_c = d_c} = h_{ca}\left(T_{c,d_c} - T_a\right) \tag{9}$$

$$-k_c\frac{\partial T}{\partial z}\bigg|_{z_c = d_c} = h_{cfp}\left(T_{c,d_c} - T_{p,0}\right) = -k_p\left(u\right)\frac{\partial T}{\partial z}\bigg|_{z_p = 0} \tag{10}$$

$$-k_c\frac{\partial T}{\partial z}\bigg|_{z_c = 0} = h_{sc}\left(T_s - T_{c,0}\right) \tag{11}$$