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A HYBRID DRYING PROCESS: CYLINDER DRYING WITH THROUGH AIR AFTER-DRYING

S.J. Hashemi[1] and W.J. Murray Douglas[2]

[1]Department of Chemical Engineering, University of Tehran, Tehran
[2]Department of Chemical Engineering, Pulp & Paper Research Centre, McGill University, Montreal

BACKGROUND

Cylinder drying and air drying of paper

High paper machine capital costs provide a permanent incentive for increased productivity. Pikulik et al. [1] discussed the evolution of machine speed for printing grades to about 2000m/min. Karlsson [2] considered potential developments for the all too common bottleneck of cylinder drying. Extensive studies at McGill examined the possible integration of impingement air drying with cylinder drying, providing one source concerning multiple technique drying, Bond et al. [3], in hybrid dryer sections, Hashemi and Douglas [4, 5]. Hybrid drying for printing paper recently became an industrial reality with a dryer section consisting of alternating cylinder and high intensity impingement air drying at the Nordland Papier mill in Germany, Sundqvist and Anderson [6]. Thus, although impingement air drying was long considered applicable only to tissue and toweling in Yankee dryers, machine builders now propose the integration of these two techniques to produce hybrid dryer sections for heavier grades.

The other basic type of air drying, i.e. through air drying, is distinguished by the manner of air – sheet contacting. In through drying the moisture removal is obtained by drawing hot unsaturated air or combustion gas through the permeable web. For the heat and mass transfer of drying, this intimate contact between the drying medium and wet fibres decreases the distance for transport from the thickness of the sheet for cylinder or impingement air drying, in the order of 100 microns, to the dimension of pore size and fibre thickness for through air drying, 10 microns and less. Further, through air drying increases the area for these transport processes from sheet external surface area to the entire internal surface area within the sheet. Having these advantageous characteristics for heat and mass transfer and with the drying medium at 150–400°C, exceptionally high through drying rates are obtained, to around 300kg/m^{2}h, an order of magnitude greater than about 20kg/m^{2}h for cylinder drying. Through air drying also provides the ability for good cross-machine (CD) control for elimination of moisture streaks. Through air drying has long been practiced industrially for production of the highly permeable grades, tissue and toweling.

Processes involving air through flow

Early work with air flow through wet sheets involved the use of conditions giving either mechanical dewatering alone or mixed with some through drying. In a 1966 patent, Holden [7] proposed several devices for blowing air through a wet web to remove water. This concept was extended in a number of studies by Kawka and associates [8–14]. Building upon the work of Holden, Kawka invented other techniques for passing air through a sheet at lower pressure than by Holden. Kraft paper produced as sack paper along with newsprint were two grades tested. For example, with 70g/m^2 sack paper of initial solids content 31% (initial moisture content of X_o=2.2kg water/kg dry), Kawka and Ingielewicz [8] reported obtaining solids contents up to 43% (X_f=1.32kg/kg) with 0.6s exposure time to unheated air passing through the sheet at air velocity below 5m/s. When using air preheated to 70°C, Kawka and Szwarcztajn [12] obtained solids contents to 60% (final moisture content of X_f=0.67kg/kg). In the above approach water is removed from a compressed sheet using a through flow of air at high pressure, up to 200kPa. Thus water removal is obtained mostly by displacement dewatering accompanied by a limited amount of drying. For this reason these studies provide little guidance concerning the pure drying process of through air drying, which operates at significantly lower air pressure and velocity through the moist sheet.

Burgess et al. [15, 16] provided results from both a pilot plant and a mill trial of a technique called the “Papridryer” which involves simultaneous use of impingement and through air drying. Two series of tests were performed with newsprint and corrugated paper to determine the influence of operating variables on the drying rate. This testing of the use of simultaneous impingement and through air drying did not lead to a commercially viable process. Moreover these findings do not provide insight concerning the performance of the pure through air drying processes, the focus of the present study.

Constraints on use of through air drying

Two key impediments which have prevented the use of through air drying for printing and heavier grades are the high capital and operating cost of the fan or blower to achieve the flow of drying air through the wet sheet, and the tendency of through air drying to give locally nonuniform drying which may decrease product quality for printing. As only the first of these obstacles is well known, the aspect of drying nonuniformity is highlighted here. For through air drying, the characteristic of local nonuniformity of drying has been explored by the authors [17, 18]. In through air drying, the local drying nonuniformity derives from local nonuniformity in the through flow rate, which in turn derives from the local nonuniformity in sheet structure. Thus the quality of the formation of the paper being dried is fundamental to through drying nonuniformity. For this reason these studies were carried out using a machine-formed papers. Although the quality of sheet formation is the basic determining factor, the extent of through drying local nonuniformity is affected by the severity of drying process parameters. Thus this work investigated the effects on drying local nonuniformity which derive from both through drying process parameters and paper structure parameters, as well as from the interaction of these two sources. With this objective two experimental approaches were used, the measurement of either local sheet moisture content or local pore exit air temperature. Such experiments established that an important consequence of increased local drying nonuniformity is to advance the start of the falling rate drying period. This is a deleterious effect because an earlier onset of the falling rate period reduces the sheet average drying rate and thereby increases drying time or dryer size. A strong and sensitive relation was established between drying nonuniformity and critical moisture content, the latter defining the onset of the falling rate period. These investigations also defined the effect of initial moisture content on the index of drying nonuniformity, with this effect being very strong in the moisture content range above the fibre saturation point, but becoming negligible when lower initial moisture contents were used. As a general conclusion, these investigations established that if through drying is be used effectively in drying grades of paper heavier than its present use for tissue and toweling, a central constraint is local drying nonuniformity.

These explorations [17, 18] established that for any possibility of some use of through air drying for heavier papers, attention should be focussed on the use of lower drying intensity conditions and starting through drying at a low moisture content. In order to avoid both the low permeability caused by free water in the pores and the excessive local drying nonuniformity which reduces drying rate by increasing the critical moisture content, through drying should not be started at initial moisture contents sufficiently high that there is water in the inter-fibre pores. For through air drying a sheet of specific grammage and quality of formation, there is an interrelationship between initial moisture content, drying intensity and drying nonuniformity. The latter is likely to be constrained by product quality considerations. In this case there remains an interplay between initial moisture content and drying intensity, i.e. the higher one of these variables is, the lower must be the other variable in compensation. The present investigation was therefore designed to address the other disadvantage, the high cost of providing the flow of drying air through moist sheets heavier than tissue and toweling, to extend the drying rate – drying nonuniformity relations, and to integrate these pressure drop and drying rate factors which control the application of through air drying to heavier papers.

Drying of kraft paper

Two drying configurations are currently used in kraft paper manufacturing. Most kraft paper is dried completely in a series of steam heated cylinder dryers. Some kraft sack paper is dried using a combination of cylinder dryers with an air impingement floater dryer to enhance paper strength properties. In the latter technique the major part of sheet shrinkage occurs with unrestrained drying in the floater dryer over the range of about 1 down to 0.25kg water/kg dry. Figure 1 illustrates these techniques, both of which have a low drying rate relative to through air drying.

Figure 2 shows a typical evolution in paper moisture content in cylinder drying where typically the sheet passes over 40 to 80 steam heated cylinders depending on the efficiency of dryers, paper basis weight and paper machine speed. Previous studies with semi-permeable papers [19, 20] indicated that using through air drying at the moisture content at which the sheet enters paper machine dryer sections not only requires a very high fan power for air flow through the paper, but may degrade product due to local nonuniformity in drying.

The perspective of the present study is to evaluate the possibility of some kind of application of the through air drying process to heavier papers, even if for only part of the total drying operation, i.e. in some novel type of hybrid drying. Drying rate characteristics are highlighted but product quality considerations, having been a major criteria in our earlier work on local nonuniformity of through air drying, also condition the strategy of the present investigation.

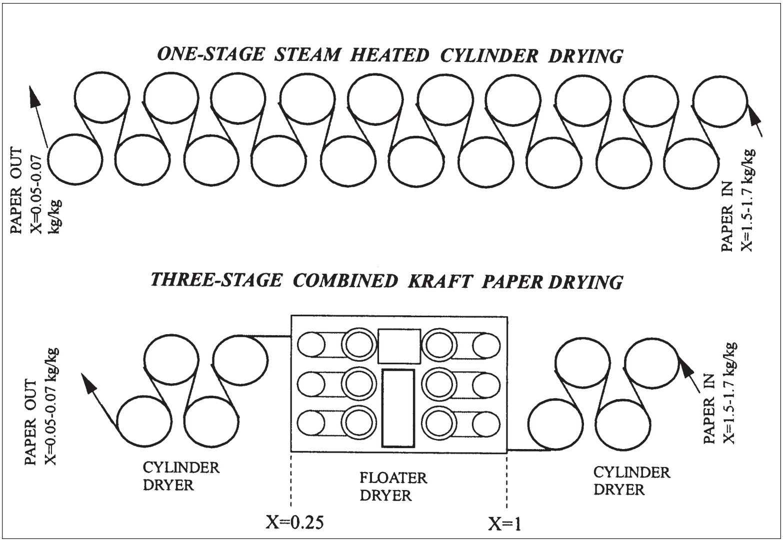

Figure 1 Drying configurations for kraft paper

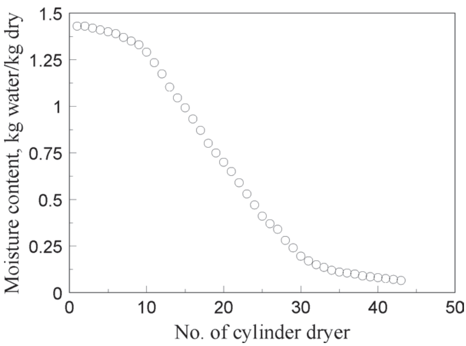

Figure 2 Evolution of moisture content in cylinder drying

OBJECTIVE

To examine strategies for achieving, with printing and heavier grades, the advantages of through air drying (very high drying rate, good CD moisture control) while minimizing the disadvantages (high cost of achieving air through flow, tendency for local nonuniformity of drying).

EXPERIMENTAL

For 3 grades of machine-formed commercial unbleached kraft papers of moderate fines content, produced as sack paper, the permeability and drying characteristics were determined in the experimental facility described by Hashemi et. al. [19]. This facility enables operation at constant air through flow rate, G, as the sheet goes from wet to dry, a substantial advantage over the much simpler operation at constant pressure drop across the sheet, which produces results of limited relevance to process fundamentals. For air inlet temperatures, T_i, of 20–90°C, through flow rates, G, of 0.2–0.4kg/m^{2}s were used, corresponding to a pressure drop across the moist paper in the range 10–50kPa. Employing air temperatures below those used commercially is essential to enable accurate documentation of the complete drying history and determination of fundamental characteristics of the through air drying process which are needed to devise new drying strategies. The principal specifications of these papers are recorded in Table 1. Of particular importance in the present study, the fibre saturation point (FSP) values given in Table 1, determined by defined standard procedures, are accepted as the best indication of the condition when the fibres are fully saturated with water but there is no water in the inter-fibre pores. Thus the FSP moisture content defines the transition during drying from a 3-phase network with both water and air in the pores between saturated fibres, to a 2-phase system of unsaturated fibres and water-free pores.

Table 1 Properties of dry paper for the three commercial grades used

Paper type	*Grammage g/m^2*	*Thickness μm*	*Fines Content %*	*Pulp Freeness ml*	*Fibre Satn. Point Kg/Kg dry*	*Permeability* ×10^{14} m^2*
Kraft paper 1	46.7	102	14.7	357	0.88	3.6
Kraft paper 2	100.3	188	13.6	603	0.99	12.1
Kraft paper 3	54.7	112	11.6	406	0.87	2.4

RESULTS

Figures 3 and 4 show experimental measurements which characterize the through air drying of paper. The results represented here are for one grade of kraft paper but for different levels of initial moisture content for the sheet

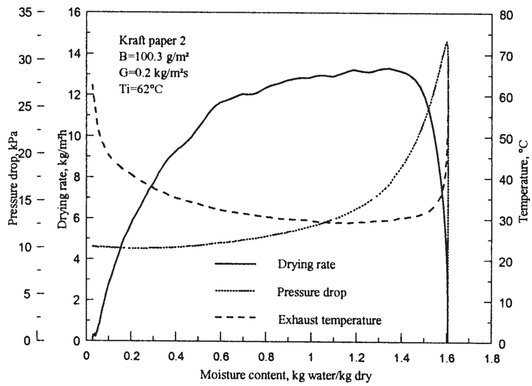

Figure 3 Through air drying for initial moisture content higher than FSP

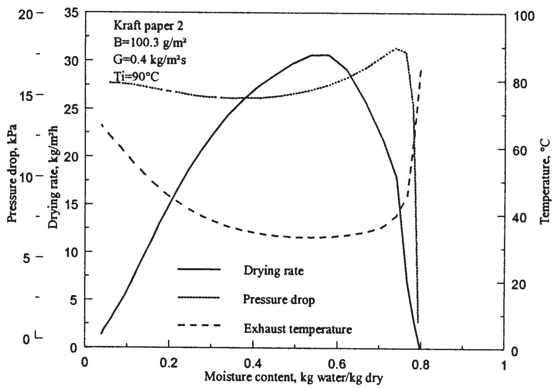

Figure 4 Through air drying for initial moisture content lower than FSP

entering the through dryer. Drying rate, R, is given as kg/m^{2}h, as is the standard practice in work on paper drying. Figure 3 is for an initial moisture content, X_o, of 1.6kg/kg dry, a level in the range of that entering paper machine cylinder dryer sections, while Figure 4 shows the drying characteristics for a sheet entering the through dryer with initial moisture content of,

X_o, 0.8 kg/kg dry, slightly below the fibre saturation point, FSP, of this grade. The quite different evolution of both drying rate and pressure drop for the air flow through the sheet for these two levels of sheet initial moisture content is central to the present investigation, and will be analyzed in detail in the subsequent sections.

Momentum transport

The momentum transport aspect of through air drying, reflected in the curves of Figures 3 and 4 for pressure drop of air flow through the moist paper, is now treated. Figure 5 shows the pressure drop-sheet moisture content profiles for all three types of kraft paper used, when through dried with air of inlet temperature, T_i=60°C, at air through flow rate, G, of 0.4kg/m^{2}s, starting from a moisture content of about 1.6kg/kg, which is about double the FSP moisture content of these grades. The major differences between these pressure drop curves are due to the differences in the properties of these sheets, i.e. their fines content, permeability, freeness of the pulp, basis weight and in the local nonuniformity of sheet structure, formation. The results might be considered anomalous in that kraft paper 2, of highest basis weight, has the lowest pressure drop. Kraft papers are made from pulps having been subjected to considerable differences in the extent of beating of the pulp suspension. The small fibrils on the surface of the fibres generated by beating

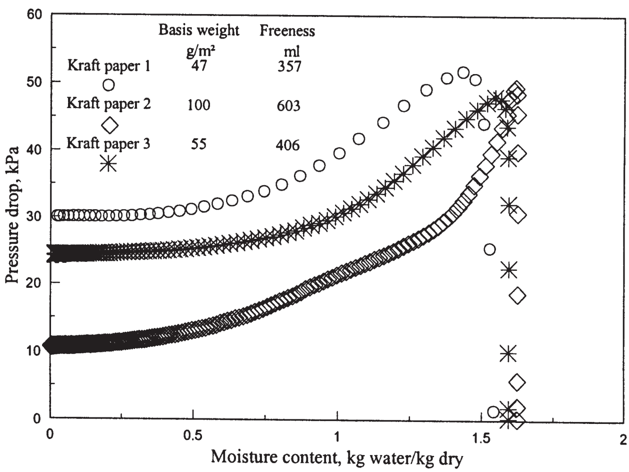

Figure 5 Effect of moisture content on pressure drop for air flow through paper

provide better interfibre bonding, increasing the paper strength. The effect of beating on the pulp is determined by the standard test of pulp freeness. The freeness of kraft paper 2 is 603ml, considerably higher than that of kraft papers 1 and 3, i.e. 357 and 406ml, respectively. Thus the thickest paper, kraft paper 2, is made from least beaten pulp, giving it the lowest pressure drop in spite of its high basis weight. Previous work here [20, 21] has shown that the permeability of moist and dry paper is much affected by the extent of beating. Relative to paper 1, paper 3 has slightly higher basis weight, a lower fines content and a higher freeness. Figure 5 shows that the net effect of these several differences is a lower pressure drop for kraft paper 3 than paper 1 for the same through flow of air. The pressure drop of the through flow of drying air, such as displayed on Figure 5, is now subjected to a momentum transport analysis in order to examine the effect of initial moisture content for through air drying.

Permeability and specific surface area for dry kraft paper

The use of standard procedures of statistical analysis showed that flow through all types of paper tested here may, with R^2>0.95, be treated by Darcy's law:

$$\frac{\Delta P}{v} = \frac{L}{k} G \tag{1}$$

where L is paper thickness, m; ν kinematic viscosity, m^2/s; G air mass flow rate, kg/m^2s and k the Darcy permeability, m^2. A study [22] of transport phenomena behavior of machine formed printing papers dried from initial moisture contents of 1.3 to 1.7kg/kg showed that the paper permeability was neither a function of sheet moisture content at the start of drying nor of process parameters of through air drying. Polat et al. [23] likewise reported this same conclusion for the case of unfilled kraft handsheets dried from initial moisture contents in the range of 2.5 to 1.5kg water/kg dry. In the present study it was also found statistically that the temperature of the through flow air at the inlet of the dryer, T_i, does not affect the sheet permeability. However with respect to one important aspect, the results of the present study differ importantly from those published previously. Specifically, the present investigation establishes that the permeability of both moist and dry paper differs substantially with the moisture content at which through drying is started, when this parameter is varied over the range between about the fibre saturation point value, FSP, and that typical at the start of industrial drying of kraft paper, i.e. about double the FSP value.

As it is not intuitively evident why the permeability of paper which has been through air dried should vary with the moisture content at which through drying starts, this behaviour is now examined. The understanding of this finding relates to the characteristic of local nonuniformity of drying when carried out by a through flow of air, an aspect first tested in two previous studies [17, 18]. Consider first the case of a paper which is through dried starting from an initial moisture content well above that of the FSP value. When the average moisture content of such a sheet has been reduced by drying to the FSP value, our drying nonuniformity studies established that not all the remaining water is associated with saturated fibres at the FSP. Due to local nonuniformity of drying, caused by the local nonuniformity of sheet structure and permeability, some free water is still present in the smaller pores while some locally thinner parts of the sheet have a moisture content considerably lower than the FSP. Thus although the sheet average moisture content is at the FSP value, due to local nonuniformity in drying there is a local moisture content distribution across the paper and correspondingly, the sheet average permeability is lower than would otherwise be the case. By contrast, for a sheet which enters the dryer with its moisture content at the FSP, the local moisture content is uniform at this value, all water is in saturated fibres, and the sheet average permeability is lower. Also, from the previous studies noted of local nonuniformity during through air drying, when paper is through dried from a moisture content below the FSP value, the sheet shrinks more uniformly and thereby provides less driving force for local nonuniformity of the through flow.

Thus the sheet structure is different when through dried from initial moisture content above and below that of the FSP. Polat et al. [23] studied the effect in through air drying of varying initial moisture content, but not for X_o extending to below X_o=1.5kg/kg, a moisture content well above the FSP value for all grades of paper. As sheet shrinkage occurs mostly in the moisture content range of 1.0–0.25kg/kg, therefore their conclusion is correct, as is the case also for results presented in [22] where the printing grade commercial paper was through dried with initial moisture content higher than 1.0kg/kg, i.e. above the FSP value. The present study has now added the perspective that, when initial moisture content is varied both above and below the FSP value, paper permeability is dependent on this variable and that this dependence derives from corresponding effects on the local nonuniformity of paper structure. When dried from a moisture content at or below the FSP value, the lower local nonuniformity of drying produces a sheet with less local nonuniformity, hence a sheet of lower permeability. Table 2 shows that drying from about the FSP value rather than twice this moisture content produces a dry sheet of permeability up to about 20% lower. This lower permeability derives

Table 2 Effect on permeability of kraft papers from initial moisture content of through drying

Paper type	*Thickness* µm	*Permeability, k* m^2 *for* $X_o = FSP$	*Permeability, k* m^2 *for* $X_o > FSP$	*% Decrease in permeability*
Kraft paper 1	102	3.03×10^{-14}	3.55×10^{-14}	15
Kraft paper 2	188	9.76×10^{-14}	12.06×10^{-14}	19
Kraft paper 3	112	2.23×10^{-14}	2.35×10^{-14}	5

from a locally more uniform sheet, so drying from the lower level of initial moisture content produces more uniform dry paper, better for printing and thus of higher product quality.

As paper permeability is sheet structure dependent, efforts have been made to relate it to properties of the porous medium by assuming a model of the structure. Because of the complexity of structure of sheets from wood pulp fibres, as an alternative most models use highly idealized geometries that can be described with just a few parameters. These models are of three types: those based on flow through networks of conduits, on flow around solid obstructions (drag theories), or based on empirical correlations. The most common phenomenological approach, based on geometric considerations, is the Kozeny-Carman equation

$$a_p^2 = \frac{1}{\kappa}\frac{\varepsilon^3}{(1-\varepsilon)^2}\frac{1}{k} \tag{2}$$

for determining specific surface a_p, m^2/m^3, where ε is porosity and κ the Kozeny constant, generally taken as 5.55. With porosity entering Equation (2) with a power of 3, this property must be determined precisely. If porosity is not determined directly by mercury porosimetry, it may be estimated from paper thickness measured according to CPPA standard D4, its basis weight and fibre density, ρ_f. The accuracy of thickness by caliper is limited due to surface roughness and paper compressibility. Kraft pulp fibre density is usually taken, with reason, as that of pure cellulose, 1550kg/m^3, with this value being often assumed for TMP fibres also. With these uncertainties, porosity was also determined here by mercury porosimetry. The shortcomings of the Kozeny-Carman equation to calculate the specific surface area of paper, especially in presence of fines and for beaten pulps, were discussed in [22]. However this equation could be used here as the purpose of this study is the comparison of papers of the same grade, kraft paper, and of similar fines content, 12–15%. Table 3 records the porosity and specific surface area of these papers, determined as indicated above. In through air drying a sheet is dried internally, not just at its external sheet surface area, therefore having a higher specific surface means a larger area for drying, hence a higher drying rate, a lower drying time. For a sheet which is through dried from an initial moisture content of the FSP rather than about double the FSP value, Table 2 showed that the dry sheet permeability is lower, while Table 3 reveals the important finding that the specific surface is higher.

Table 3 Porosity and specific surface of through dried kraft papers

Paper type	*Thickness* µm	*Porosity*	a'_p m²/g For X_o = FSP	a'_p m²/g For Xo > FSP
Kraft paper 1	102	0.705	0.930	0.858
Kraft paper 2	188	0.656	0.465	0.419
Kraft paper 3	112	0.685	1.039	1.013

Permeability of moist and dry kraft paper

The permeability of moist paper is difficult to determine, hence there is very limited information available concerning this property which is fundamental to the analysis and performance of through air drying. With the special equipment and procedure used for determining moist paper permeability in the present study, permeability was generally calculated using Darcy's law. However because of the difficulty of determining the paper thickness-sheet moisture content relation, the results are expressed as the modified permeability, k/L. At each moisture content there were from 24 to 36 values of the ΔP-G data available to calculate permeability. The two sets of ΔP-X-G data, i.e. those based on experiments with through drying from an initial moisture content around the FSP value, and the other set for starting through drying from a moisture content about double the FSP value. Results from these two sets of experiments were used separately to calculate two corresponding sets of modified permeability. Thus one set of k/L results were determined for the range from about X=1.4kg/kg to dryness and the other set for the range from about X=0.75kg/kg to dryness.

Figure 6 shows the modified permeability of the three types of kraft paper, through air dried from two levels of initial moisture content, i.e. around the FSP and about double the FSP value. For the paper made from the least

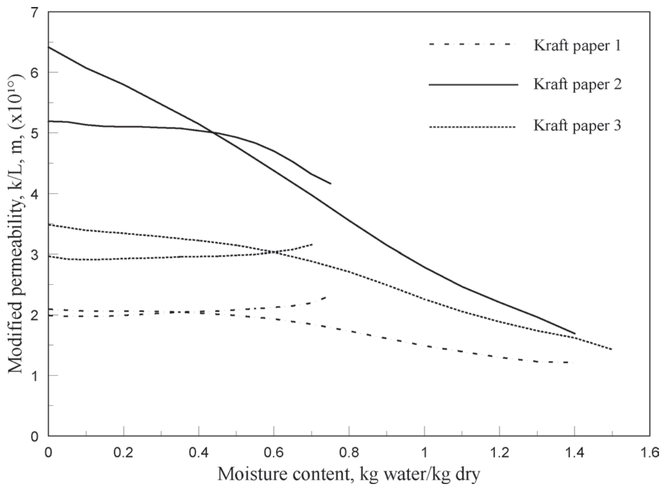

Figure 6 Effect on modified permeability of kraft paper from initial moisture content of through drying

beaten pulp, kraft paper 2, with correspondingly the highest modified permeability, its permeability increases by almost 5 orders of magnitude as the sheet is through dried from the high level of initial moisture content, about 1.4kg/kg. Kraft papers 1 and 3, made from more highly beaten pulps, have a lower modified permeability initially at 1.4kg/kg moisture content. Also, in contrast to kraft paper 2, made from less beaten pulp, the permeability of papers 1 and 3 does not increase nearly as much during drying. The permeability of papers 1 and 3 increase by only 1 to 2 orders of magnitude during through drying from 1.4kg/kg moisture content. The less beaten pulp used for kraft paper 2 produces a more permeable sheet than the more beaten pulps of the furnishes of kraft papers 1 and 3. Thus paper 3, of slightly lower fines content (11.6%) than that of paper 1 (14.7%) has a higher permeability from the use of the less beaten pulp, of higher freeness. The much larger increase in permeability of paper 2 during drying would derive from being made from the least beaten pulp fibres, which produce a sheet of lower strength that would offer less resistance to the development during drying of local nonuniformity of sheet structure, which is the source of higher permeability.

For $100 g/m^2$ kraft handsheets from unbeaten pulp, Polat [24] reported that the permeability increases sharply during drying and does not level off until dryness. That finding for handsheets is now found to be consistent with the permeability – moisture content behavior for commercial kraft paper 2 from lightly beaten pulp. Figure 6 indicates that for the more strongly beaten pulps used for kraft papers 1 and 3, the permeability of these stronger sheets does not change as much while the sheet goes from wet to dry. In our study [21] of through drying a number of commercial papers it was observed that for sheets from beaten pulps, the modified permeability may even decrease over the low range of moisture approaching dryness. This behavior is also seen on Figure 6 for kraft papers 1 and 3 when through dried from a moisture content near the FSP value.

Drying rate characteristics

Any industrial application of the present study would involve process modeling, for which the parameters describing the through air drying process would be required in order predict drying kinetics for drying conditions not tested in the lab. Previous work [19] has established that five parameters are required to describe the through air drying process. Thus the relationships to drying conditions must be determined for these five parameters, i.e. constant drying rate R_c, initial critical moisture content, i.e. sheet moisture content at the onset of constant drying rate period X_i, final critical moisture content X_c for the start of falling rate drying, and two parameters which determine the shape of the increasing and falling rate drying period curves, n_i and n_f. In the next sections the dependence of these parameters on drying conditions will be treated.

For the set of data for the initial moisture content about double the FSP value, the effects of through drying process parameters are similar to those previously reported for commercial grades of paper, [19]. For the three grades of kraft paper used now, Figure 7 shows the drying rate (R-X) curves for the same initial moisture content, of about 1.6kg water/kg dry, and under the same through drying conditions. Statistical analysis of the through drying parameters for the three types of kraft paper used here, when through dried from the high level of initial moisture content, shows there is no significant difference in their drying rate characteristics. The most impressive aspect of this comparison is that, where the permeabilities of these 3 types of paper on Figure 6 differed by orders of magnitude the drying rate curves are essentially indistinguishable. The most sensitive through drying parameter, final critical moisture content, X_c, is always in the range of 50 to 60% of the initial moisture content, the values of X_c/X_o being 0.53, 0.58 and 0.50 respectively for paper types 1, 2 and 3. The correlation developed by Polat [25] for R_c was tested and could be used here but his correlation for initial critical moisture content X_i, the moisture content

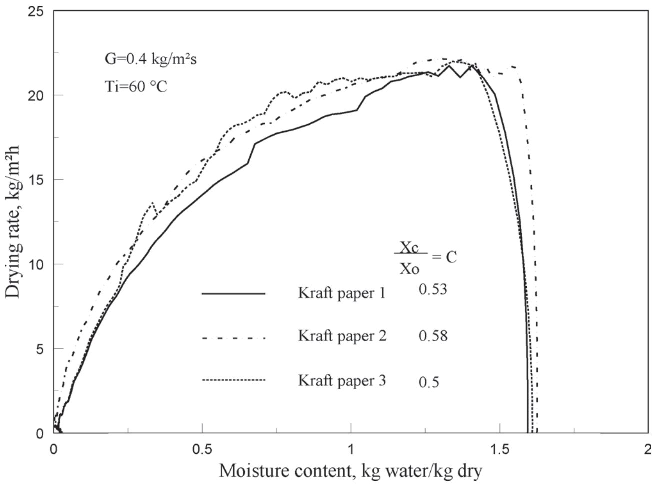

Figure 7 Drying rate curves for 3 types of kraft paper: X_o>FSP

for the transition from the increasing rate to the constant drying rate period, needed to be modified to predict these values precisely for the present case.

The same similarity in through drying rate curves of these three types of kraft paper is observed, Figure 8, for drying from the lower level of initial moisture content, i.e. X_o=FSP. Again it is remarkable that although the permeabilities of these papers are different by up to three orders of magnitude, Figure 6, the drying rate curves show no significant difference.

Quantitative analysis of drying rate curves

For the case of initial moisture content at about the FSP value, techniques of both Chen [26, 27] and Polat [25] were used to analyze through air drying rate curves for the three types of paper used here. Chen's models could be used for kraft papers 1 and 3 but due to inflection at the dry end of the drying rate curve of kraft paper 2 this model must be modified for the falling rate drying period. The moisture content at which this inflection occurs, X_{INF}, is a function of drying intensity. The parameters in Equations (3) and (4) below, were determined by fitting a polynomial to the R-X data. The previous model for the falling rate drying period was thereby modified to:

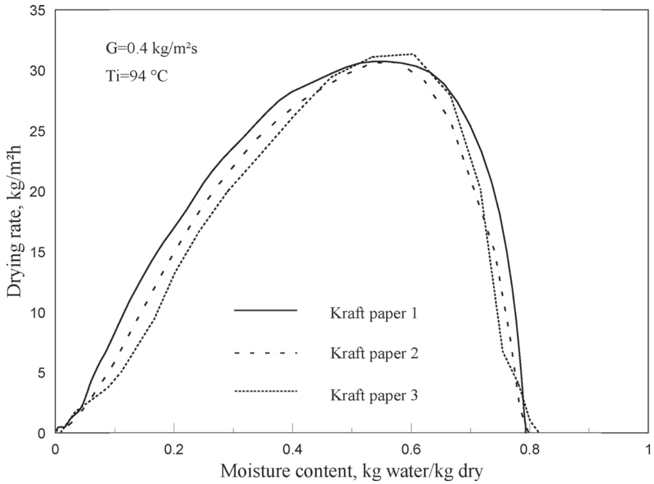

Figure 8 Drying rate curves for 3 types of kraft paper; X_o = FSP

$$\frac{R}{R_c} = 1 - \left(1 - \frac{X - X_f}{X_c - X_f}\right)^{n_f} \qquad X_{INF}<X<X_c \tag{3}$$

$$\frac{R}{R_c} = mX \qquad X<X_{INF} \tag{4}$$

As the constant drying rate period was very short in most cases, i.e. X_i–X_c<0.15 X_o, frequently a single value, X_c=X_i, was determined as the moisture content where R=R_{max}. The values of the through air drying process parameters X_i, R_c, X_c, n_i, and n_f were thereby determined for kraft papers 1, 2 and 3, plus values of X_{INF} and X_f for kraft paper 2. Neither Polat's nor Chen's correlations for X_i, X_c and R_c for handsheets could be used to predict these values for the commercial kraft papers.

As it was noted earlier that there was no statistically significant difference between the R-X curves for the three kraft papers, only results obtained for kraft paper 1 were used to derive full correlations for the five parameters of the through air drying process. Only those experiments carried out with heated air, T_i>60°C, were used to obtain the correlations.

The correlation for X_i, which defines the transition from the increasing rate to the constant rate drying period, is

$$X_i = aR_s^b X_o^c \tag{5}$$

where a, b, and c are 1.623, –0.224 and 0.912, with an R^2 correlation value of 0.90. Due to differences in the drying mechanism this correlation differs substantially from those derived for paper through dried from an initial moisture content double the FSP value. For starting through drying from X_o around the FSP, initially all the water is in the fibres, with no water in the pores and hence all the pores are open to the through flow of air. That is why the increasing drying rate period is very short when drying is started from the lower level of initial moisture content, at about the FSP value or lower. In this drying rate period the drying rate increases as sheet approaches the adiabatic saturation temperature. Figure 9 shows the very good agreement between the experimental and predicted values of X_i.

The correlation to predict the constant drying rate, R_c, is similar to that reported previously for commercial papers [19]. Likewise the onset of the falling rate drying period could again be predicted from initial moisture content as given in Table 4.

The critical moisture content was related to through drying process variables as:

$$X_c = aX_0^m R_s^p G^q \tag{6}$$

The correlation parameters a, m, p, and q are 3.24, 0.81, –0.26 and 0.68 respectively, with an R^2 correlation value of 0.96. For the commercial kraft

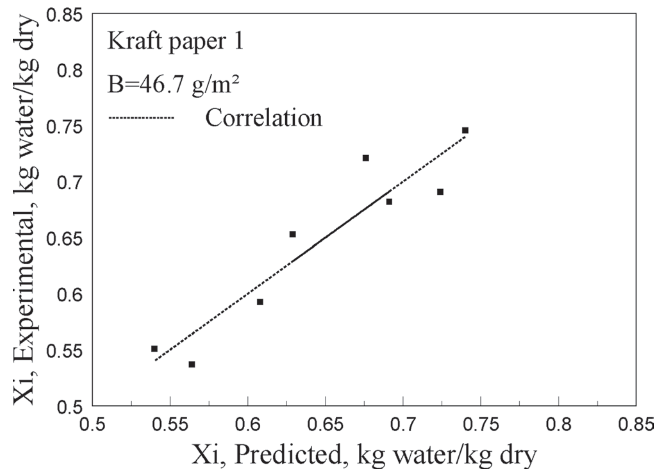

Figure 9 Correlation for X_i

Table 4 Critical moisture content for kraft papers

Paper Type	X_c/X_o	$\sigma_{Xc/Xo}$
Kraft paper 1	0.65	0.10
Kraft paper 2	0.61	0.10
Kraft paper 3	0.70	0.06

paper of the present study the ratio of critical to initial moisture content, X_c/X_o, is higher than reported in previous studies for a range of handsheets from furnishes of kraft, TMP, and TMP-kraft blends, [21, 25] and for commercial papers [19]. The behavior of the through air drying process is very sensitive to sheet structure, which in turn is sensitive to many papermaking parameters. Thus general correlations for widely different types of paper should not be expected, but must be determined for specific cases. Figure 10 shows the satisfactory agreement between experimental and predicted values of X_c.

The description of the through drying process is completed by determining the shape of the increasing and falling rate regions of the R-X curves using the two parameters, n_i and n_f, introduced by Chen [27]. The average values of n_i and n_f for the papers used here are listed in Table 5. When these three papers are dried from an initial moisture content of about the FSP value, i.e.

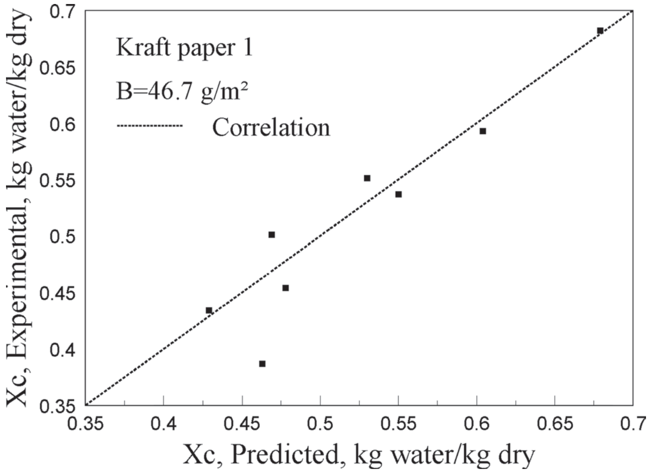

Figure 10 Correlation for X_c

Table 5 Parameters n_i and n_f for kraft papers

Paper Type	n_i	σn_i	n_f	σn_f
Kraft paper 1	3.3	0.4	1.6	0.3
Kraft paper 2	3.6	0.2	1.6	0.3
Kraft paper 3	3.5	0.4	1.3	0.2

from the initial condition where all water is associated only with the fibres, there is no significant difference between the n_i and n_f parameters which characterize the drying rate curves.

Effect of initial moisture content

The central obstacle to the use of some through air drying for heavier grades of paper is the cost of obtaining the through flow. Therefore the present study focused on obtaining the process characteristics when through drying was started at lower values of X_o, hence at higher permeability of the moist sheet, corresponding to lower capital and operating cost of providing the through flow air. Comparison between the two drying rate curves for the same paper, Figure 11, reveals some surprising characteristics. This commercial kraft paper was through dried under the same conditions, but one starting at an initial moisture content in the range found for paper entering paper machine dryer sections and the other at about one half this initial moisture content, around the FSP value. Over the overlapping range of moisture content, the lower the critical moisture content, the higher the drying rate. Thus when through drying started at 0.78kg/kg dry, just below the fibre saturation point for this grade, the critical moisture content (ca. 0.5kg/kg) was only about 1/3 of that experienced when through drying was started at the higher value. The lower the moisture content for the onset of the falling drying rate period, the faster the drying.

The shaded area between the two drying curves on Figure 11, which cross at a moisture content of about 0.7kg/kg dry, represents the advantage of through drying from the lower X_o. Over the moisture content range from 0.7kg/kg to dryness, drying rate is substantially higher for starting through drying at the value around the FSP. This surprising behavior, higher drying rate for starting drying at a lower moisture content, could not have been anticipated. When through drying was started from about the FSP moisture content, the falling rate curve shifts to the left and upwards. This much more advantageous falling rate curve means that for the last and most difficult part

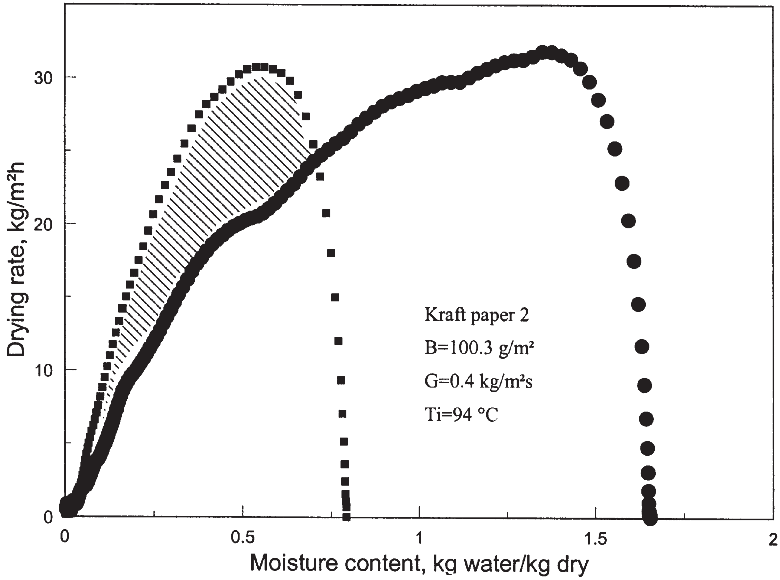

Figure 11 Enhancement of through drying rate for a lower initial moisture content

of drying, the drying time required is much shorter. When through air drying is started from lower levels of initial moisture content, at the FSP value or below, the size of the dryer required is appreciably smaller.

The preceding sections provided the quantitative relationships for R_c, X_i and X_c, relative to through drying process conditions, G, mass through flow rate of the drying air, T_i, the drying air inlet temperature, B, paper basis weight and the initial moisture content, X_o, along with the R-X relationships during the increasing and falling rate drying periods in terms of n_i and n_f. This procedure applied with this through air drying process model enables prediction of the drying rate and drying time for any desired drying conditions. The possibility of using through air drying as a part of overall drying process may thereby be evaluated.

Enhancement of drying efficiency

With discovery of this advantage from starting through air drying at a sheet moisture content about half the typical paper machine dryer inlet moisture content, Figure 11, this effect was investigated further. Thus this 100g/m^2

commercial kraft paper was through dried under the same conditions from 7 levels of initial moisture content ranging from 0.78 down to 0.24kg/kg dry. The results from these tests, Figure 12, show the surprising characteristic that the maximum value of through drying rate does not, as would be expected, decrease as X_o is decreased, but remains remarkably constant. An equally important finding concerns the effect of X_o on the falling rate period. The critical moisture content, X_c, marking the onset of the falling rate period, is seen on Figure 12 to decrease steadily from about 0.56 to 0.21kg/kg dry as X_o is reduced from 0.78 to 0.24kg/kg. These large reductions in X_c are highly advantageous because of the associated large increase in drying rate, which translates to a large reduction in drying time. For the lowest value of X_o tested, 0.24kg/kg, the constant rate period has just disappeared, leaving only falling rate drying. As it is the falling rate period which exerts by far the strongest influence on drying time and thereby on size of an industrial dryer, Figure 12 establishes that as X_o is decreased below the FSP value, the falling drying rate curve becomes increasingly advantageous to the process of through air drying.

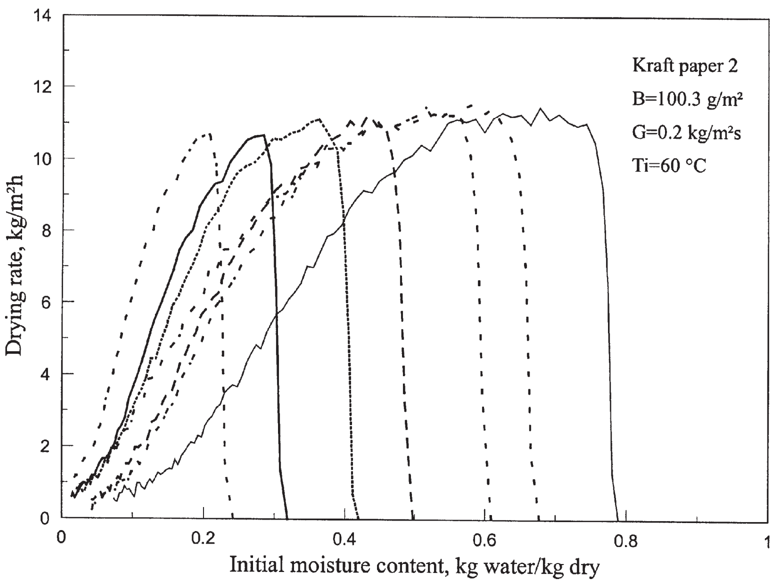

Figure 12 Enhancement of through drying characteristics for initial moisture contents below FSP value

To illustrate this finding, Figure 13 shows the values of the through air drying rate at three specific moisture contents: 0.1, 0.15, and 0.2kg/kg dry. It is seen that when through drying is started at values below the fibre saturation point, drying rate at low moisture contents improves greatly as X_o is decreased from 0.8 to 0.24kg/kg dry.

For the set of experiments for which Figure 12 gives the effect of initial moisture content on the drying rate curves, Figure 14 provides the pressure drop curves for the drying air flow through the moist sheet as it goes from wet to dry. Where Figure 12 documents the major changes in drying rate curves, Figure 14 shows that there is no significant change in the pressure drop characteristics of the through flow. One can conclude that for variation of sheet initial moisture content in the range from the fiber saturation point down to about 0.24kg/kg, the air through flow pressure drop across the moist paper is essentially unaffected.

The effects of initial moisture content on through drying rate and on through flow pressure drop characteristics which are provided by Figures 11–14 are for one of the grades of paper used in this study, kraft paper 2. Similar effects were observed for the other kraft papers. For example, for the case of kraft paper 1, Figure 15 shows the improvement in drying rate curves as initial moisture content is decreased from the FSP value down to 0.24kg/kg. For kraft paper 1, Figure 15 shows that as initial moisture content is

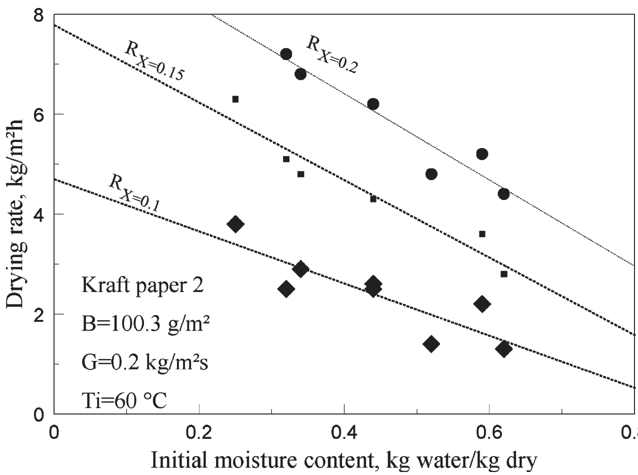

Figure 13 Enhancement of drying rate from reducing initial moisture content

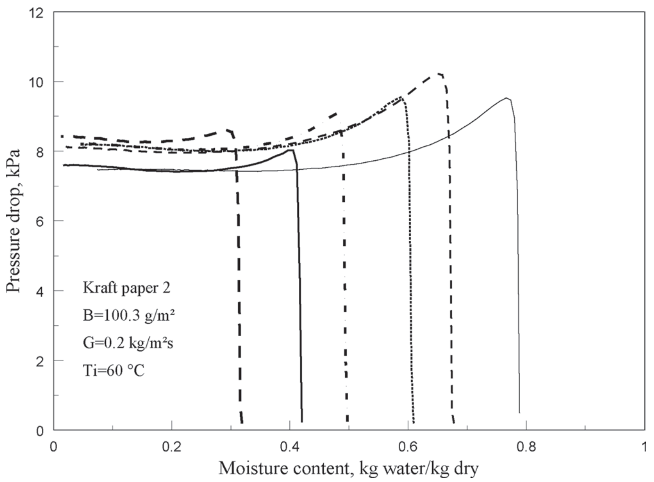

Figure 14 Effect on through flow pressure drop for initial moisture contents below FSP value

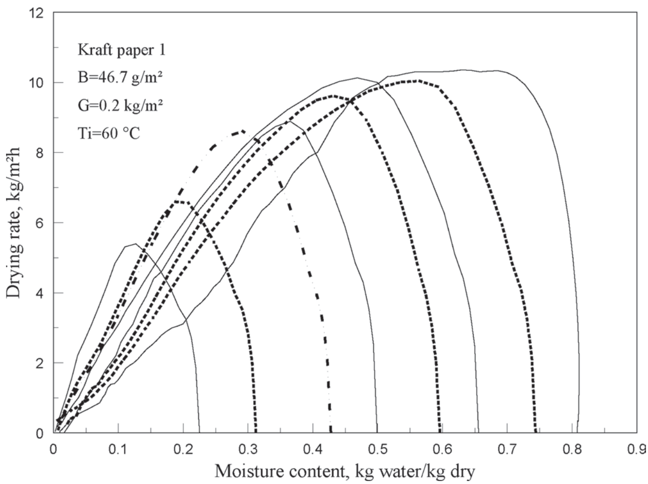

Figure 15 Enhancement of through drying rate characteristics for initial moisture contents below FSP value: Kraft paper 1

decreased from the FSP value, the falling drying rate part of the R-X curve shifts to the left and upwards, as recorded for kraft paper 2 on Figures 11 and 12. However for kraft paper 1 these shifts in the R-X curve with decreasing X_o are not as pronounced as with kraft paper 2, with the critical moisture content, X_c remaining constant only for the range of X_o down to 0.65kg/kg, below which X_c decreases. Thus for kraft paper 1 the distinct advantage from use of a lower initial moisture content in the range below the FSP value is again found, but the extent of this advantage is less marked than for kraft paper 2.

Bond et al. [28] showed that the drying rate curve for the falling rate period of impingement air drying of paper could be approximated as linear with dry basis moisture content, X. As examination of Figure 15 shows that the same approximation could be applied here, Figure 16 presents the values of the slope of the falling rate curve for kraft paper 1. Thus for sets of experiments with 60°C air at two levels of through flow rate, G of 0.2 and 0.4kg/m^{2}s, Figure 16 presents the effect on the falling rate curve for reducing the initial moisture content below the FSP value. As the initial moisture content is decreased, the increase in slope of falling rate drying period seen on Figure 16 corresponds to a higher drying rate for a lower initial moisture content. The two sets of data shown could be fitted to two lines with R^2 correlation values of 0.83 and 0.87. The higher slope for the higher intensity drying condition

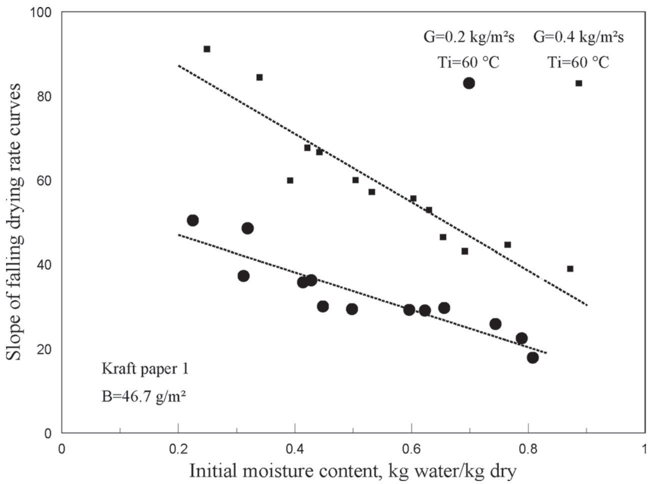

Figure 16 Effect of initial moisture content on slope of falling rate drying curve: Kraft paper 1

(G=0.4kg/m^{2}s) indicates that the improvement in falling drying rate with reduction in sheet initial moisture content is more significant at the higher drying intensity.

For kraft paper 1, Figure 15 shows the maximum drying rate, R_{max}, decreases as sheet initial moisture content for through drying decreases down to X_o=0.25kg/kg. Figure 17 shows this trend in R_{max} for the same two data sets for kraft paper 1 shown on Figure 16. As would be expected, the decrease in maximum through drying rate R_{max} is greater for the higher intensity drying condition (G=0.4kg/m^{2}s). However due the important effect from the shift of the falling rate curve to the left, corresponding to a reduction in critical moisture content, there is a significant improvement in through drying performance in spite of the reduction in R_{max} as sheet initial moisture content is decreased.

Figures 16 and 18 each reflect one important consequence (R_{max}, and slope of falling rate curve) from using levels of initial moisture content below that of the FSP. However determination of the effect that this has on drying time integrates all features of the drying rate curves. Thus for kraft paper 2 the drying rate curves of Figures 11 and 12 were used to determine the most comprehensive performance characteristic, drying time. The size of a dryer is dominated by the lower drying rate region near the end of the falling drying rate period as the sheet approaches dryness. Therefore drying time was determined for taking the paper from a moisture content of 0.15kg water/kg

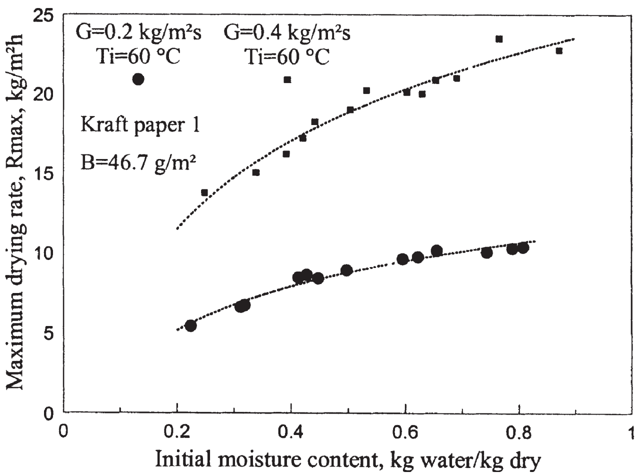

Figure 17 Effect of initial moisture content on R_{max}: Kraft paper 1

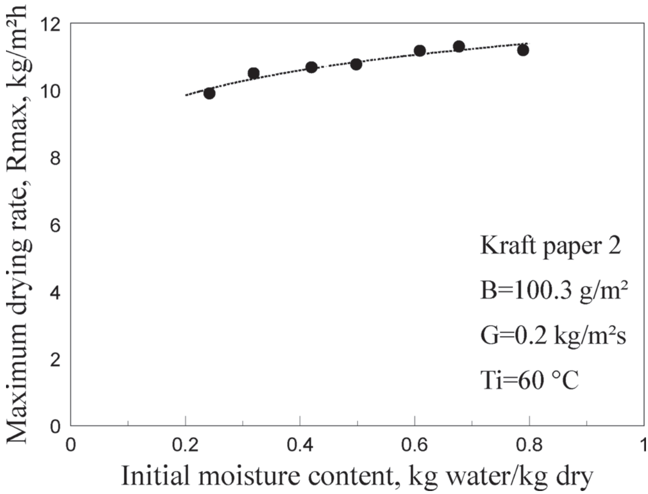

Figure 18 Effect of initial moisture content on R_{max}: Kraft paper 2

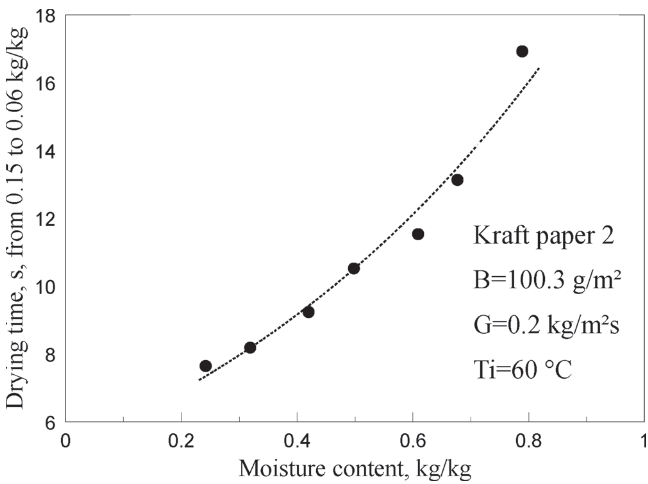

Figure 19 Reduction in drying time for initial moisture content below FSP value: Kraft paper 2

dry down to dry, defined as X_f=0.06kg/kg. These drying time results, Figure 19, show the impressive reduction in drying time for the slowest part of drying, 0.15kg/kg to dryness. As X_o is reduced from 0.78 to 0.24kg/kg, the time of drying from 0.15 to 0.06kg/kg is reduced substantially, by about a factor of 2. Over this low moisture content range, 0.15 to 0.06kg/kg, cylinder drying is very slow because of low rate of heat conduction into nearly dry paper of low thermal conductivity as well as low rate of water vapor transport from the interior of the nearly dry sheet.

INDUSTRIAL APPLICATION

Most kraft papers are dried in a single technique dryer, the cylinder drying process, although for product quality reasons sack paper is dried over an intermediate part of the moisture content range by lower intensity air impingement drying in a floater dryer, as illustrated in Figure 1. For single technique drying by hot surface contact heat transfer in a cylinder dryer section, a set of 40 to 80 steam heated cylinder dryers are required, depending on the grade and basis weight of the paper. The first set of through drying experiments of the present study was carried out with paper at initial moisture content of about 1.5kg/kg, a value typical of present commercial practice with cylinder dryers. The results of these tests relate to the idea of replacing the complete cylinder drying process by through air drying. Although through drying from an initial moisture content around 1.5kg/kg gives very high drying rates relative to cylinder drying, this advantage is obtained at excessive cost for pressure drop for the air flow through the low permeability sheet at the wet end of the dryer.

The more important, second set of through drying experiments used a range of initial moisture contents from the about 0.8kg/kg, near the fiber saturation point value, down to a quite low moisture content, 0.24kg/kg. The controlling characteristics of the through air drying process are the critical moisture content X_c, the constant or maximum drying rate, R_c or R_{max}, and the pressure drop required for the air flow through the moist sheet. These characteristics combine to establish a clear incentive for the alternative of using through air drying only to complete the drying over the low moisture content range where cylinder drying rates are very low. Typically about a third of the cylinders are needed just to reduce sheet moisture content from 0.25kg/kg to dryness. This final section of a cylinder dryer is therefore the most advantageous range for conversion to hybrid drying with cylinder drying followed by through air after-drying.

SUMMARY AND CONCLUSIONS

Through air drying characteristics of kraft paper were studied using three types of commercial kraft paper. Two levels of initial moisture content were used. The higher level was typical of the moisture content entering the cylinder dryer section of paper machines, around 1.5kg/kg dry. The lower level of initial moisture content ranged from the FSP value, about 0.8kg/kg dry for the papers used, down to 0.24kg/kg. The momentum transport and through drying rate behavior of each set were examined separately. The permeability of these three types of dry and moist kraft paper was determined using the proper momentum transport equation. The effect of beating, measured as freeness of the pulp furnish, has more effect on paper permeability than the range of fines content (12–15%) or grammage (47–100g/m^2) investigated. One novel finding is that initial moisture content also significantly affects the permeability of dry and moist paper. This effect was related to differences in sheet structure resulting from the local nonuniformity of drying, which is much reduced by starting through air drying from initial moisture content below the FSP value. The specific surface of these kraft papers was calculated for comparison purposes.

When through air drying is started at an initial moisture content around the FSP value, the permeability does not change much as the sheet is taken to dryness. However when through drying is started at the high moisture level used, around 1.5kg/kg dry, the permeability increases greatly as the sheet goes from wet to dry. The latter behavior derives from the high level of local nonuniformity of through drying when it is started at a high initial moisture content, about double the FSP value. High local nonuniformity of drying may also have a deleterious effect on product quality, so this is another factor reinforcing the incentive for starting through air drying at lower moisture content levels, below the FSP value.

Drying rates were found to be insensitive to those sheet structural parameters that were found to affect so greatly the permeability and the pressure drop for air flow through the sheet. In order to provide a quantitative model of through air drying for process modeling we determined the through drying characteristics such as the values of the constant drying rate, R_c, or maximum drying rate, R_{max}, the end of increasing drying rate period, X_i, and the beginning of the falling drying rate period, X_c. Correlations of the process characteristics were derived, based on the comprehensive experimental data obtained.

A finding of great practical importance is that during the falling rate period, which is the dominant factor controlling dryer size, the through drying rate improves continuously as initial moisture content is decreased. By contrast, reducing the initial moisture content from around the FSP value, about 0.8kg/kg, down to 0.24kg/kg, has no significant effect on the pressure drop required for the air flow through the sheet, i.e. on the ΔP-X relationship.

Thus the present study establishes a potential economic niche for a new kind of hybrid drying, a hybrid of cylinder drying followed by through air drying, with the through after-dryer used for just the final stage of drying where sheet air permeability is highest, where the cost of achieving the air through flow is lowest, and where the drying rate advantage (through air drying over cylinder drying) is exceptionally high. Based on the results of this study, cylinder drying should always be continued until the moisture content has been reduced sufficiently that none of the remaining moisture is in the interfibre pores, as this is the source of local nonuniformity in through air drying which is bad for both drying kinetics and product quality. For values of initial moisture content from the FSP down, the incentive for the use of through after-drying increases with decreasing the moisture content for starting the through drying stage. The most appropriate choice of moisture content at which to start the through after-drying would be determined by a techno-economic analysis for the sheet characteristics of the specific case.

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Transcription of Discussion

A HYBRID DRYING PROCESS: CYLINDER DRYING WITH THROUGH AIR AFTER-DRYING

S.J. Hashemi[1] *and W.J. Murray Douglas*[2]

[1]Department of Chemical Engineering, University of Tehran, Tehran
[2]Department of Chemical Engineering, Pulp & Paper Research Centre, McGill University, Montreal

Hannu Paulapuro Helsinki University of Technology

What happens to the important printing paper properties like smoothness, absorbency, dimensional stability compared to conventional drying?

Murray Douglas

The simple answer is that I do not know. I am reporting to you the first measurements that we have done on the idea of through after-drying. These first measurements focus on the drying rate aspects, on drying capacity aspects. As I acknowledged at the outset, paper properties are what paper companies sell, so they are always the bottom line. We have not yet measured any paper properties for the case of through After-Drying. However, I point out that what appears from the process point of view to be an advantageous way to use the concept of through after-drying would be at quite low moisture contents. So you only replace the very low cylinder drying rates towards the end of the falling rate period drying with the very high drying rates from through air drying. By the time you start the through after-drying at 15% moisture content, the sheet structure is essentially set. We would expect that the dry paper properties would not be affected much by removing the last moisture quickly by through air drying rather than slowly by cylinder drying.

Jean-Francis Bloch EFPG-INPG

First, I would like to thank you for this very interesting presentation. My question concerned what you have called "modified permeability". In fact you claimed to use Darcy's Law and the classical Kozeny-Carman equation and you say that the shortcomings come from the specific surface evaluation. However, usually we use these kind of laws for saturated media. In the case when the porous medium is not saturated, we have to include a so-called "relative permeability", which takes into account the saturation. So do you think that the shortcomings come from the evaluation of the specific surface or because your measurements are not carried out in a saturated medium?

Murray Douglas

I did not stress it in the presentation, but those who are familiar with permeability will have noticed, that the plot I showed for the evolution of permeability going from wet to dry is of modified permeability, that is not K but was K/L. There is always some uncertainty with measuring thickness for moist paper where dry paper is not much of a problem. For very wet sheets, it becomes increasingly difficult to make a reliable measurement of the sheet thickness so instead of representing results as pure permeability, we represented them as modified permeability K/L for our purposes. This was to see what happens with the evolution of permeability as you go from wet to dry and, in particular, what difference it makes to the dry sheet whether you start through air drying at the high moisture level that will correspond to the sheet going into the dryer section or at lower moisture contents. Further than that, we really did not use the permeability. We thought initially we might be focusing more attention on that, but for the reasons that you saw in the presentation, we focused much more on the drying rate aspect and the permeability aspect. So we did not do anything more on the permeability, but looked at that more or less out of curiosity. We can see that certainly the permeability of dry paper is a function of how that sheet is dried.

William Sampson University of Manchester

Can you say what size the sample is that you are drying in your rig?

Murray Douglas

The sheets are about 15 *cm* diameter.

William Sampson

I was wondering, do you record the grammage of the samples after you have dried them? I ask because many of the curves look like they could scale on to each other. They might do this because some of the variability that we see between them could come from a few $g\ m^{-2}$ difference

Murray Douglas

The grammage of all was determined after we dried them.

William Sampson

It might be nice to look at that in future; I think it is quite likely that they will fall on one line often.

Tetsu Uesaka Mid Sweden University

I wonder if you could make a comment on the local moisture non-uniformity in this hybrid drying configuration? It goes back to your presentation of last time at FRC.

Murray Douglas

I talked about how important local non-uniformity is. The interaction of the local non-uniformity of the sheet structure with the local through flow is fundamental to through after-drying. The answer to your question is we have previously reported complete measurements of local non-uniformity for all the conditions of through after-drying that we have presented today. In the slide for Figure 12, where we have the vertical reference line at a moisture content of 0.2 *kg/kg*, for which the drying rate increased by a factor of 5 when you go from initial moisture content of 0.8 down to initial moisture content of 0.25 *kg/kg*. Why? 100% of the answer to that question is local non-uniformity. When you start your initial moisture content at only 0.25, then by the time you get down to 0.2 *kg/kg*, you have hardly any local non-uniformity. In the previous FRC, we documented that if you started at a normal initial moisture content, by the time you get down to a moisture content of 0.2 *kg/kg*, you have large local non-uniformity, and that is the basis why through after-drying is so effective, with this very substantial and surprising increase in drying rate. It is all because of reducing the local non-uniformity.

Discussion

Wolfgang Bauer Graz University of Technology

I have a question about the experimental part. I think you took commercial kraft sack paper samples from a paper machine, which were dried and then you rewetted them again. Did you ever try to dry all the way from the wet pulp?

Murray Douglas

No, the answer is we did not. It would be better than what we did if we got wet sheets formed on the machine from the mills. Since this was the first time that anyone had ever measured the drying rate characteristics for the idea that we now call through after-drying, we did it the simpler way. From other work we have done with through air drying of never-dried sheets, we knew that this would make negligible difference to the drying rate results.

Marit Van Lieshout Paperlinx

I was wondering by your last remark about the way you obtain your samples. How do you know that the fibres were saturated, because the literature is quite divided over whether fibres will be rewetted? So, I was wondering was there water in your fibres or was it more in between your fibres?

Murray Douglas

We equilibrated the sheets for a substantial period of time in a controlled environment. For this reason, complete thermodynamic equilibrium had been established and the water had redistributed itself throughout the sheet and the water was taken up by the fibres.

Marit Van Lieshout

But you did not check the fibre water content, you did not measure it explicitly?

Murray Douglas

We did not examine individual fibres afterwards but the times that we used were sufficiently long that the fibres had come to equilibrium moisture content.