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EXPERIMENTAL TECHNIQUE FOR TRACKING THE EVOLUTION OF LOCAL MOISTURE NONUNIFORMITY IN MOIST PAPER FROM WET TO DRY

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ABSTRACT

Local nonuniformity of moisture content, a basic characteristic of moist paper, affects efficiency and hence cost of paper drying, and may influence product quality. Such local nonuniformity may become even more of a problem with the current interest in combining higher intensity air convection drying and cylinder drying to produce the required higher capacity hybrid dryer sections of the future.

Direct determination of local sheet moisture content under dynamic conditions during drying is unacceptable because the measuring instrument presence would change local moisture content. A novel indirect technique was developed for quantitative, precise determination of local nonuniformity of moist paper by monitoring continuously the local exit pore air temperature at many positions immediately below a moist sheet subjected to air through flow. This technique was used to investigate local nonuniformity for moist machine-formed papers of grammage 19–55 g/m^2, and 20–100 g/m^2 handsheets of variable formation. The effect of formation and basis weight on local nonuniformity was quantitatively documented. Formation was characterized using the new method of partitioning formation nonuniformity into its components as a function of scale of formation. The results provide some evidence that it is the components of formation nonuniformity in the range of larger scale of formation, 8 to 37 mm, which most affect moisture local nonuniformity while the formation components at 0.8 to 3 mm scale of formation appear less important. Such knowledge is relevant to the development of the improved drying processes of the future.

INTRODUCTION

Although for dry paper the local nonuniformity of the sheet, including its local thickness, grammage and porosity, has long been of interest, the local nonuniformity of moisture content for moist paper as it goes from wet to dry in a dryer has received little study because of the difficulty in making such measurements. Such moisture nonuniformity is of fundamental interest for understanding moist sheet structure. Recently, moisture nonuniformity has become of considerable practical interest because of the current focus on new designs of paper dryers to overcome the machine speed bottleneck at the dryer section through introduction of various high intensity air convection drying techniques [1–4]. Relative to the current standard practice of cylinder drying, the higher intensity drying conditions of air drying increases the magnitude of moisture local nonuniformity. Air drying makes major changes in the evolution of the moisture content history of the sheet as it goes from wet to dry, which in turn can affect product quality. There are two basic kinds of air drying, distinguished by the type of air – sheet contacting. In one contacting technique, impingement drying, the moist sheet passes under an impingement flow field from a multiple array of air jet nozzles. Alternatively, in through air drying of a wet, permeable web the moisture removal is obtained by drawing hot unsaturated air through the permeable web. In the latter case the exceptionally good air-fibre contacting can give order of magnitude higher drying rates than the cylinder drying process universally used now for printing and heavier grades of paper. As moisture local nonuniformity during air drying is affected by the formation nonuniformity of the sheet, the present study develops a technique for tracking the moisture local nonuniformity and uses this method to investigate its relation to the formation nonuniformity.

PAPER STRUCTURE – LOCAL MOISTURE NONUNIFORMITY EVOLUTION

The local nonuniformity of moisture content of paper while being dried is driven by the local nonuniformity of formation of the sheet. One expression of formation nonuniformity is given by the distribution of local grammage, the measurement of which depends on the fineness of resolution of the measurement. In their work on characterizing the formation of paper Cresson and Luner [5] provided the local grammage distribution of kraft handsheets of various formation quality. Due to the expense and slowness of obtaining maps of local grammage by radiographic techniques, the widely used practical alternative is to obtain the approximate equivalent of local opacity maps by light transmission image analysis. Although local opacity can be calibrated to local grammage, in common practice this is not done. Figure 1 shows the local grammage distribution of a standard kraft handsheet produced with such a calibration using the image analysis facility described in [6].

Robertson [7] pointed out that local uniformity of paper applies not only to grammage but also to thickness, porosity and density, and thereby to local permeability. A sample illustration of these local nonuniformities is given by the scanning electron micrograph of a cross section of newsprint, Figure 2.

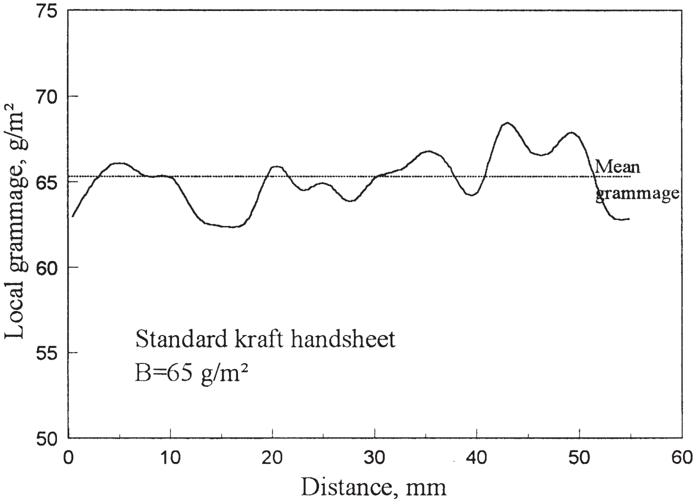

Figure 1 Local grammage distribution.

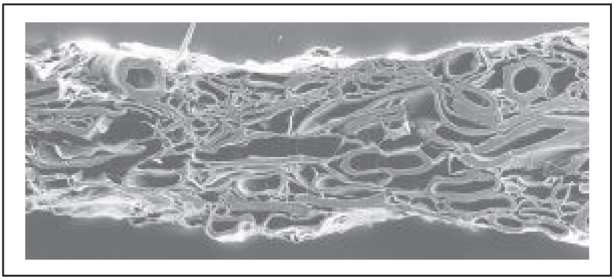

Figure 2 SEM cross section of TMP paper.

Although local grammage of fibres is only one component of the local nonuniformity of paper structure, it is more easily measured than the distribution of local porosity, density or permeability and, moreover, is a dominant factor which can be used to indicate the degree of nonuniformity. Local grammage nonuniformity results from the paper having flocs separated by the interfloc regions, originating at the moment the sheet is formed from a suspension having regions of flocculated fibres. With this local nonuniformity of the distribution of fibres, a moist sheet has also a locally nonuniform moisture content. As a sheet goes from wet to dry in any drying process this initial local moisture nonuniformity will evolve, possibly being amplified and passing through a maximum moisture nonuniformity, en route to the dry sheet condition.

The present study focuses on the evolution of local moisture nonuniformity in moist paper from wet to dry, including the extent to which moisture nonuniformity is affected by formation nonuniformity and other parameters.

EXPERIMENTAL

Measurement strategy

A general technique for monitoring the evolution of local moisture nonuniformity of a moist sheet during drying is to determine the local moisture content profile of partially dried paper. A shortcoming of this technique with interrupted drying is that it does not document the evolution of local moisture nonuniformity continuously during the drying. Knowing how nonuniformity evolves during drying could provide insight into the mechanisms of this phenomenon and thus how it could be minimized. As it is difficult to measure local moisture content continuously during drying, a feasible alternative is to monitor continuously the local exit pore air temperature immediately below a sheet subjected to air through flow. As long as there is any water present in the pores, such sampling of the temperature of the air in the pores of the sheet is not affected by local moisture content. Once there is no pore water, so that all remaining water is in the moist fibres, the temperature of the air in the pores is sensitively dependent on the sheet local moisture content. It is during the period of drying when the fibres are below the fibre saturation point moisture content that drying rate is mostly determined and that paper properties are entirely determined. Therefore the fact that the method of sampling the nonuniformity of the temperature of the local pore air exiting a sheet subjected to air through flow is applicable only below the fibre saturation point condition means that this method relates to the most important moisture region during drying.

Description of experimental technique

For monitoring the evolution of local exit pore air temperature from wet to dry with air through flow the equipment used is a modification of that described by Hashemi et al. [8]. Sheet average moisture content was calculated indirectly by monitoring continuously the humidity of the air exiting the sheet with a fast response IR air humidity analyzer. That facility was modified by the addition of a network of very small thermocouples located in the air flow immediately below the sheet.

Local temperature measurement could be very precise with the appropriate choice of size and type of sensor. Local exit air temperatures on the through flow exit side of the sheet were monitored by placing immediately beneath the sheet an assembly of 16 E-type thermocouples, 0.125 mm diameter, each supported inside the 150–300 mm long stainless steel sheath of 0.25 mm diameter, Figure 3. This number of thermocouples is more than adequate to provide statistically significant information on the variability of local exit pore air temperature. As this thermocouple assembly must be very close to the sheet to ensure that the air temperature measured is that exiting the sheet prior to any lateral mixing, and as these delicate thermocouples must remain at precisely fixed locations, a special sheet holder and insertion-retraction plate were needed. The sheet holder sits in the insertion-retraction plate and the thermocouples pass through its base and middle ring layers. In this way each thermocouple is positioned to remain at the center of a cell in the honeycomb support of the sheet. The 16 thermocouples are fixed on a light weight aluminum thermocouple holder ring which in turn is attached inside the insertion-retraction plate. The sheet holder occupies precisely the same

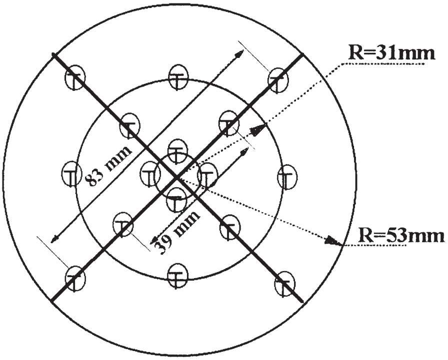

Figure 3 Thermocouple assembly.

radial position each time due to pins that fix its position on supporting plate. Precise installation of all thermocouples at 1 ± 0.1 mm below the sheet is a demanding operation.

Removing the sheet holder assembly from the dryer between each test would damage the fragile thermocouples, hence it was essential to keep the base and middle ring layers of the sheet holder, including the honeycomb sheet support, in position permanently. In this way for each experiment only the top ring layer, which has no connection with the thermocouples, need be removed to replace a dried sheet with a wet one. However the original insertion-retraction plate, described by Hashemi et al. [8], was designed to accommodate only one sheet holder which, if it must remain in the equipment between experiments, would become hot, thereby distorting the measured exit pore air temperature through being a heat source. To prevent this effect a new insertion-retraction plate was constructed with two holes the outside diameter of the sheet holder, only one which ever carries the sheet holder. During the heat-up period and between experiments the insertion-retraction plate was positioned with the sheet holder out of the dryer and the matching opening inside the dryer. The equipment with the new sheet holder and insertion-retraction plate was successfully tested against leakage.

A PAP-611 data acquisition board developed at the Pulp and Paper Research Institute of Canada was used along with very accurate thermocouple amplifiers and a precision adjustable cold junction compensator, quite sensitive to any change in data acquisition terminal panel temperature. The raw data obtained by the data acquisition software were later processed with a spreadsheet processing file written using macro commands in Quatro Pro and Fortran.

Thermocouple assembly specifications

Accuracy and time constant are important in the choice of thermocouples. According to NIST Monograph 175, Bruns and Strouse [9], the E-type thermocouple (Nickel-Chromium alloy versus Copper-Nickel alloy) has the highest Seebeck coefficient of types of thermocouples in our temperature range. Thermocouple response time is a direct function of its bead size. According to the manufacturer, for a 0.25 mm bead unsheathed E-type thermocouple the response time to a step function of 800°C for reaching to 95% of the true value is 0.05s in still air and 0.004s in air flowing at 20 m/s.

For the present purpose the appropriate size of thermocouple must be larger than the biggest pores for air flow through the sheet. Corte [10] gave the range of pore size distribution of dry paper as 1–100 μm. Polat et al. [11] established that with an air through flow the bigger pores are opened to the flow of air at the beginning of drying while smaller pores start to contribute progressively as the sheet moisture content decreases. For 60 g/m^2 handsheets from unbeaten, unfilled kraft pulp they showed that at a moisture content of 1.5 kg/kg dry, the effective pore size for air flow was about 15 μm, 0.015mm. Thus a thermocouple inside a 0.25 mm O.D. sheath is about 15 times the size of the biggest pores from which the air flow exits.

Another constraint on the size of thermocouple derives from the key importance of sheet formation on local moisture nonuniformity. It is generally agreed that the scale of local grammage nonuniformity which is considered formation extends from 0.5 mm to several centimeters. As a thermocouple inside a 0.25 mm diameter sheath is then half the size of the lower limit of formation nonuniformity, this pore air temperature sensor is sufficiently small to respond to any effects from even the smallest scale of formation nonuniformity. As the layout of thermocouples, Figure 3, shows that the 16 thermocouples measuring the exit pore air temperature are distributed over a 83 mm circle, this design also achieves the objective of being sensitive to any effects on the evolution of local pore air nonuniformity resulting from local grammage nonuniformity at the upper limit that is considered formation, i.e., several centimeters.

Thus the exit pore air temperature sensing system used here is capable of determining the effect of any local grammage nonuniformity over the range of scale of formation from 0.5 mm to about 40 mm. As the through flow air exits at a linear velocity in the range 0.18–0.35 m/s for the present experiments, a 0.125 mm bead inside a 0.25 mm sheath is estimated to have a very

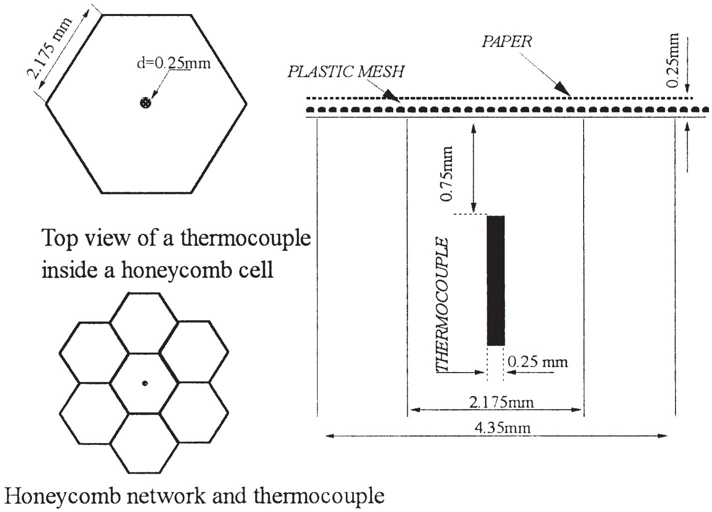

Figure 4 Thermocouple layout.

fast response time fully adequate for the shortest drying time from the onset of the falling rate period to dryness, a few seconds.

In treating exit pore air temperature as a "local" value, a basic question is: how local is local? This depends on how much radial mixing occurs in the pore air between exiting the sheet and reaching the thermocouple. Figure 4 shows the precise dimensions for a thermocouple positioned within a cell of the 5 mm thick honeycomb sheet support used. With no radial mixing the air temperature measured would correspond to that coming from an element of the sheet the size of thermocouple sheath, 0.25 mm diameter. With complete radial mixing, the measured temperature would correspond to the average air temperature from an element of the sheet the size of the honeycomb cell, about 4 mm across. For the range of flow rates and temperatures used in this study, the linear velocity of pore air exiting at the adiabatic saturation temperature is about 0.18 to 0.35 m/s. For the equivalent diameter of a honeycomb cell, the corresponding Reynolds numbers are in the range 48 to 93. As the flow exits the sheet as a plug flow and starts transition to a very low Reynolds number laminar flow, it is evident that the amount of radial mixing will be negligible while advancing only 1 mm (the paper-to-thermocouple spacing) in a honeycomb cell of hydraulic diameter about 4 mm. This analysis indicates that the exit pore air temperatures obtained here correspond to those from a region of the sheet of diameter only slightly greater than 0.25 mm, and are therefore indeed quite local.

Performance tests

A performance check of the thermocouples at various inlet air temperatures and flow rates was performed in order to assure the desired accuracy of ±0.5°C. One of the thermocouples was rendered inoperative during the small adjustments in positioning and was not replaced due to the long procedure required. Thus this assembly monitored the exit air temperature immediately below the sheet at 15 lateral positions.

A different type of test of the technique was made by drying a sheet of highly uniform structure with an air through flow. For this test fiberglass filter paper was used and the local exit pore air temperatures monitored. For better clarity Figure 5 shows the output of only 5 of the 15 thermocouples. For a sheet of such uniform structure the local exit pore air temperatures are seen to diverge very little during the important latter part of the drying, the variation between thermocouple readings being only about ±0.5°C. This graph establishes that the large differences in local exit pore air temperature

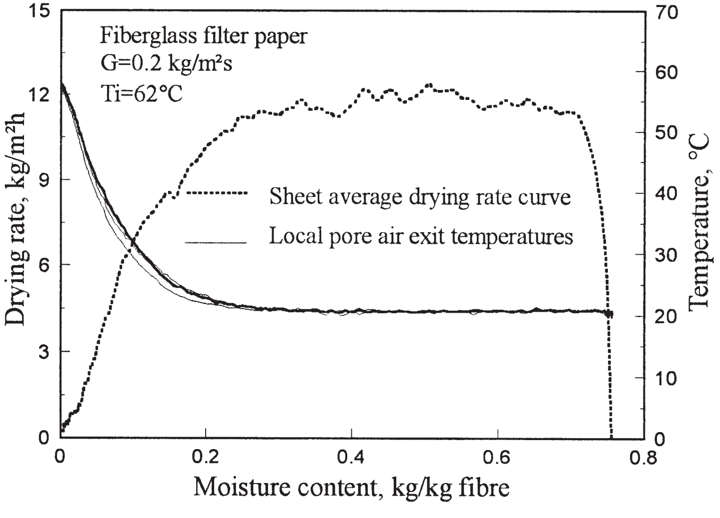

Figure 5 Local pore air exit temperature for a uniform sheet.

subsequently measured are directly related to nonuniformity in sheet structure, not to the accuracy of temperature measurement.

RESULTS

Demonstration results

A typical result for a kraft handsheet, Figure 6, shows the profiles of local exhaust air temperature at 15 lateral positions as well as the sheet average drying rate curve, both as a function of sheet average moisture content. Within the accuracy of the thermocouples there is at first negligible divergence of local pore air exit temperatures while there is still water in the pores above the fibre saturation point moisture content. During this time the paper assumes the adiabatic saturation temperature, 23°C in this case, and the air in the pores cools to approach that temperature as it flows through the pores of this packed bed of wet fibres. All subsequent measurements also showed this behavior. Local pore air exit temperatures begin to increase when water is no longer present in the pores of the small element of paper just above that particular thermocouple. Thus on Figure 6 the dispersion of local pore air exit temperature is seen to increase to a maximum, then subsequently

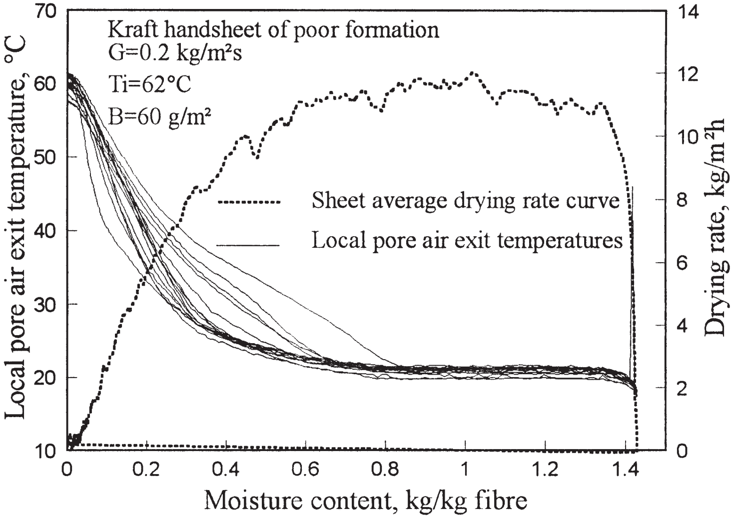

Figure 6 Local pore air exit temperature profiles and drying rate curve.

decrease to a very low level as the sheet approaches dryness. Such a probing of local pore air temperatures, not easy to determine, has not previously been reported.

The standard deviation and coefficient of variation of local pore air exit temperature were introduced as the dimensional and nondimensional indices of nonuniformity, to reflect quantitatively this nonuniformity for the moist sheet. The development and decay of local nonuniformity in a moist sheet during drying is indicated here by plots showing the dispersion of T_e as a function of sheet moisture content, such as Figure 7. For examining the effects of parameters however, it is useful to have a single index of local nonuniformity, for which the coefficient of variation of T_e at a particular value of moisture content X is used. Examination of the development and decay of σ_{Te}, the standard deviation of T_e, indicated that 0.4 kg/kg fibre is an appropriate value of sheet average moisture content at which to calculate the coefficient of variation for T_e. By this point in the drying, the local nonuniformity has developed substantially, but has not yet started to decay. The coefficient of variation of T_e at the chosen value of moisture content is denoted the "index of moisture nonuniformity", $I_{MNU.}$This index of pore air temperature nonuniformity, reflecting local moisture content nonuniformity, corresponds exactly to the definition of formation number – the coefficient of variation of local grammage of fibres. The distribution of local pore air exit temperatures is shown as the 4σ value of this dispersion, thus indicating

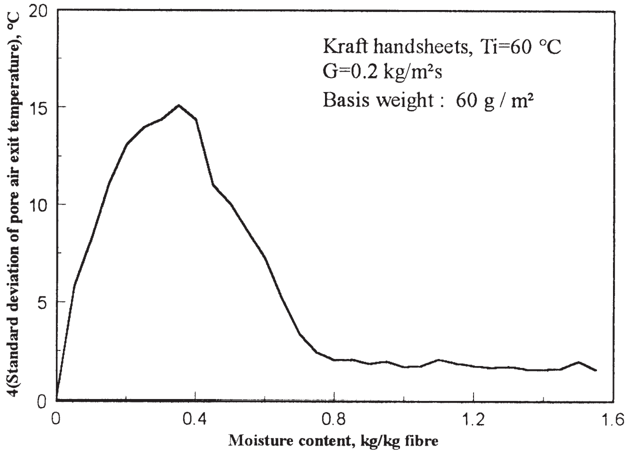

Figure 7 Dispersion in local pore air exit temperature.

the substantial ±2σ range of T_e. This form of representation of local nonuniformity is for convenience referred to here as the "4σ curve".

Effect of paper basis weight

While the formation of all paper webs is nonuniform, this degree of nonuniformity becomes progressively less for thicker paper because of the greater opportunity for compensation in the sheet thickness direction between locally nonuniform regions. However at the other extreme, when paper grammage is so low that the sheet structure no longer corresponds to a thin packed bed but approaches that of a screen, the nonuniformity in local moisture content and pore air temperature should also decrease.

Figure 8 provides quantitative verification of these expectations. The index of moisture nonuniformity, I_{MNU}, decreases with any change in basis weight around a maximum I_{MNU} value which occurs at a basis weight of about 40 g/m^2. The decrease in I_{MNU} for higher paper basis weight results from the lower nonuniformity of thicker sheets, as noted above, while the I_{MNU} decrease for lower grammage derives from the sheet structure changing from a thin packed bed towards that of a screen. On both sides of the maximum value of I_{MNU} the decreases are seen on Figure 8 to be large, indicating a high sensitivity to sheet grammage for pore air and moisture local nonuniformity.

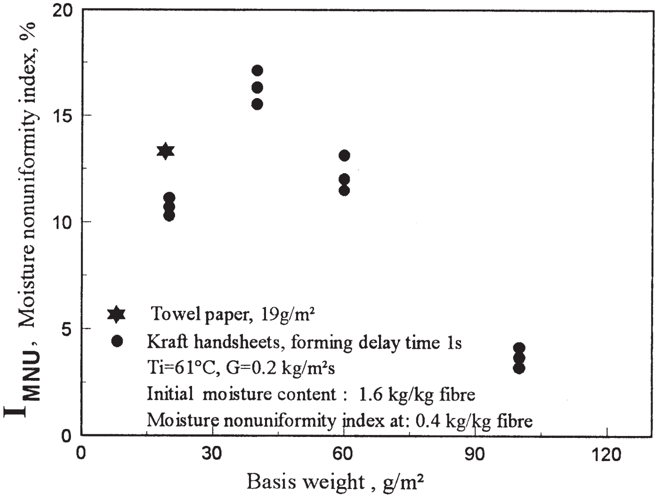

Figure 8 Effect of paper basis weight.

The lower pore air-moisture nonuniformity for the lightest weight non-standard handsheets is found also for the case of machine-formed towel paper of 19 g/m^2 basis weight. Comparing on Figure 8 the local nonuniformity for papermachine towel paper with that for handsheets of the same basis weight shows that in this case also the generally greater nonuniformity of structure for paper machine formation applies.

Effect of formation: variable handsheet forming

With the complexity of the distribution of fibres in the aqueous suspension and of the process by which the sheet is produced from this suspension, nonuniformity of structure is a fundamental characteristic of paper. The effect of formation on nonuniformity of local pore air temperature and hence on local moisture content was studied using handsheets of different quality of formation obtained with the well known technique of varying the delay time before the fibre suspension is released to form the handsheet. The minimal delay time, t_d of 1s, produces a sheet of better formation than that from a paper machine, the quality of formation decreasing as the time for fibre flocculation is increased. For sheets made using 1, 10 and 100s delay time Table 1 documents the I_{MNU} values calculated at $X = 0.4$ kg/kg, while Figure 9 shows the 4σ-X curves of the dispersion of local exit pore air temperature for handsheets of various quality of formation dried similarly from an initial moisture content of about 1.6 kg/kg fibre. There is little difference in the local exit pore air temperature nonuniformity for the sheets of 1s and 10s delay time but the large effect of the degradation of formation quality with a 100s delay time is apparent on Figure 9.

As quality of sheet formation drops, drying time increases. Thus a direct consequence of the increased local nonuniformity of pore air temperature, and hence of local moisture content, is that the sheet average drying rate will

Table 1 Effect of formation on local moisture nonuniformity index.

$T_{inlet} = 62°C$, $G = 0.2$ kg/m^{2}s, $R_c = 11.2$ kg/m^{2}h

Delay time, s	Initial moisture content, kg/kg	I_{MNU}, %
1	1.60	13.1
10	1.66	13.0
100	1.58	18.2

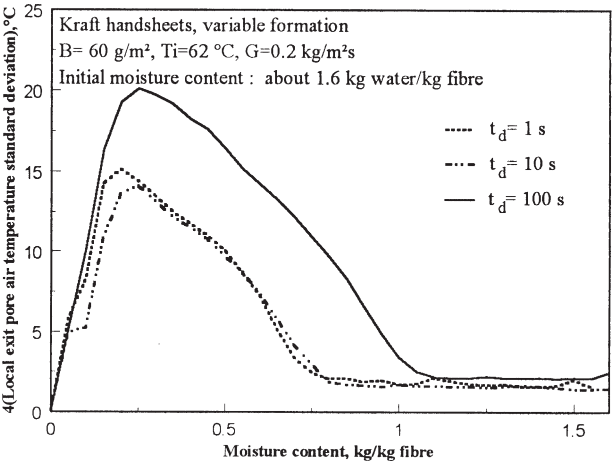

Figure 9 Effect of formation on local nonuniformity.

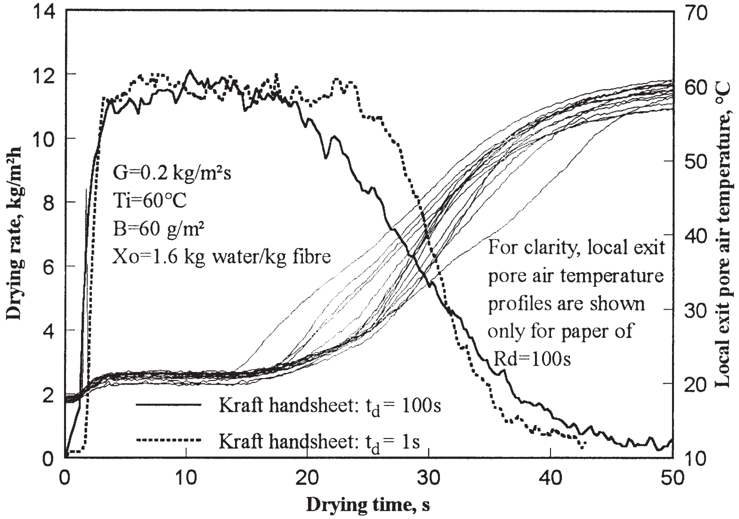

Figure 10 Effect of formation on local nonuniformity, drying rate and drying time.

start to drop earlier. This occurs because of regions of the sheet having a locally lower moisture content as evidenced by the pore air temperature starting to rise earlier in such regions. These effects are documented quantitatively in Figure 10, which shows that for about the first 13s of drying the drying rates are identical for the handsheet made with 1s and 100s delay time. With the 100s delay time handsheet, Figure 10 documents that at the moment the first one of the 15 values of local exit pore air temperature starts to rise, which is seen to occur after about 13s of drying, the sheet average drying rate immediately starts to drop significantly from the constant rate drying value. Thus with the poor formation sheet for 100s delay time, local elements of the sheet with low grammage begin entering the falling rate period after only 13s of drying. By contrast, the drying rate curve on Figure 10 shows that the good quality sheet (1s delay time) remains at the constant drying rate for about twice as long, until about 26s of drying time. Also, to reach a moisture content of 0.05 kg/kg fibre the poor quality sheet requires 21% longer drying time (52s vs. 41s). Thus Figure 10 clearly demonstrates the sensitive connection between sheet average drying time, formation quality, and local nonuniformity of sheet moisture content as indicated by nonuniform local pore air temperature.

Characterizing paper formation

Although the technique of varying the delay time in forming handsheets is an accepted experimental technique of varying the quality of laboratory made paper, a general method of determing paper formation is required. If the distribution of fibres in a sheet of paper were random the local grammage would be described by a Poisson distribution, but the process of forming the sheet leads to deviation from such a distribution. The only widely accepted expression for formation has been the coefficient of variation of local grammage, “formation number”, or the equivalent for local opacity. The considerable variety of formation test instruments which have been in use for some time each give different measures of some simplified aspect of formation nonuniformity, generally as a single-number index of formation. These commercial instruments are incapable of reflecting the complexity of sheet structure, in particular, how the local nonuniformity of grammage is distributed across the sheet. Such test instruments give, on inconsistent and arbitrary scales, propriety formation indices which do not reflect the complexity of formation.

Bernié and Douglas recently reported a new technique for characterizing paper formation in which the local nonuniformity of formation is partitioned into its components as a function of scale of formation. In an extensive series of publications, from Bernié and Douglas [12] to [13], they have demonstrated the utility of this way of describing formation relative to effects from papermaking parameters and effects on paper properties. These formation components are the intensities of formation nonuniformity, determined as a function of the scale of formation over the range from tenths of millimeter to several centimeters. Typically 10 components are determined, i.e. at 10 values of scale of formation. Such a set of values of intensity of formation nonuniformity as a function of discrete values of scale of formation, reported as a line, constitutes a *Paper Formation Line*. As formation of a sheet is typically compared to that of a reference sheet, this is done quantitatively in this method by presenting the results as the ratio of the intensity of local nonuniformity of the test sheet relative to that, at the same scale of formation, for an appropriate reference sheet. Each value on a Paper Formation Line is one component of formation nonuniformity. Each such value is the formation nonuniformity component at that value of scale of formation. As no arbitrary or proprietary factors need be used at any stage in the rigorous processing of intensity of formation nonuniformity, these components constitute a fundamental yet easily understood description of the spatial distribution of formation nonuniformity.

Effect of formation: components of formation

The empirical treatment of effect of formation quality provided in the earlier section can now be made quantitative through use of the "components of formation – scale of formation" method. As Figures 9 and 10 recorded the effect that varying the formation quality of 60 g/m^2 handsheets has on local nonuniformity and drying rate, Figure 11 provides the Paper Formation Lines of these sheets. The formation nonuniformity components of these handsheets are expressed on Figure 11 relative to the standard handsheet made with 1s delay time. These Paper Formation Lines show that the increase in delay time from 1s to 10s increases the intensity of formation nonuniformity only moderately. By contrast, further increase in forming delay time to 100s increases the formation nonuniformity intensity substantially, to about double at scale of formation 8 mm, and to between 3 and 4 times higher nonuniformity over scale of formation 14 to 37 mm.

It has long been realized qualitatively that increasing handsheet forming delay time increases the large flocs in sheet structure. Now the method of partitioning formation nonuniformity relative to scale of formation shows this effect quantitatively. Moreover, the partitioning of formation shows that increasing forming delay time has relatively little effect on nonuniformity at small scale of formation, over the 0.8–3 mm range. Thus although increasing

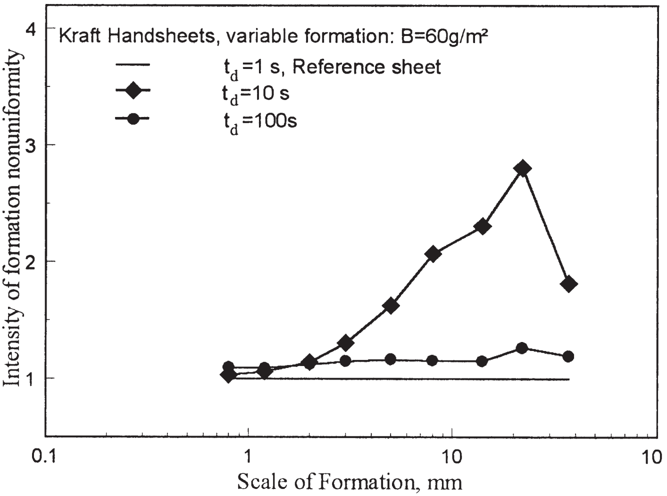

Figure 11 Formation components for Kraft handsheets of variable formation.

handsheet forming delay time decreases the quality of formation, it is a poor technique in that it decreases formation very selectively, leaving formation nonuniformity in the small scale region changed only slightly relative to the changes produced over the large scale of formation range.

Returning to the effect on local nonuniformity and drying rate recorded on Figures 9 and 10, it would appear now from Figure 11 that these changes are probably produced primarily by the components of formation in the large scale of formation range, 8–37 mm, simply because these increases for the handsheet formed with 100s delay time are so much greater than those over the small scale range of 0.8–3 mm. However, strictly speaking, to come to a definite conclusion it would be necessary to use additional techniques of varying the quality of formation which permitted changing the formation nonuniformity selectively with respect to scale of formation.

Interpretation of factors controlling local nonuniformity

With the recent availability of the components of formation method of characterizing paper formation it is now possible to integrate the effect of formation with the effect of local nonuniformity of pore air temperature – local moisture content, for a variety of paper types, both handsheets and machine

Table 2 Specifications and moisture nonuniformity index of papers tested.

	$T_{inlet} = 62°C$, $G = 0.2\ kg/m^2s$		
Paper Type	Grammage g/m^2	Initial moisture content, kg/kg	I_{MNU}, %
Towel paper	19	3.07	13.3
Handsheet	20	2.70	13.7
Sack paper, S1	46.7	1.59	10.3
Sack paper, S2	54.7	1.65	12.8
Kraft Handsheet, $t_d = 1s$	60	1.60	13.1
Kraft Handsheet, $t_d = 10s$	60	1.66	13.0
Kraft Handsheet, $t_d = 100s$	60	1.58	18.2

formed. Thus the experimental program was extended to include two commercial sack papers of about 50 g/m^2 basis weight. These sack papers were made from a pure kraft furnish. Table 2 lists the key parameters for all types of paper for which local moisture nonuniformity was investigated by the continuous monitoring of local exit pore air temperature.

Figure 12 shows the Paper Formation Line of just the commercial towel paper, expressed relative to a special 20 g/m^2 handsheet made with a forming time to give approximately the same formation quality as the machine-formed towel paper. The Figure 12 results show that the objective of about the same formation quality was achieved, in that the formation nonuniformity of these two sheets is the same over the regions 0.8–1.2, and 14–22 mm scale of formation, while the towel paper is of higher formation nonuniformity over the 2–11 mm range of scale but has lower nonuniformity (better formation) at 37 mm scale of formation. Any of the numerous formation test instruments giving a single-number index of formation would indicate that the towel paper was either of better or worse quality formation than this 20 g/m^2 handsheet. In either case such instruments would give an incorrect answer because the reality is that the towel paper has both better and worse formation than this handsheet, depending on which scale of formation is of interest. Table 2 shows that the values of index of moisture nonuniformity, I_{MNU}, of these two sheets are essentially the same within measurement accuracy (13.3% and 13.7%). Therefore the effect of the various formation nonuniformity differences in the opposite direction evidently cancel the corresponding effects on moisture nonuniformity.

Figure 13 shows the formation components comprising the Paper Formation Lines for all sheets tested, with the exception of the 60 g/m^2 handsheet

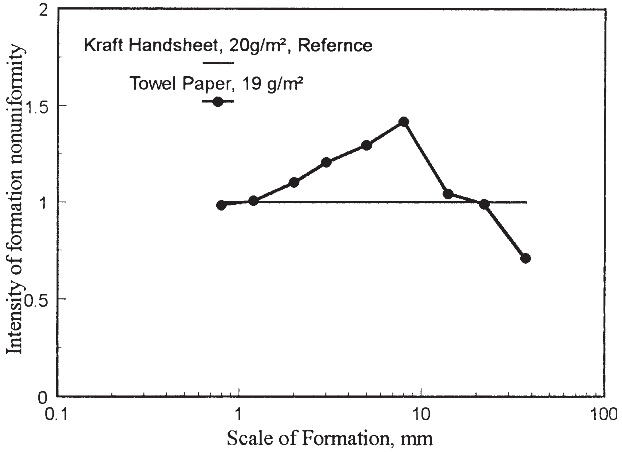

Figure 12 Formation components of towel paper relative to a Kraft handsheet.

with 10s delay time. These results were omitted because on the scale of Figure 13 this sheet would not appear distinguishably different from the standard handsheet at 1s delay time, the sheet used as the reference for expressing the intensity of formation nonuniformity. The Paper Formation Lines for towel paper are different on Figures 12 and 13 because of the different reference sheets used, but the same comparison of formation between these two light weight sheets is seen on both figures.

With respect to the nature of the difference in formation between the two commercial sack papers it is interesting to note on Figure 13 that these two Paper Formation Lines cross, as occurred also for the two light weight sheets on Figure 12. Thus again it is impossible to state that the formation of one sack paper is better than the other. In fact sack paper S2 is better (lower formation nonuniformity) from 0.8 to 3 mm scale of formation, while from 5 to 37 mm scale it is sack paper S1 which has the better formation. This reality is revealed by the partitioning of formation nonuniformity relative to scale of formation.

It was noted earlier that Figures 9, 10 and 11 provided some indication, without conclusive proof, that the moisture local nonuniformity was influenced primarily by the components of formation in the large scale of formation range. Figure 13 provides further such evidence, still inconclusive, that the large scale components of formation nonuniformity are more important in determining moisture local nonuniformity. This observation derives from

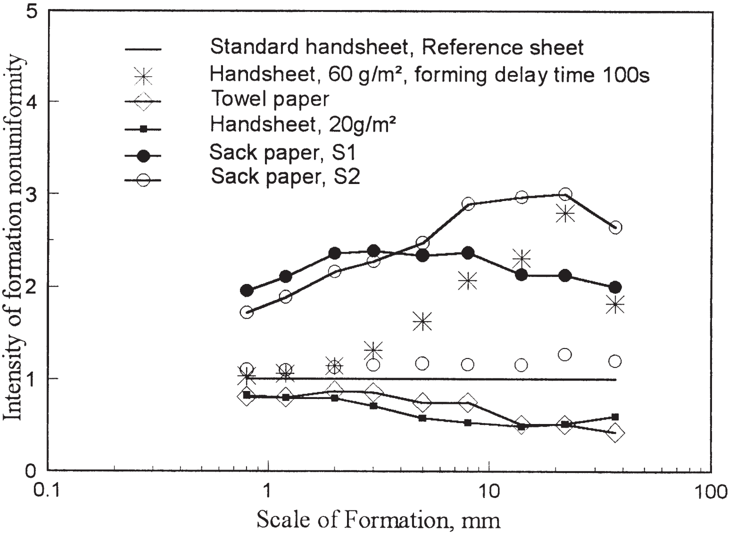

Figure 13 Formation components of handsheets and machine-formed paper.

two pieces of evidence on Figure 13. In Table 2 the moisture nonuniformity index value for the $t_d = 100s$ handsheet is much larger (more moisture nonuniformity) than for the $t_d = 1s$ handsheet, while Figure 13 shows that the formation nonuniformity for these two sheets is similar over the small scale of formation range but is much worse for the $t_d = 100s$ handsheet for the large scale of formation range. These results show that formation nonuniformity over the larger range of scale of formation certainly affects moisture nonuniformity. It is not possible to conclude from these results whether the smaller range of scale of formation affects moisture nonuniformity because in this range there is not sufficient difference between handsheets made with 1s and 100s delay time.

The second piece of evidence comes from comparing the formation nonuniformity and the moisture nonuniformity index for the two sack papers. Figure 13 shows that relative to sack paper 1, sack paper 2 has better formation (lower formation nonuniformity) at smaller scale of formation but poorer formation at larger scale of formation. As the I_{MNU} values of Table 2 show moisture nonuniformity for sack paper 2, again the evidence points to the large scale of formation range as being more important for moisture local nonuniformity.

With the various evidence identified above that it is formation nonuniform-

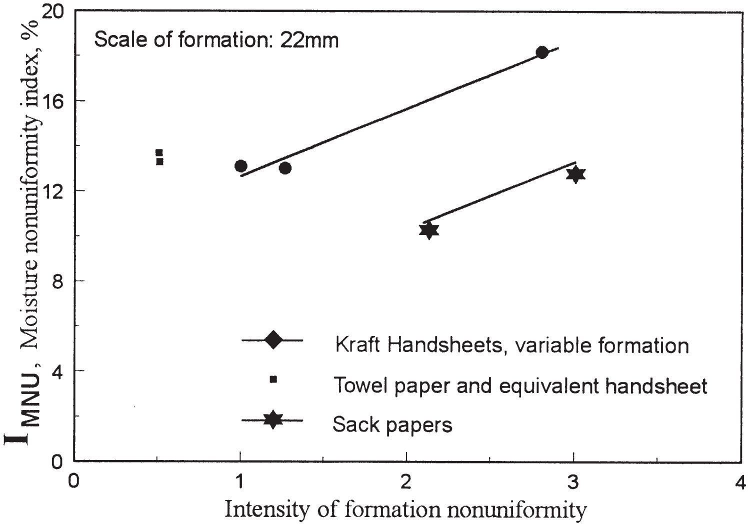

Figure 14 Moisture nonuniformity index and formation nonuniformity at 22 mm scale of formation.

ity over the larger range of scale of formation which appears to affect moisture nonuniformity most sensitively, Figure 14 shows the moisture nonuniformity index values from Table 2 relative to formation nonuniformity at a scale of 22 mm. For variation in the 22 mm components of formation nonuniformity Figure 14 indicates that with both handsheets and commercial sack paper, the moisture nonuniformity increases (gets worse) as formation nonuniformity increases (gets worse). The relation indicated by Figure 14 is plausible, but not definitively proven. It must again be emphasized that to determine the formation – moisture nonuniformity relation conclusively, this study would need to be extended to a considerably greater number of sheets, representing a wide diversity in type of formation quality.

In closing it should be appreciated that the moisture local nonuniformity of moist paper while being dried is a complex issue, more difficult yet than the various nonuniformities which characterize the much more easily measured dry paper – its local thickness, grammage, porosity for example. The present study has used the approximation of tracking local pore air temperature as indicative of local moisture content. Also, the single-number index of local nonuniformity used, I_{MNU}, is a further approximation, taken at a single value of sheet average moisture content. This single-number index is used to represent the complete record, from wet to dry, of the dispersion of local pore air temperatures that are reported here in Figure 9 for some sample cases. Moreover the extent of moisture local nonuniformity is dependent on numerous parameters, including basis weight, the initial moisture content and such furnish dependent variables as fibre saturation point. Although the various approximations necessary in this initial study of moisture local nonuniformity certainly leave some uncertainties, the novel experimental technique developed here has revealed several aspects of the interrelationships between the variables for moist paper as it goes from wet to dry.

SUMMARY

A measurement technique was developed to track the evolution of local moisture nonuniformity continuously in moist paper as it goes from wet to dry. With the difficulty of making such measurement this has not been done previously. As direct local moisture content measurement cannot be made continuously during drying, the indirect method used was to monitor local pore air exit temperatures at 15 locations over an 83 mm diameter sheet subjected to drying under a mild air through flow, using precision thermocouples in a 0.25 mm diameter sheath. This geometry assured that if local moisture nonuniformity is affected by formation nonuniformity in any range of scale of formation from sub-millimeter to several centimeters, such effects would be sensed.

The technique permitted precise monitoring of the development and decay of local nonuniformity. As a simplified index of local nonuniformity, I_{MNU}, the coefficient of variation of local pore air exit temperature at a sheet average moisture content of 0.4 kg/kg dry was used. Measurements with sheets from about 20 to 100 g/m^2 established that local moisture nonuniformity is very sensitive to basis weight, with a maximum in I_{MNU} at about 40 g/m^2. Moisture nonuniformity decreases sharply for either higher and lower grammage as the sheet approaches either a thick packed bed or a screen. Local moisture nonuniformity was shown to lead to significantly increased drying time, an undesirable process characteristic.

The effect of quality of formation on local moisture nonuniformity was investigated through the use of both handsheet and machine-formed paper of variable formation. Formation was determined using the new "components of formation-scale of formation" method, which proved very revealing concerning the nature of formation differences. For the effect of formation nonuniformity on moisture nonuniformity, it is clear that poorer formation is associated with worse moisture nonuniformity. The results were consistent with the hypothesis that moisture nonuniformity is more sensitive to formation nonuniformity in the 8 to 37 mm range than in the 0.8 to 3 mm region of scale of formation. However to establish with certainty which components of formation, over which range of scale of formation, control the moisture local nonuniformity, experiments would need to be carried out with a much larger number of sheets, representing a wide diversity in type of formation quality. These uncertainties and reservations notwithstanding, the present study with a novel experimental technique has provided some unique measurements and insight concerning the local moisture nonuniformity of moist paper as it goes from wet to dry.

NOMENCLATURE

B	Basis weight, g/m^2
G	Air mass through flow rate, kg/m^{2}s
I_{MNU}	Index of moisture nonuniformity, %
R_c	Constant drying rate, kg/m^{2}h
t_d	Formation delay time, s
T_e	Pore air exit temperature, °C
T_i	Inlet drying air temperature, °C
X	Paper moisture content, kg water/kg dry fibre; X_o, initial moisture content

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Transcription of Discussion

EXPERIMENTAL TECHNIQUE FOR TRACKING THE EVOLUTION OF LOCAL MOISTURE NONUNIFORMITY IN MOIST PAPER FROM WET TO DRY

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Kari Ebeling UPM-Kymmene Corporation

Could you please comment if part of the non-uniformity is due to the re-distribution of the flow volume. You allow the floc size to increase by delaying the drainage by 200 seconds and get these very large flocs of size 22 mm and up to 35 mm. The flow in narrow channels is related to the third or fourth power of the radius. In a badly flocculated sheet the radii would increase 3–5 fold. It would mean that the flow volume through the big pores would become 500 fold, and there would be less air to go through the other places and that would contribute to the non-uniformity of thorough drying of bad formation sheet structures (self diverging).

Murray Douglas

A very detailed question, it takes me into the area of speculation, because it is not related directly to our measurements. I think Dick Kerekes would be more able to answer this question than I am, someone who knows more about fibre suspensions flow in the session that we had previously (CPJ Bennington Pages 255–287 Volume 1) that looked into the relationship between what happens in the fibre suspension flow and the consequences of that in the formation of a sheet, certainly that is not an area I work in, and I have only peripheral knowledge of it. It is clear that the structure of the sheet when you break down the formation non-uniformity into components is very clear that it is necessary in order to understand other factors as well, not only moisture non-uniformity but other factors as well. In terms of moisture non-uniformity it is clear that the largest scale floc structure does affect moisture non-uniformity, it is still an open question as to whether at the smaller scale does until we have more data. As to the relationship between the geometry of the forming section this takes me out of my expertise.

Dick Kerekes University of British Columbia

In one of your earlier graphs, you varied the formation by the different settling times. You showed that you had very good formation with 1 second, worse at 10 seconds, and then at 100 seconds it almost went back to what was the reference sheet.

Murray Douglas

It didn't go all the way back, at the highest scale of formation, the hand sheet with the 100 second retention time was not as bad at 37 mm relative to the standard hand sheet, as it was at 22 and 10 mm, but it still was very much worse than the standard hand sheet although not as bad as some of the lower.

Kit Dodson Departmen of Mathematics, UMIST

The graph is mis-labelled, and the legend on your slide is wrong.

Dick Kerekes

The reason I brought it up is because in your very next slide there is a clear difference between the index of moisture non-uniformity. You showed the 100 second one to be clearly worse and it did not coincide with the formation. I think that should be checked out.

John Peel Retired

When you relate the scale of the moisture non-uniformity to the scale of the formation, to what extent will that depend on the spacing between the sensors which is about 4 mm apart?

Murray Douglas

My first comment is that I did not relate the scale of moisture non-uniformity to the scale of formation non-uniformity – that would be a very interesting thing to do by additional work in which you then vary in a systematic way the positioning of the thermocouples under the sheet. You will then be able to associate the intensity of moisture non-uniformity with the scale of moisture non-uniformity, because I did not do that you can accuse me of inconsistency, as I say that you must absolutely do that for formation on non-uniformity, we did not do it for moisture non-uniformity. If you go back to the Figure 3 which shows the lay out of the thermocouples in fact there are half of them in the centre have spacing of roughly 4 mm between them and the ones of the outer are 10–12 mm in between. The n while impressive in one sense is certainly too small to be able to separate even if we had segregated them that is too small a number for n, in order to make that segregation. It is true that in subsequent work one can segregate the scale of moisture non-uniformity in exactly I insist that formation of non-uniformity be segregated. We can do now for formation non-uniformity but for moisture non-uniformity that will be a lot of work.

Shri Ramaswamy University of Minnesota

The evolution of moisture non-uniformity during drying which is a reflection of temperature non-uniformity should be a function of initial moisture distribution as well as basis weight distribution, how do you ensure that the initial moisture distribution is uniform despite the mass distribution being non-uniform?

Murray Douglas

The initial moisture distribution is of course not equal, even at equilibrium there is non-uniformity in moisture. In the companion study that I referred to briefly at the beginning where we used a direct measurement technique instead of the indirect measurement technique; we recorded for a moist sheet completely at equilibrium the coefficient of variation of local moisture content measured a number of times is about 3%, so it is certainly not zero but it is much smaller than the levels of non-uniformity created during the drying process.

Patrice Mangin Centre Technique du Papier

One of the factors we seem to take for granted is an exact relationship between formation and the moisture non uniformity. One might wonder where the moisture lies in the sheet structure. In your paper, you tend to assume moisture resides mainly in large flocs. However, I keep remembering former work (e.g. Page and many others) on paper drying mechanisms that would indicate that not only large flocs are giving rise to moisture nonuniformity. What about the rest of the sheet? You indicate that in the lower section you find non-uniformity at 22 mm. Have you looked at all the parts, other dimensions? Did you choose 22 mm because it was there that you find the best correlation? I am truly puzzled. I do not understand an exact relationship between the formation and moisture non-uniformity; there are plenty of other factors to take into account.

Murray Douglas

You are quite right there are plenty of other factors, I talked about only one other factor here and that was basis weight. The moisture non-uniformity occurring during drying is a very sensitive function of basis weight, a function of the furnish certainly, different types of fibres whether it is fibres with or without lignin will make a big difference. Certainly moisture non-uniformity during drying is not, I never said that it was a function of formation on non-uniformity, simply that formation on non-uniformity is one of the important variables that determines the degree of moisture non-uniformity during drying. It is just one of a number of variables but since we always face this problem in paper making research in variety of process and product properties of identifying the role of the quality of formation therefore it was one that we isolated to have a careful look at, but it is only factor influencing the non-uniformity of moisture content.