Effect of High Temperature Drying of Recycled Paper on Heat Transfer Rates and Sheet Properties

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ABSTRAT:

This paper presents a study on the effect of high temperature on paper drying rates and properties for both virgin and recycled pulp. Recently, there has been considerable interest in increasing the rate of paper drying to increase production. The use of gas-fired dryers (high temperature drying) is one method to increase the drying rate. With gas-fired dryers, one or more conventional dryers are replaced with a gas-fired dryer. The gas-fired dryer can provide internal shell temperatures in excess of 200 ^oC, which significantly increases the drying rate. However there are several issues with such an installation. These include, the change in the heat transfer rates (drying rates), the effect on paper properties especially curl and strength properties and the ideal location of such dryers. The process variables studied include the effects of temperature, moisture level, recycling, refining and basis weight on heat transfer and paper properties. The results of this study provide information that optimizes the location of the high temperature dryers. In the ideal location, the heat transfer rates are maximized with minimum effect on sheet properties. Sheet curl was found to be a function of recycling, refining, basis weight and drying temperatures.

This study found that the paper-shell contact coefficient is dependent on shell temperature. The heat transfer coefficient was found to be constant in the constant rate drying zone and in the first following rate zone, but decreased with an increase in shell temperature in the second following rate zone. If a gas-fired dryer were located in either the constant rate zone or in the first following rate zone, a single gas-fired dryer would be expected to increase the drying rate by 2 to 4%.

INTRODUCTION:

The Gas Institute of Technology (GIT) in Chicago, Ill has developed a new gas heated cylinder that is designed to increase production on dryer limited machines. With funding from the US Department of Energy, the Minnesota Department of Commerce sponsored work at GIT and Western Michigan University (WMU) to commercialize this process.

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To study the effects on this unit a pilot version was installed on the pilot machine at Western Michigan University. In these trials, Chudnovsky and Kozlov (1) showed the advantages of a gas fired dryer over a steam-heated dryer. The trial consisted of replacing one steam heated dryer on WMU's pilot machine with a gas-fired dryer and producing 126 lb/1000 ft^2 linear board. They were able to increase the surface temperature to 260 ^{O}C, showed a significant increase in efficiency with low NO_x emissions. A Flynn ribbon burner model T- 534 was selected and the basic configuration is shown in Figure 1.

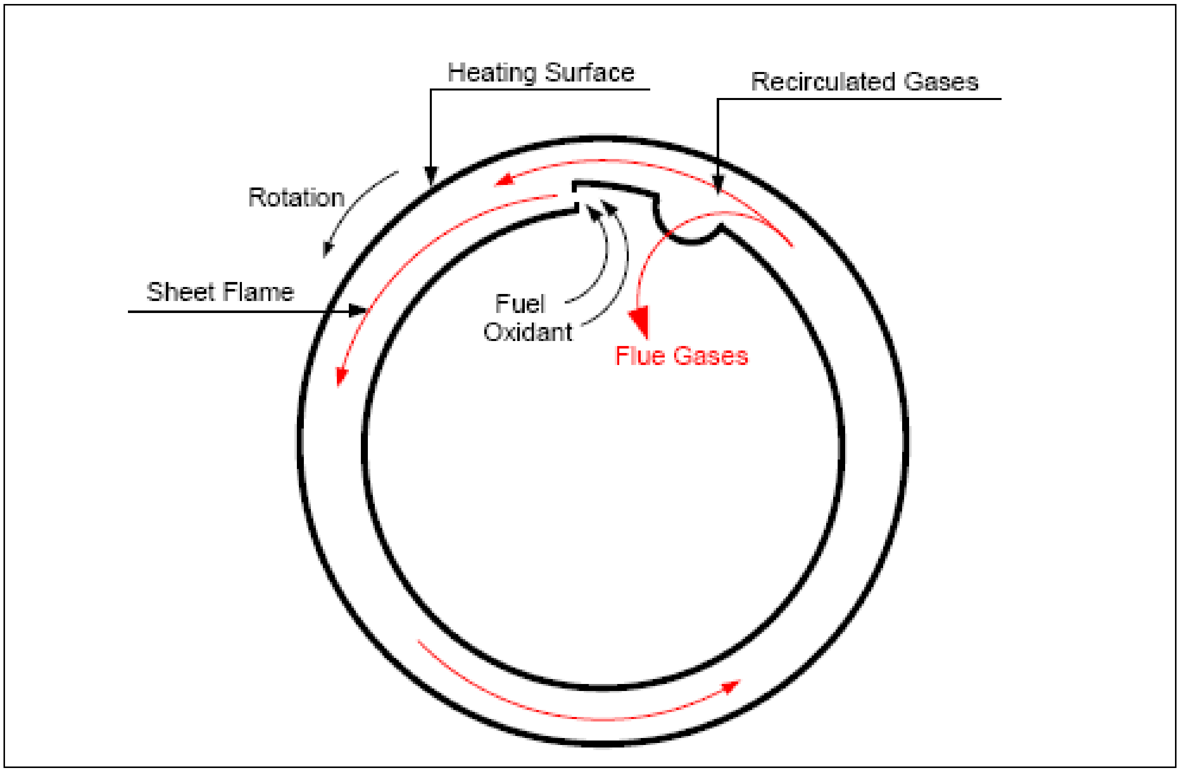

Figure 1. Gas Fired Paper Dryer, US Patent 6,877,979 (1)

Cylinder Drying: In conventional paper drying, iron drums 5 to 6 ft in diameter are heated with steam. Due to ASTM pressure codes, the steam pressure is limited to 160 psig (1) or about 190 ^{o}C. Resistance to heat transfer from the condensing steam in the dryer cylinder to the paper includes the condensate layer, scale, the metal shell, and the contact coefficient between the shell and the paper. Of these, the contact coefficient is the most critical. Different studies, as described by Wilhelmsson, *et al.* (2), have reported that the contact coefficient accounts for from 35 % to 75% of the total heat transfer resistance. Due to these resistances to heat transfer, the maximum surface temperature is about 150 ^{o}C (3).

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Because of the importance of the paper-shell contact coefficient to heat transfer and its uncertainty, the majority of the experimental studies (2-8) on paper drying have focused on quantifying this parameter. These studies can be divided into machine trials, dynamic laboratory studies and static laboratory studies. As described by Wilhelmsson *et al.* (2), there are several advantages to static laboratory studies. The major advantages are that a laboratory system provides a defined environment, allows many different conditions to be studied and provides rapid drying data collection and analysis. A major result of these studies is finding that the contact coefficient is highly dependent on the water/solids ratio of the paper. For example, Wilhelmsson, *et al.* (2) found that the contact coefficient decreases from about 800 $W/m^{2o}C$ to 200 $W/m^{2o}C$ as the moisture ratio in the paper decreased from 1.0 g-water/g-solids to 0.2 g-water/g-solids. These studies also report that the contact coefficient tends to decrease with shell temperature (although there are conflicting findings in some of the papers on this effect), and is independent of fabric design and fabric tension within standard commercial ranges.

The drying rate can be described by the rate of heat transfer from the dryer shell to the paper. The heat entering the paper heats the water and solids in the paper, evaporates water or is lost by radiation and convention. After a short heating period, the majority of the heat is used to evaporate the water in the paper. Equation 1 describes the heat flux from the dryer shell into the paper.

$$Q = h_c(T_{shell} - T_{paper}) \qquad (1)$$

Here, Q is the heat flux W/m^2, h_c is the paper-shell contact coefficient $W/m^{2} \cdot {}^oC$, and T is the temperature ^oC of the paper and the shell.

The paper temperature during drying is in the range of 70 ^oC to 90 ^oC and due to the rapid increase of the water's vapor pressure with temperature is unlikely to exceed 100 ^oC.

Previous Studies of High Temperature Paper Drying: The use of high temperature gas heated dryers, especially if only a few are installed in dryer chain is not expected to significantly affect most of the physical properties of the paper. However, it is well known that curl can result from non-uniformly dried paper. When paper dries faster on one side versus the other side, a tendency for the paper to curl toward the side dried last exists (9).

With an initial installation of a gas-fired paper dryer, either one or two steam cylinders can be replaced with gas-fired cylinders. The key considerations for this decision are the effect of the difference in drying (more drying on one side) on the drying rate and on the sheet curl.

Commercial Application: Major potential sites for this technology include recycled board mills limited by dryer capacity. The initial commercial paper dryer considered for this gas-fired dryer was a multiple ply board machine. In this installation the paper was heated only on one side through the first five dryer cans that dried using multiple steam heated dryer cans in three sections. Although, curl was not a problem with the products produced on this machine, several paper samples were collected and the curl was measured. It was found that curl was present and the sheet curled away from the side heated in these first five dryer cans. By shutting the steam off to different dryer cans in the second dryer section, it was shown that sheet curl was influenced by the amount of drying on each side of the sheet. The recommended location of a single gas-fired dryer was such that it would counteract the natural curl present in the sheet due to the first dryer cans.

EXPERIMENTAL:

Experimental System: The experimental system was designed to simulate heat transfer into the paper during a typical paper cylinder drying paper process. Figure 2 shows the experimental system designed for this study.

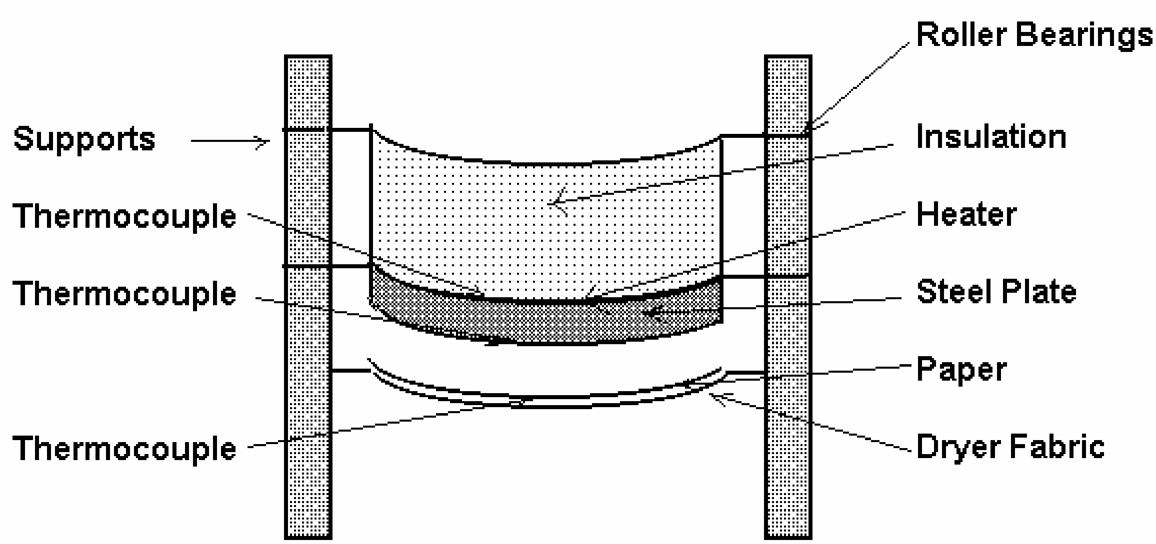


Figure 2, Experimental Paper Drying System

The experimental system consists of a heated steel platen, a dryer fabric, and thermocouples. Data are collected using three type E thermocouples and a temperature data acquisition system manufactured by Computer Boards Inc. The thermocouples are located in the paper, at paper-heater interface and at the heater shell interface.

The paper is placed on the dryer fabric and a one-half inch 304 stainless steel plate, heated by a thermal-heating pad manufactured by Heater Designs. As the heater is lowered onto the paper, the data acquisition program is started.

The system was designed to simulate heat transfer on a paper dryer cylinder. The curvature of the metal shell used in these experiments is that of a 2 m diameter dryer cylinder. According to Stowe (6), the typical fabric tensions used on commercial dryers is in the range of 1.5 to 2.5 kN/m. Using the relationship between pressure and fabric tension, Eqn (4), the fabric tension in these experiments was determined to be 1.1 kN/m, which is slightly within the range (0.5 kN/m to 1.7 kN/m) recommended by TAPPI (8) for newsprint machines.

$$\text{Pressure} = \text{Tension} \,/\, \text{Dryer Cylinder Radius} \qquad (2)$$

To calculate paper shell contact coefficient it is necessary to know the heat flux, and the paper and shell temperatures at the interface. The heat flux is obtained using the methods described in this paper. The shell temperature is obtained from a thermal couple embedded in the shell at the interface. This thermal couple was carefully designed and fitted into the shell to ensure that it accurately measures the shell interfacial temperature. The paper temperature is perhaps the key variable in this calculation. Techniques to determine this temperature include measuring the paper surface temperature after removal from the heated surface, as employed by Wilhelmsson *et. al* (2) or using a thermal couple embedded in the paper. In this study, the embedded thermal couple was employed to determine the paper temperature at the paper-shell interface.

Experimental Results: Although several drying experiments were conducted, only representative drying curves are presented in this paper. Handsheets were made using a Noble and Woods handsheet machine at 15 seconds refining level by Mead refiner from lap SW pulp and recycled pulp. Handsheets were made at three basis weights, 60g/m^2, 120g/m^2 and 180g/m^2. Paper samples from each grade were dried at 60% initial moisture content at three different temperatures. The low temperature, 100˚C, corresponded to the average cylinder temperature used on conventional cylinder dryers producing newsprint (9). The highest temperature, 200˚C, is representative of Gas Heated Dryer surface temperature. The wet handsheets were weighed before and after drying to check the moisture content and the amount of evaporated water.

The Explicit Finite difference described by Dewitt (12) was used to calculate the shell contact coefficient. This method requires that the initial temperature of the metal surface to be known and does not have to be uniform. Equation (3) presents a good development of the explicit finite difference method.

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \qquad (3)$$

Here *T* is the temperature and *x* and *y* are the dimensions.

If the system is one dimensional in x, this equation can be written as an explicit form of a finite- difference equation as the following:

$$T_m^{p+1} = Fo\left(T_{m+1}^p + T_{m-1}^p\right) + \left(1 - 2Fo\right)T_m^p \qquad (4)$$

Here m is the dimensional subscript, p is the time subscript and $Fo = \alpha\Delta t / \Delta x^2$.

The heat flux model described above was written in visual basics for application to analyze the temperature of shell and paper surface. The excel spreadsheet serves as an input-output platform for the program. Excel's chart feature can generate the required graphs.

RESULTS:

Handsheets from virgin pulp and recycled paper were dried from 60% moisture content. The following figures show the effect of high temperature drying on drying rates, the contact coefficient and paper properties. Figure (3) shows the temperature changes of the heated platen, paper and the heat flux into the sheet.

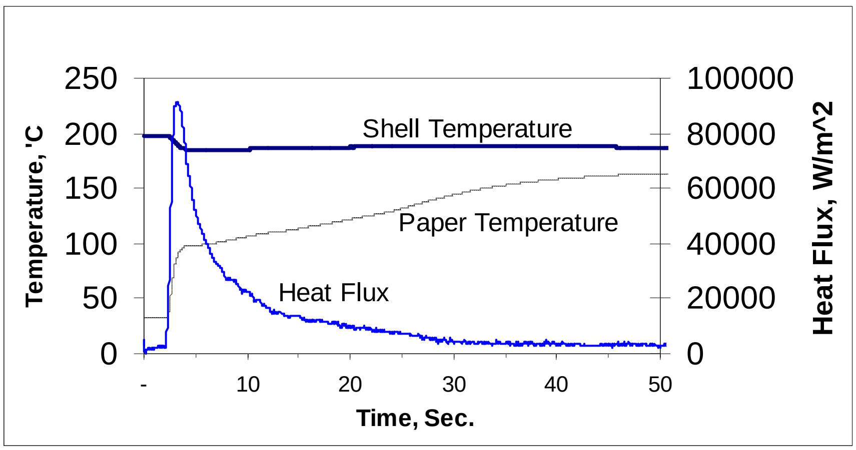


Figure 3. Heat Flux, Shell and Paper Temperatures for 120g/m^2 Lap Pulp and 200˚C Shell Temperature

The heat flux to the paper is directly related to the drying rate. Figure (4) and (5) show the drying curve and the distinct drying periods for virgin pulp and recycled paper. The first period is the warm up period where the drying rate increases continuously. The second period is the constant rate period. In this study, this period lasted for less than a second in all the drying experiments. The next period is the first falling period. The moisture content between the constant rate period and the first falling period is the critical moisture content. In the first falling rate period, the surface of the web is partly dry and its heat conductivity decreases. This causes web temperature to increase. The last period is the bound water zone. In this period, physicochemical bonds hold the remaining water. These bonds are difficult to break and this causes the drying rate to decrease.

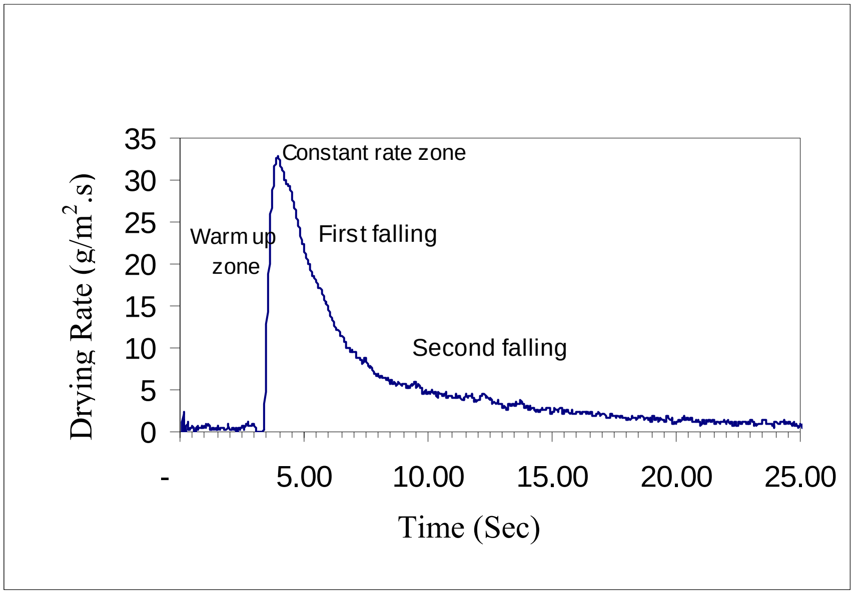


Figure 4. Drying Curve for Virgin Pulp at 40% Solid Content, 180g/m^2 and 200˚C Shell Temperature.

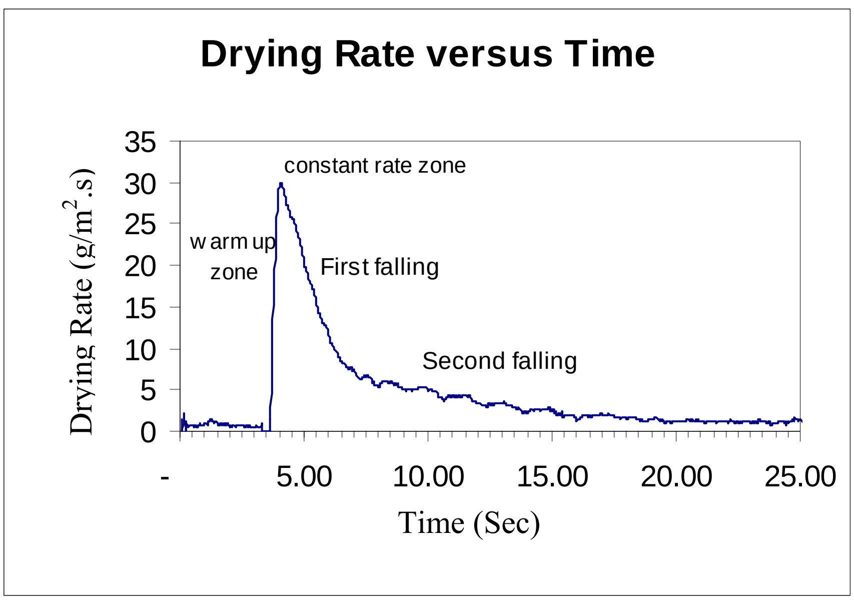


Figure 5. Drying Curve for Recycled Paper at 40% Solid Content, 180g/m^2 and 200˚C Shell Temperature.

Figures (6) and (7) show the effect of shell temperature and basis weight on the drying rates for virgin pulp and recycled paper. As the shell temperature increases, the higher temperature difference between the shell and paper assists the heat transfer. It is also clear that there is no difference in the drying rates between the virgin pulp and first recycled paper. In addition, the basis weight does not have a significant effect on the drying rate.

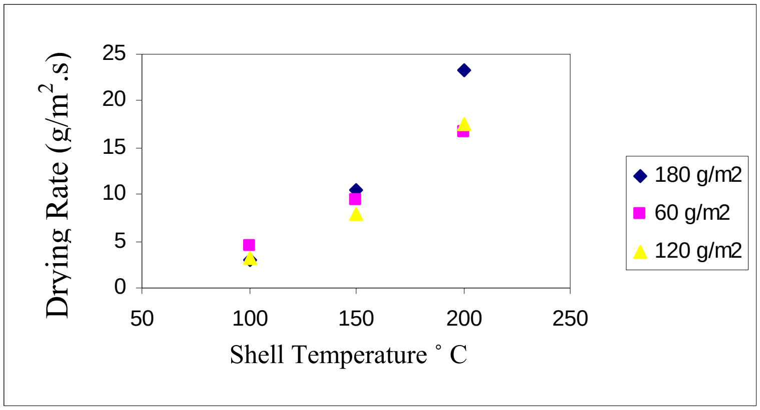


Figure 6. Effect of Shell Temperature and Basis Weight on the Average Drying Rates for Virgin Pulp in the First Falling Rate Period

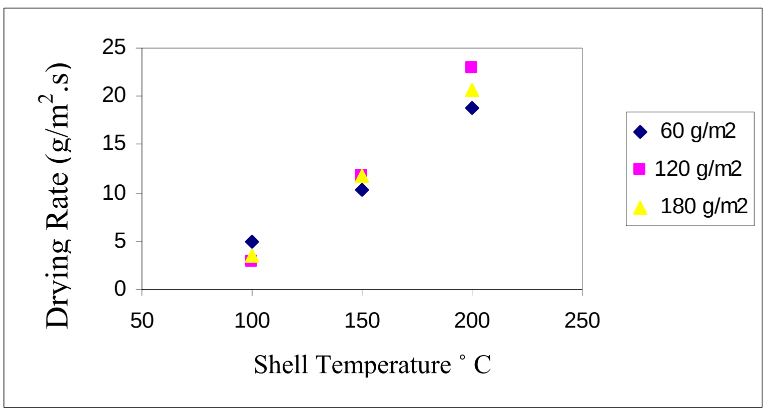


Figure 7. Effect of Shell Temperature and Basis Weight on the Average Drying Rates for Recycled Paper in the First Falling Rate Period.

After the first falling period, the paper is almost dry and the sheet conductivity decreases. Therefore, the heat transfer decreases and the drying rate slow. Figure (8) and (9) show the effect of high shell temperature on drying rate in the second falling period for virgin pulp and recycled paper. The drying rate increases contentiously as the shell temperature increases. The results show no statistical difference between drying rate for virgin pulp and recycled paper.

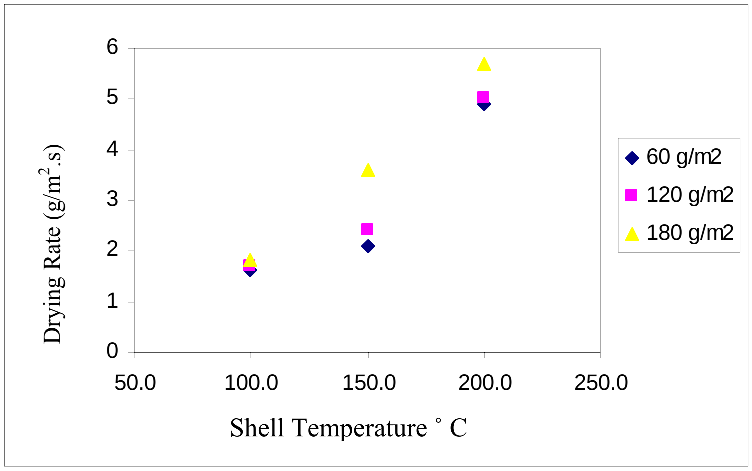
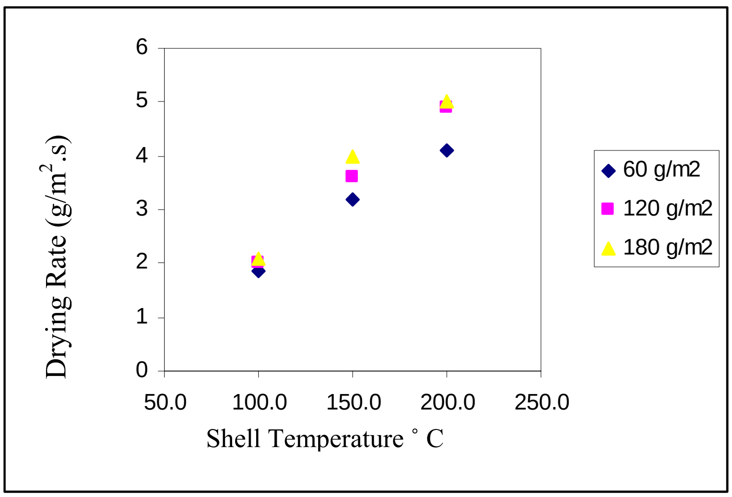


Figure 8. Effect of Shell Temperature and Basis Weight on Drying Rate for Virgin Pulp in the Second Falling Period.



F**igure 9. Effect of Shell Temperature and Basis Weight on Drying Rate for Recycled Paper in the Second Falling Period.**

The heat flux and the drying rate are affected by the shell-paper contact coefficient. The effect of the shell temperature and the basis weight on the contact coefficient is studied for the different drying periods. Figure (10) and (11) show the contact coefficient for virgin pulp and recycled paper in the first falling period. The contact coefficient in the first falling period is independent on the shell temperature. In addition, the basis weight does not affect the contact coefficient.

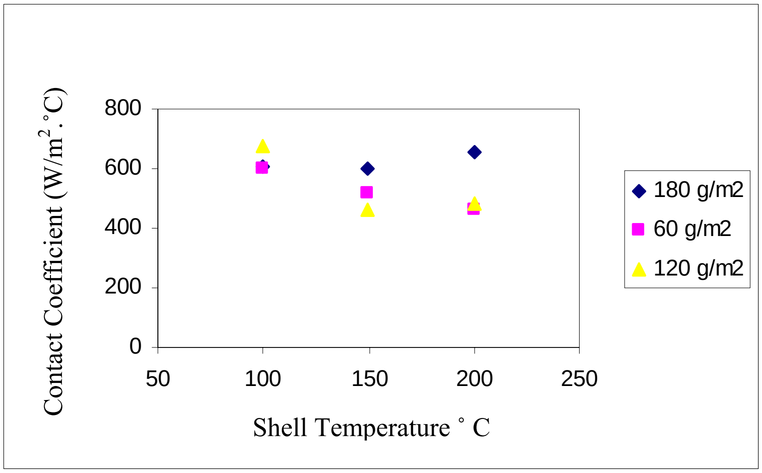


Figure 10. Effect of Shell Temperature and Basis Weight on the Contact Coefficient for Virgin Pulp in the First Falling Period.

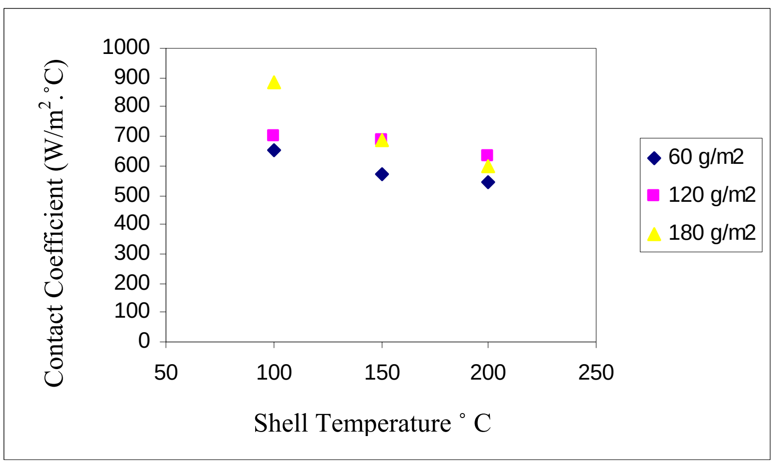


Figure 11. Effect of Shell temperature and Basis Weight on the Contact Coefficient for Recycled Paper in the First Falling Period.

After the first falling period, the remaining water is hard to remove water. The drying rate decreases with time. Figures (12) and (13) show the effect of high surface temperature and basis weight on the contact coefficient for virgin pulp and recycled paper. As the shell temperature increases, the contact coefficient decreases. The basis weight has no effect on the contact coefficient in the first and second falling period.

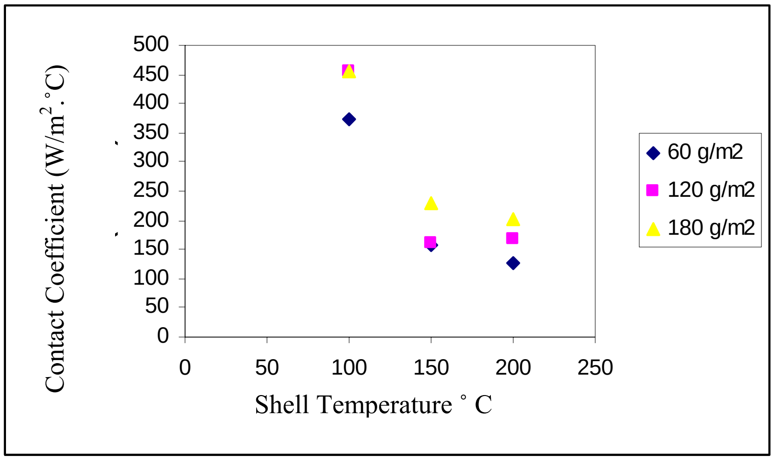


Figure 12. Effect of Shell Temperature on the Contact Coefficient for Virgin Pulp in the Second Falling Period

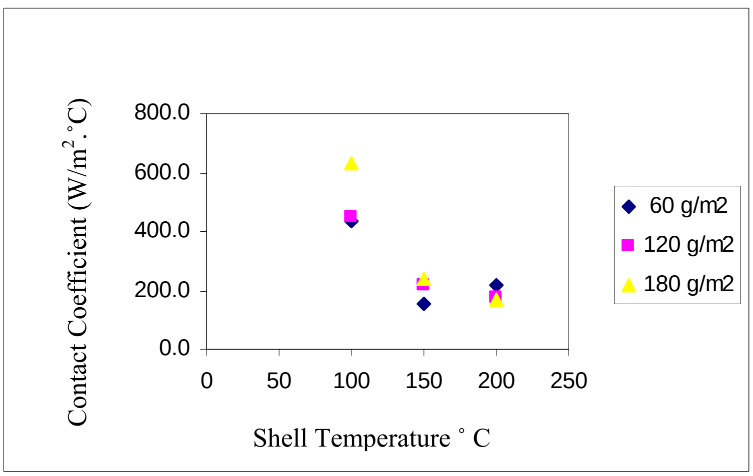


Figure 13. Effect of Shell Temperature on the Contact Coefficient for Recycled Paper in the Second Falling Period

To study the effect of the high temperature gas-heated driers on paper curl, the dried papers was cut into a 15 cm width and 15 cm length strips. Curl is measured by calculating the angle of curvature from the edge rise and the distance between the edge and the midpoint of the strip. The dried papers tend to curl away from the heated surface toward the side last to dry. The side against the dryer shell dries first and once dried cannot shrink. This non-uniform drying causes paper to curl. Figure (14) shows different paper curl at high temperatures for virgin pulp and recycled paper. The results show higher paper shrinkage and higher curl as shell temperature increases. The tendency for paper to curl is lower with recycling treatment. This can be explained by the reduction in the inter-fiber bonding when paper is recycled (3).

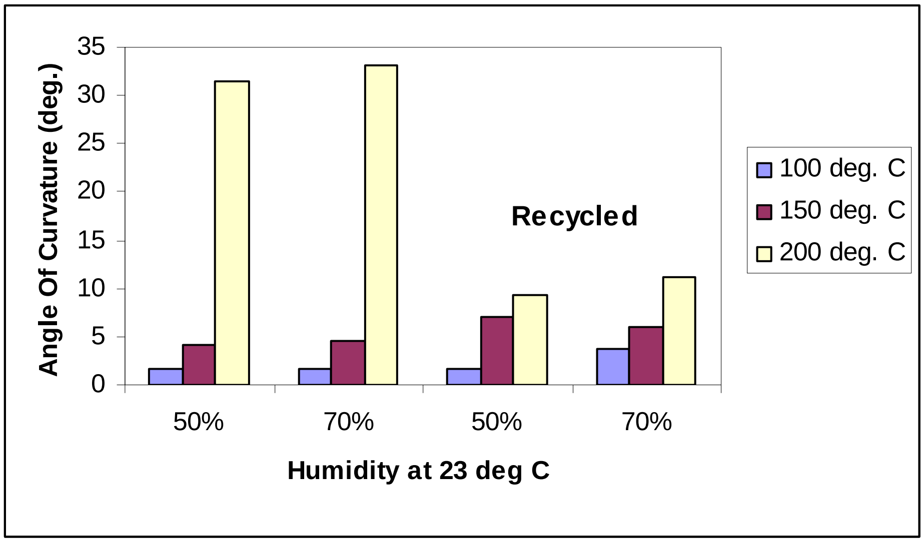


Figure 14. Effect of Shell Temperature on Paper Curl. Curl Is Measured for 180 g/m² Virgin Pulp and Recycled Paper at 50% and 70% Humidity.

To study the effect of high temperature drying on paper quality, tensile strength is measured for all the dried samples. The shell temperature does not affect the paper strength as shown in figure 15. This indicates that the high surface temperature causes no deterioration in the paper structure and the paper quality. The recycled paper has lower tensile indices than virgin pulp. The same results are obtained for the three basis weights. This decrease in the tensile strength of recycled handsheet results from the lost strength of inter-fiber bonding.

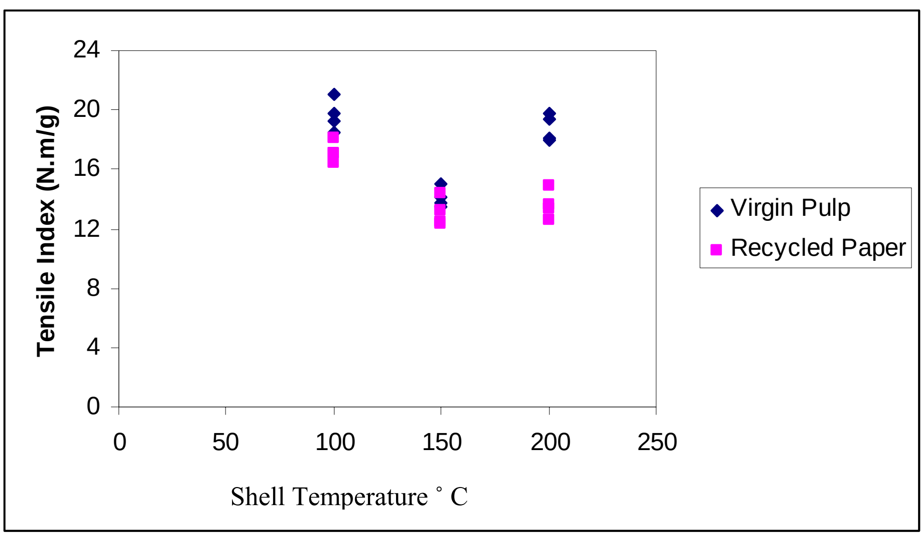


Figure 15. Effect of Shell Temperature on Paper Strength for 180 g/m² Virgin Pup and recycled Pulp

DISCUSSION:

This research examines two critical aspects of high temperature paper drying and identifies the ideal location of a gas-fired, high-temperature dryer. These two aspects stuedied are the effect of the high surface temperature on the drying rate and on the paper properties. To determine the effect of recycling, both virgin lap pulp and recycled pulp were studied. The effect on the drying rate will be discussed first, followed by the effect on the sheet properties.

As discussed earlier, the key resistance for paper drying on a heated cylinder is the contact coefficient between the dyer shell and the paper. The heat transfer and hence drying rate can be described by equation (1), where h_c is the paper-shell contact coefficient. It is unclear from the literature what effect an elevated shell temperature has on the contact coefficient. Some studies have found that this contact coefficient decreases with increasing temperature (7,8), while others have found little effect of temperature on this coefficient (3-6).

The drying curve for paper can be divided into four regions: heating, constant rate, first following rate and second following rate. The results of this study found that the paper-shell contact coefficient was not affected by the shell temperature in the constant drying rate region nor in the first following rate region, but decreased with temperature in the second following rate region. This may be due to the physical-chemical bonding of the water to the fibers that must be overcome in the second following rate region.

Both the lap pulp and the recycled pulp behaved similarly with regard to the effect of the shell temperature on this contact effect. However, the contact coefficient for the recycle pulp was somewhat higher than that for the virgin pulp in the second following rate period. This is likely due to the ability of the water to form physiochemical bonds with the fiber, which appears to be reduced by recycling.

The implication of this finding is the ideal location of a high temperature cylinder is in the middle of the drying chain. If it is place too far toward the wet end, it is likely that a vapor barrier will form between the dying and the paper, while if it is place too far toward the dry end, it will be located in the second following rate zone and the heat transfer rate and hence drying rate will not increase as fast with an increase in shell temperature.

If the high temperature dryer were located within either the constant rate or first falling rate zone, the heat transfer rate can be described by equation (1) with h_c remaining relatively constant.

$$Q = h_c(T_{shell} - T_{paper}) \qquad (1)$$

Since the vapor pressure of water rapidly increases near 100^{o}C, the paper temperature remains near 100 ^{o}C. and since the highest shell temperature with conventional steam drying is about 150 ^{o}C, the ΔT or driving force for drying can be assumed to be about 50 ^{o}C. With a gas fired drying the shell temperature can be as high as 300 ^{o}C, which results with a ΔT of about 150 ^{o}C or a drying rate of three times that present with a steam cylinder. With such a temperature there are some concerns with the use of a high temperature felt and the fire safety systems on the dryer. However, two or three times an increase in heat transfer and drying rate should be attainable. This should result in a two to four percent increase in drying rate for each high temperature dryer added.

Paper properties were the other aspect of high temperature drying that was studied. It was found that the strength properties were not affected by the increase in shell temperature. As expected the high temperature and especially one-sided drying did affect the curl tendency of the paper. In all cases the paper tended to curl toward the side dried last. In comparing lap pulp to recycled pulp, it was found that this curling tendency was less with recycled pulp.

In the commercial machine trials, it was found that the recycled board had a natural curl tendency. This tendency could be counteracted with a single high temperature drying. However, such an instillation, would not allow curl to be controlled and once the machine situation changed due factors such as furnish changes, or machine speed a negative interaction between the high temperature dryer and curl could be perceived to be present. Therefore, to ensure that curl was not increased and to provide curl control, at least two high temperature dryers should be installed on a commercial machine.

CONCLUSIONS:

The following conclusions were reached:

1. The paper-shell contact coefficient was not affected by shell temperature in either the constant rate zone nor in the first following rate zone, but decreased with increasing temperature in the second following rate zone. The decrease was present with both lap pulp and recycled pulp.
2. Based on conclusion 1, the high temperature dryer should be installed near the middle of the dryer chain and both the beginning and end of the chain should be avoided.
3. Each gas-fired high temperature dryer should increase the drying rate by 2 to 4 %.
4. High temperature drying should not affect the strength properties, but can affect sheet curl. The paper will tend to curl toward the side dried last. This effect is less for recycled paper than for lap pulp.
5. Based on conclusion 4, if only one high temperature dryer were installed this dryer needs to be located such that it counteracts the curling tendency already present in the sheet.
6. Ideally at least two high temperature dryers should be installed. This will not only guard against increases in curl, but will allow curl to be controlled be adjusting the relative temperatures of the high temperature dryers.

Acknowledgements:
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