Part II - Modelling the Drying of Three-Dimensional Pulp Moulded Structures - Drying Data Obtained from Flat Panels using Virgin and Recycled Paper Fibre

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ABSTRACT

A three-dimensional structural panel, called FPL Spaceboard, was developed at the USDA Forest Products Laboratory. Spaceboard panels have been formed using a variety of fibrous materials using either a wet- or dry-forming process. Geometrically, the panel departs from the traditional two-dimensional flat panel by integrally forming an array of perpendicular ribs and face in one structure. In the literature, significant work has been conducted to model drying of two-dimensional panels, but no known work has been done on such a three-dimensional structure. In order to optimise the drying efficiency and structural performance for this new panel, there is a need to understand the complex drying process that occurs within the panel. This paper is the second of several to discuss the modeling work. The model itself will be presented in a paper to be published. In this paper, internal temperatures, thickness, moisture content, drying rates, and mechanical properties as a function of time are presented for hardboard-like flat panels made from recycled and virgin paper fibre. The flat panel data will be used to help verify the more complex three-dimensional drying model being developed. The experimental conditions in this study are the same as used for the experimental drying of Spaceboard.

Keywords: hardboard, paper fibres, modelling, drying, recycling

INTRODUCTION

Moulded pulp structures are special woodfibre composites made from virgin or recycled fibres bonded naturally or with a minimal amount of binders. One such structure, called FPL Spaceboard (Setterholm, 1985), was developed at the USDA, Forest Products Laboratory (FPL). The basic structure for FPL Spaceboard can be described as an integrally formed three-dimensional structure having one flat (smooth) side and a structural rib pattern on the other side. Numerous structural panel configurations and sizes can be made using this process ranging from 0.3 mm to over 50 mm thick. Currently, FPL Spaceboard technology is being used to make 1.0 to 1.5 cm thick panels for use in office furniture (Blackman, 1998) and material handling applications (Hunt *et al.,* 1997). Spaceboard has been shown to have sufficient strength potential for use in heavier construction such as floor and roof panels (Scott & Laufenberg, 1995). In thinner configurations, it can be used in a wide range of packaging applications (Hunt & Gunderson, 1988).

Many physical processes occur simultaneously and interact during drying. The interactions include but are not limited to: heat and mass transfer, viscoelastic plastification and densification, and fibre-fibre bond development. These are all complicated by the changes in thermal conductivity, permeability of the fibrous mat, and the continual loss of water during drying. The result is complex three-dimensional drying that requires extensive experimentation and modelling to fully understand.

Part I of this modelling work (Nyist *et al.,* 1998), presented selected experimental data of internal temperatures and overall moisture contents as a function of drying time for FPL Spaceboard. Density distribution through the thickness and sonic modulus of elasticity (SMOE) across the face were presented. The complex nature of the data required that simpler drying data using the same fibres and process conditions be used to verify the computer model. In this study, we dried hardboard-like flat sheets and measured the temperatures through the thickness, thickness change, and moisture content, all as a function of time. We also measured SMOE for the dried sheets. The following data are results from this study. The complete data set will be used to develop and verify the three-dimensional computer model. The computer model will be presented in a paper to be published.

METHODS

The process and pressing conditions used as in this study were the same as used in two-sided drying of Spaceboard (Nyist *et al.,* 1998). The goal of this study was to measure the internal temperatures of a flat sheet during drying as well as to determine mechanical properties as a function of the process parameters. An additional lower drying temperature was added to provide three points on some curves to determine if there were non-linear effects during the drying process. We also included another fibre furnish, bleached kraft pulp, for comparison purposes. The following are the methods used to gather and analyse the data.

Fibre Furnish

Two fibre furnishes were used in this study. Both types are used to make paper, old corrugated containers (OCC) and bleached kraft hardwood. The OCC fibre was the same batch of fibres as was used by Nyist (Nyist *et al.,* 1998) in Part-I of this modelling series. The bleached kraft was virgin never-dried fibre made from a mixture of 80% hardwood 20% softwood mixture. The fibre freeness and length analysis data for the two furnishes are provided in Table 1.

Table 1. Fibre freeness and fibre length.

Fibre Type	Freeness (ml)	Fibre Length (mm)
Bleached Kraft Hardwood	359	1.57
Old Corrugated Containers	655	2.75

Forming and Pressing

Two types of sheets were needed for this study, a four-layer sheet and a full thickness sheet A 50 by 50 cm sheet former was used to wet-form the sheets. Inside the sheet former, dividers 10 cm high were used to section the fibre mat into four equal areas, 25 by 25-cm, as the sheets formed. A total of 107 sheets were formed. The sheets were divided into three groups for three different tests; 36 four-layer sheets used to measure internal temperatures, 36 full thickness sheets used to measure mechanical properties, and 35 full thickness sheets used to measure moisture content. The first two groups had equal numbers of sheets formed from the bleached kraft and OCC furnishes. The full thickness moisture content series had 27 sheets formed from bleached kraft and 8 formed from the OCC furnish.

The target sheet weight was 0.316 g/cm^2. The target weight for the layered sheets was one quarter of the full thickness sheets, 0.079 g/cm^2. The layered sheets were formed using 0.4 % consistency (fibre wt./(fibre wt. + water wt.)) at 20 cm forming height. The lower consistency used improved sheet formation. For the full thickness sheets, a consistency of 1.0 % at 30 cm water height was used for the bleached fibres and 0.8 % for the OCC. Again the lower consistency improved sheet formation with the long fibre OCC furnish.

After forming, the 50 by 50-cm divided sheet was wet-pressed to remove excess free water. A screen, the same as used for the bottom, was placed on top of the sheet. The package was transferred to a hydraulic press. Because both fibre types have low freeness, the wet-press closure rate was decreased to ensure that internal hydraulic water pressure did not destroy the sheet The closure rate for the thinner layered sheets was 2.1 cm/min and decreased further to 1.1 cm/min for the thicker sheets. The sheets were pressed at 4,500 kPa for 30 seconds to dewater the sheets. The four 25 by 25 cm sheets were then stored for later use in testing.

Drying

To obtain the internal sheet temperatures during drying, nine pressing conditions were used for this study, three pressures and three temperatures, Table 2. These variables (except for 120°C) were the same as used for the two-sided drying study of FPL Spaceboard (Nyist *et al.*, 1998). Two replicates at each of the 9 conditions were used.

Four individual layers were assembled as shown in Figure 1 to produce a layered sheet Thermocouples were place on top, between each of the layers and the bottom. Temperatures at the 5 locations, hydraulic pressure, and thickness data were collected at intervals of 0.5 seconds for the first 90 seconds, at intervals of 1.0 second for the next 90 seconds, and at intervals of 2.0 seconds for the remaining time.

For the sheets for mechanical testing, only pressure and thickness data were measured during drying. For the fill thickness sheets used to measure moisture content vs. time, temperature (from thermocouple 1), thickness, and hydraulic pressure were measured

Sheet weight and thickness were recorded just prior to drying. This included measuring each layer used for the layered sheets. Average moisture contents and bulk fibre density (dry fibre weight/wet volume) prior to drying are listed in Table 3. Weights and thicknesses were measured as quickly as possible after being removed from the press. The sheets were then placed in an oven set at 105°C for several hours to obtain oven-dry weights and thicknesses.

Sonic Modulus

Full thickness sheets were placed in a 22°C and 50% RH conditioning room for over one and a half weeks before testing. A stress wave timer was used to measure stress wave times across the diagonals of each panel. The SMOE was calculated using the following formula

$$SMOE = (V^{2})\,(d)\,(c)\,(1/g)$$

where SMOE = sonic modulus of elasticity (GPa), V = velocity (m/s), d = density (kg/m^3), c = conversion factor (N/kg), and g = gravitational constant (m/s^2).

Table 2. Process variable matrix for pressing the fibre mats.

	Temperature		
P	300 kPa - 120°C	300 kPa - 150°C	300 kPa - 180°C
	600 kPa- 120°C	600 kPa - 150°C	600 kPa - 180°C
	900 kPa - 120°C	900 kPa - 150°C	900 kPa - 180°C

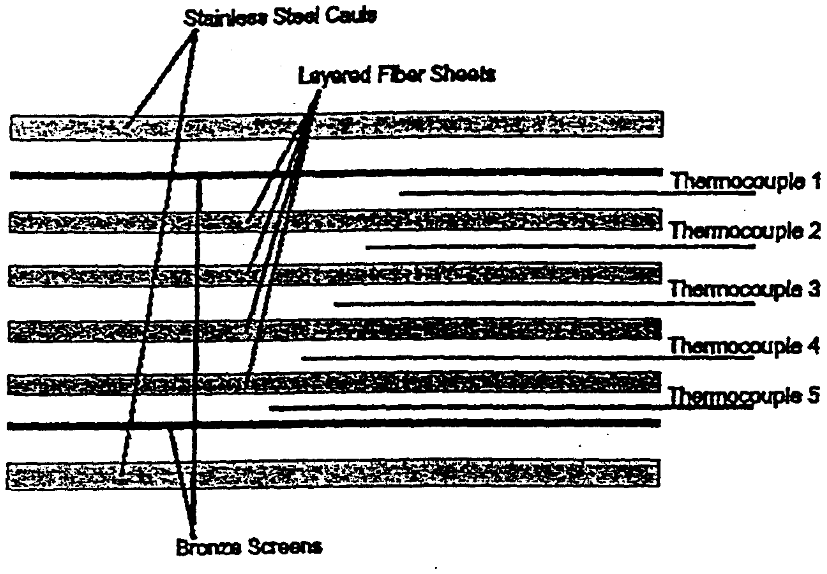


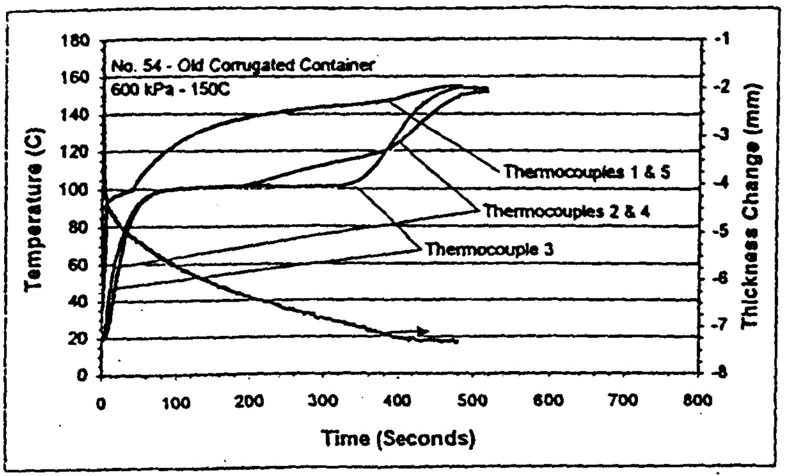
Figure 1. Four layer fibre sheet with the thermocouple arrangement for measuring temperatures during drying.

RESULTS AND DISCUSSION

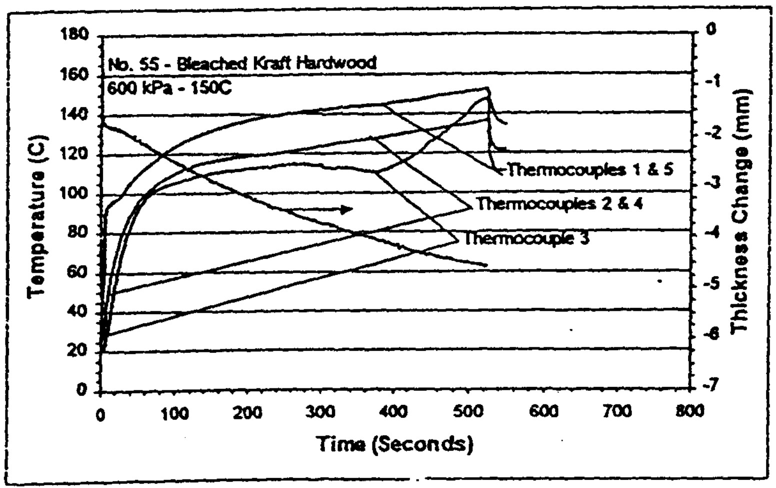
The main results from this study are the internal temperatures, moisture content, thickness, and drying rates as a function of time for the 9 drying conditions. These results will be used to test the three-dimensional computer model on a simple two-dimensional sheet. The results from the full three-dimensional model will be published at a later date. The effects on mechanical properties are also important for modelling and determining final properties of structures that experience similar processing conditions. SMOE data are presented as a function of pressing conditions.

Temperatures

Figures 2a and 2b show typical curves of temperatures from the 5 thermocouples and thickness change as a function of time. Table 3 lists average core temperatures and corresponding steam pressure for each of the pressing conditions. Core temperatures for the OCC, Figure 2a, barely increased above 100°C, whereas the bleached kraft hardwood, Figure 2b, increased significantly above 100°C. The high temperature for the bleached kraft furnish indicates a pressurised steam environment in the core, most likely caused by a lower sheet porosity that inhibits moisture from escaping. Fibre freeness, a measure of water flow, for the bleached kraft fibre is lower than OCC, Table 1. In the future, freeness may provide some correlation with moisture flow through a sheet during the drying process.



(a) Old corrugated container fibre



(b) Bleached kraft hardwood fibre

Figure 2. Temperature and thickness change as a function of time at 600 kPa pressing pressure and 150% platen temperature.

Both fibre furnishes show an increase in temperatures at the ¼ points, thermocouples 2 & 4, before the temperature in the core, thermocouple 3. For the OCC this could indicate the fibres are essentially dry. Whereas for the sheets made from bleached kraft furnish, the increase in temperatures 2 & 4 could indicate a higher pressurised steam environment. In classical drying theory, temperature rise is associated with the absence of water. For the recycled corrugate fibre, the fibre structure is porous enough to release the steam pressure generated. We see this with the near flat 100°C core temperature. AS the fibres dry from the outside-in, the dry-line reaches the ¼ points allowing the temperature to increase above 100°C. However, for the bleached kraft furnish, we believe the temperature rise at thermocouples 2 & 4 was due to a pressurised steam environment and not that the fibres are dry. The reason is that at the end of the drying cycle when the pressure was released the temperature immediately decreased indicating steam release to atmospheric pressure, Figure 2b. This did not happen with the OCC fibre, Figure 2a.

Toward the end of the drying cycle, for both fibre furnishes, an unexpected temperature profile occurred. The middle temperature, thermocouple 3, shows a decrease followed by a rapid increase above that at the ¼ thicknesses, thermocouples 2 & 4. The decrease indicates a net decrease in the energy balance for that area for a period of time. The decrease seems to begin at the same time that the temperatures at thermocouples 2 & 4 begin to increase, a net energy increase. The unexpected temperature profile is due to several interacting factors including: moisture gradient that increases toward the centre, a density gradient that decreases with increased moisture content, porosity that decreases as density increases, and heat transfer coefficient that decreases as moisture content decreases and increases as density increases.

Thickness and Moisture Content

Figure 3 shows thickness change for both fibre furnishes as a function of time at 600 kPa pressing pressure and the temperatures 120, 150, and 180°C. Initially these curves were intended to provide information on density as a function of time. However, after reviewing these graphs we saw the significant differences between the two fibre types and process conditions and wanted to determine if these graphs might also be useful to correlate with moisture content as a function of time. Total thickness change was greater for OCC as shown in Figure 3. The reason thickness change is greater for OCC is that the average fibre length, Table 1, for OCC is longer and forms a thicker sheet, as is evident with bulk fibre density, Table 3. The final thicknesses for the sheets made from bleached kraft furnish were thinner and had higher density than for those made from OCC furnish, Table 4.

We measured moisture content and thickness as a function of time at two press conditions, 300 kPa - 150°C and 600 kPa - 150°C, and found excellent correlation. Figure 4 shows the percentage residual water (100 x residual water/initial water) and thickness as a function of time for both OCC and bleached kraft hardwood at the second press condition. The residual water scale was linearly correlated with thickness (thickness change = 0.0135 x (residual water) - 5.9). We will use the thickness data in the computer model for both density and moisture loss as a function time. If we know moisture loss as a function of time (drying rate) then we can use this information together with internal temperatures to help calculate the energy balance as a function of time.

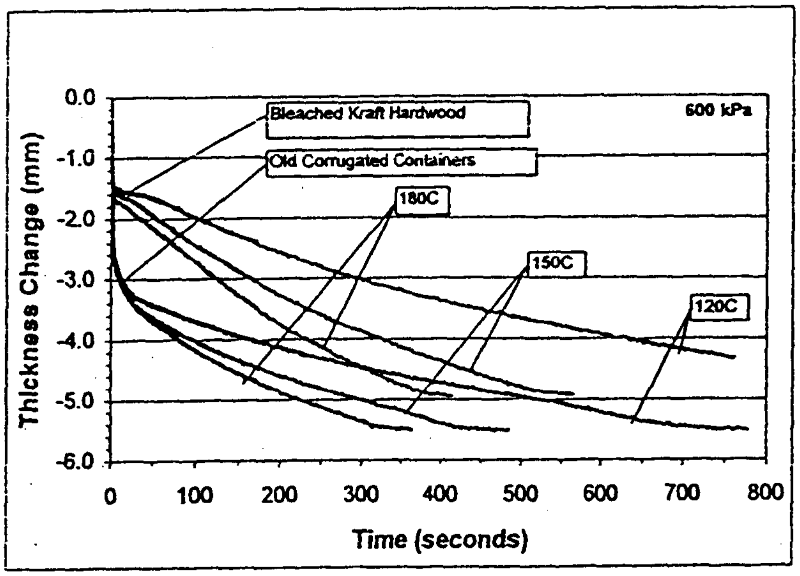


Figure 3. Thickness change as a function of time at 600 kPa pressing pressure.

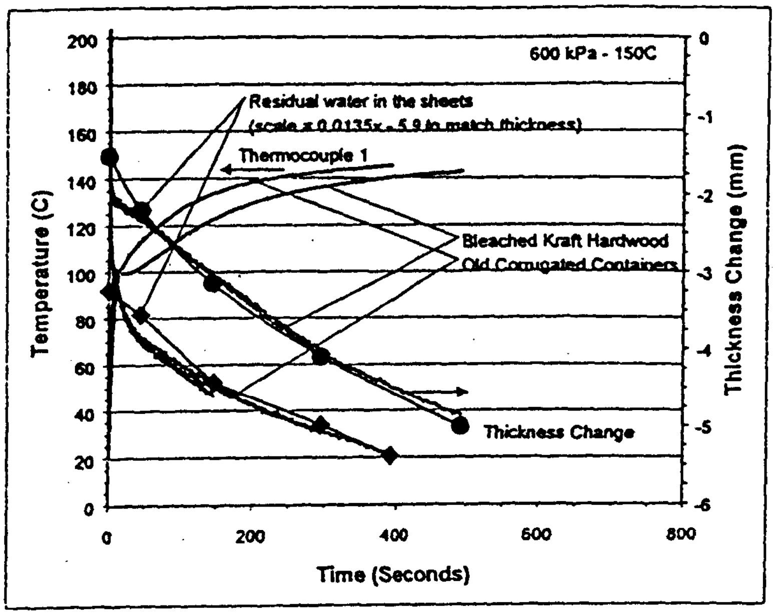


Figure 4. Percent residual moisture in the fibre sheets, thickness, and temperature at thermocouple 1 as a function of time.

Drying Rates

The effects of process variables on the overall drying rates (water loss/(time x sheet area)) for the layered flat sheets are shown using the two-factor interaction graph in Figure 5. Figure 5 ‘is interpreted by the interaction of row and column variables. The values at each pressing condition are listed in Table 3. The interactions show recycled fibre had a faster drying rate than the bleached kraft hardwood (first row or first column). The faster rate may have been due primarily to the more porous fibre structure of the OCC as evident by the low temperatures in the core, Figure 2a. The drying rate increased with pressure for the OCC but increased only slightly for bleached kraft. The increased pressure for the bleached kraft furnish most likely reduced the sheet porosity enough to eliminate any gains in fibre-to-fibre heat transfer coefficient. Drying rates for both fibre furnishes increased significantly as temperature increased, with OCC being faster at all temperatures. The effects on drying rate for the two fibre furnishes seems to be linear for temperature and non-linear for pressure.

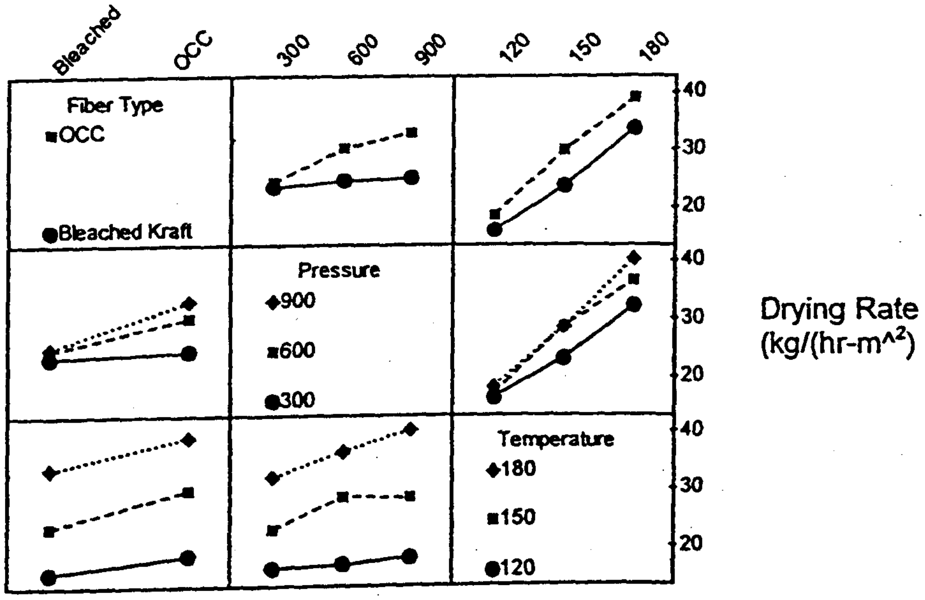


Figure 5. Two-factor interaction effects on drying rates.

Sonic Modulus of Elasticity

The effects of process variables on SMOE are shown using the two-factor interaction graph in Figure 6. Figure 6 is interpreted by the interaction of row and column variables. The values at each pressing condition are listed in Table 4. The interaction graph shows sheets made from bleached kraft hardwood were stiffer than those made from OCC. For both furnishes SMOE increased non-linearly with pressure but remained essentially unchanged with increased platen temperature. We believe the increased pressure increased the density resulting in more fibre-to-fibre bonds. The SMOE seems to be near the maximum and any additional pressure would result in minimal increase in stiffness. SMOE correlates 1:1 with tensile MOE (Hunt & Vick, 1999).

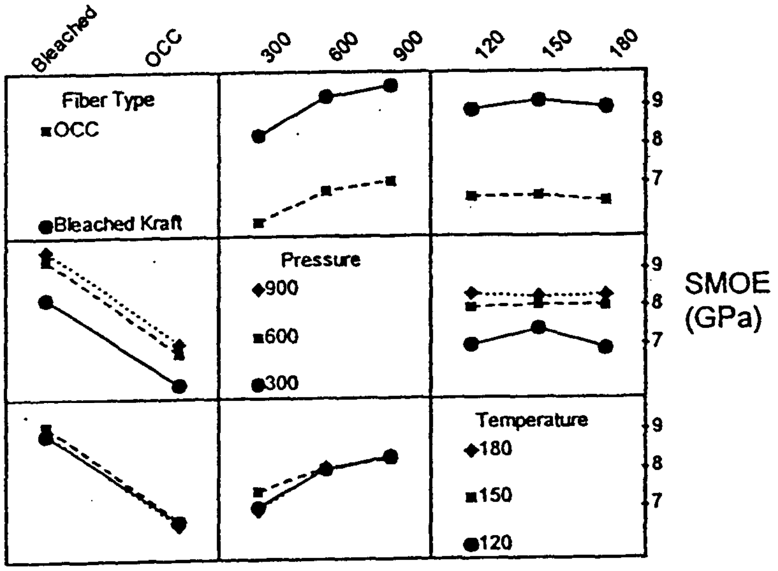


Figure 6. Two-factor interaction effects on sonic modulus of elasticity.

Table 3. Summary of results for the flat layered sheets.

Pressure (kPa)	Platen Temperature (C)	Moisture Content (%)	Bulk Fibre	Average core Temperature (C)	Gage Steam Pressure @ Core T (kPa)	Drying Rate (kg/hr-m^^{2})
Bleached Kraft Hardwood						
300	120	55.5	479	110	42	15.9
600				110	42	15.9
900				113	58	15.8
300	150			118	84	22.2
600				118	98	24.4
900				125	130	24.7
300	180			118	84	32.5
600				128	148	33.7
900				135	210	34.9
Old Corrugated Containers						
300	120	55.9	386	100	0	17.1
600				100	0	18.2
900				102	7	20.8
300	150			100	0	24.3
600				103	7	33.4
900				103	8	32.5
300	180			100	0	31.9
600				103	8	39.5
900				105	20	45.8

[1] Bulk density calculated on a dry fibre basis

Table 4. Summary of results for the flat full sheets.

Pressure (kPa)	Platen Temperature (C)	Initial Moisture Content (%)	Bulk Fibre Density[1] (kg/m^3)	Dry Density (kg/m^3)	Drying Rate (kg/hr-m^^{2})	SMOE, (GPa)
Bleached Kraft Hardwood						
300	120	58.9	430	996	17.5	8.07
600				1083	17.4	9.17
900				1115	17.9	9.40
300	150			1015	24.0	8.55
600				1080	26.6	9.16
900				1116	27.5	9.60
300	180			984	35.4	8.02
600				1080	38.1	9.31
900				1105	38.4	9.46
Old Corrugated Containers						
300	120	50.1	408	899	12.9	5.88
600				967	13.3	6.74
900				1020	13.8	7.17
300	150			927	19.7	6.22
600				1080	23.4	6.86
900				998	25.9	6.83
300	180			885	25.7	5.75
600				957	33.4	6.69
900				1000	36.3	7.07

[1] Bulk density calculated on a dry fibre basis

CONCLUSIONS

Internal temperatures and thickness changes obtained during the drying for the hardboard-like sheets made from paper fibres will be used to help verify the more complete computer model for drying three-dimensional fibre structures. The complete three-dimensional drying model will be published at later date.

The internal temperatures for the two furnishes show significant differences in drying conditions within the sheet. Higher internal temperatures occurred within the bleached kraft furnish that had a lower freeness, shorter average fibre length, and higher initial fibre compaction or bulk fibre density. The higher internal temperatures indicates moisture flow out of the sheet is restricted, resulting in a pressurised steam environment within the sheet. Toward the end of the drying cycle, for both fibre furnishes, an unexpected temperature decrease and subsequent increase at the middle of the sheet is a result of the complex interactions of heat and mass transfer, viscoelastic densification, and fibre-fibre bond development. This interaction will require further analysis with the computer model to fully understand what is happening inside the sheet..

In this study, thickness changes as a function of time were significantly different between the two fibre furnishes and for each of the process conditions. Thickness change was found to correlate with overall sheet moisture. Since thickness change vs. time correlates with sheet moisture it could be used to determine drying rates without having to conduct time consuming moisture content vs. time studies. For the computer model we will use the thickness curves to calculate the sheet moisture content as a function of time. Thickness change will also be used to calculate the overall change in density as a function of time. Since thickness change information only measures the overall change, further studies are needed to determine the moisture and density gradients through the thickness of the sheet as a function of time.

Drying rates were faster for OCC. In the future, it maybe possible to correlate initial process information such as freeness, fibre length, bulk density, fibre morphology with drying rate. Initial correlation would be based on fluid flow effects during forming. More work needs to be done in this area.

Mechanical properties are influenced more by pressure than temperature. Density development correlates with mechanical properties. While increased density increases properties it also decreases porosity which affects drying rates. While the computer model we are developing will help to optimise drying rates, there is a need to also correlate drying processes to a given final sheet performance characteristic associated with the drying variables and basic fibre properties. More work needs to be done in this area.

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