Effect of high-temperature drying of recycled paper on heat transfer rates and sheet properties

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ABSTRACT: A gas-fired paper dryer (GFPD) was evaluated in pilot- and full-scale environments. A corresponding study was done on the effect of high temperature on paper drying rates and paper properties. The process variables studied include temperature, moisture level, refining, and basis weight. In an ideal location, heat transfer rates are maximized with a minimum effect on sheet properties. Sheet curl is a function of recycling, refining, basis weight, and drying temperatures and can be minimized by correct placement of the GFPD. Results of this study indicate optimal installation location.

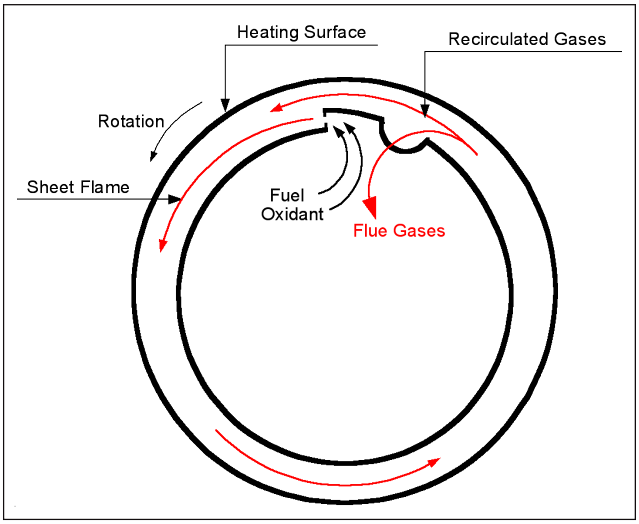
The heat transfer coefficient is independent of the shell temperature in the constant rate drying zone and in the first following rate zone, but decreases with an increase in shell temperature in the second following rate zone. If a gas-fired dryer is located in either the constant rate zone or in the first following rate zone, the overall drying rate increases by approximately two to four percent per single gas-fired cylinder. By using several gas-fired dryers, it is possible to increase the overall drying rate by as much as 20%.

Application: This technology could help mill personnel increase paper machine drying rates and production rates on dryer limited machines and increase overall mill energy efficiency.

Paper drying is the most energy-intensive and temperature-critical aspect of papermaking, using approximately 67% of the total energy required for papermaking. Paper machine speeds, and consequentially production rates, are frequently limited by dryer capacity. Conventional paper drying uses a series of cast iron drums internally heated by condensing steam. The use of steam requires the drums to meet American Society of Mechanical Engineers (ASME) codes for pressure vessels, which limits the steam pressure to 1100 kPa and the steam temperature to 190°C. The drum surface temperatures are even lower. A great deal of research activity [1-3] has been devoted to developing new high efficiency, high rate paper drying equipment. Several gas-fired alternatives were proposed, but only ABB [1] was able to introduce its design into the commercial market.

Gas Technology Institute (GTI), in cooperation with Western Michigan University (WMU), Groupe Laperrier and Verreault (GL&V) USA Inc., and Flynn Burner Corporation (FBC), have been working to develop an innovative approach to gas-fired drying systems. These efforts recently resulted in the combining of low NOx ribbon flame, advanced heat transfer enhancement technologies [4] that can significantly improve paper drying efficiency, decrease specific energy consumption, and overcome the limitations of pre-mixing while still producing stabilized combustion.

To study the effects of high-temperature drying on the process and properties, a gas-fired paper dryer (GFPD) was installed on the pilot paper machine at WMU. Results from these trials [5] show the advantages of a gas-fired dryer over a steam-heated dryer. The trial consisted of replacing a steam-heated dryer on WMU's pilot machine with a gas-fired dryer and producing linerboard. The test drum location was varied to explore the optimal performance. The GFPD produced a surface temperature of 260°C and significantly increased the drying rate and efficiency with lower NOx emissions compared to the steam-heated dryer. **Figure 1** shows the basic GFPD design. Following these trials, a full-scale GFPD was designed, engineered and successfully demonstrated at the GL&V Paper Drying facility in Hudson Falls, N.Y.



1. Gas-fired paper dryer, US Patent 6,877,979 [4].

Cylinder drying

In conventional paper drying, cast-iron drums 1.5 m–1.8 m (5 ft.–6 ft.) in diameter are heated with steam. The condensate layer, the scale, the metal shell and the contact coefficient between the shell and the paper offer resistance to heat transfer from the condensing steam in the dryer cylinder to the paper. Of these resistances, the contact coefficient is the most critical. Studies described by Wilhelmsson [6] reported that the contact coefficient accounts for 35%–75% of the total heat transfer resistance. Due to these resistances to heat transfer, the maximum surface temperature is approximately 150°C [3].

Due to the importance of the paper-shell contact coefficient to heat transfer and its uncertainty, most experimental studies [6-12] on paper drying have focused on quantifying this parameter. These studies cover three categories: machine trials, dynamic laboratory studies, and static laboratory studies. The major advantages of static laboratory studies [6] are that they provide a defined environment, allow many different conditions to be studied, and provide rapid drying data collection and analysis. These studies have shown that that the contact coefficient is highly dependent on the water/solids ratio of the paper. For example, the contact coefficient decreases from approximately 800 W/m²°C to 200 W/m²°C as the moisture ratio in the paper decreases from 1.0 g-water/g-solids to 0.2 g-water/g-solids [6]. The contact coefficient generally tends to decrease with shell temperature, and is independent of fabric design and fabric tension within standard commercial ranges.

The drying rate is 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 convection. Equation 1 describes the heat flux from the dryer shell into the paper during paper drying.

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

where
Q = heat flux, W/m²
h_c = paper-shell contact coefficient, W/m²°C
T = temperature of the paper and the shell, °C

The paper temperature during drying is typically between 70°C and 90°C, and is unlikely to exceed 100°C due to the rapid increase of the water's vapor pressure.

Previous studies of high-temperature paper drying

Lang and others [8] studied the effect of high surface temperature drying on the drying rate and product quality in two commercial insulations. Using a gas-heated dryer, they increased the shell temperature to over 250°C and compared the drying rates at 132°C to those at 230°C and 290°C. The drying rates of linerboard increased by 100% and newsprint by 200% with no detrimental effect on paper properties.

The use of high-temperature gas heated dryers, especially if only a few are installed in a dryer chain, should not affect most physical properties of the paper [13]. However, curl can result from non-uniformly dried paper. When paper dries faster on one side than on the other, the paper tends to curl toward the side dried last [14]. Typically, initial installation of a gas-fired paper dryer replaces one or two conventional drying cans with gas fired dryers. The key considerations for this decision are the effects of the difference in drying, such as uneven drying, on drying rate and sheet curl.

Commercial application

Major potential sites for this technology are 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 dryer consisted of a serpentine run through the first 5 dryer cans, where the paper was heated on only one side, followed by 3 double tier sections. By shutting the steam off to different dryer cans in the second dryer section, the amount of drying on each side of the sheet affected the amount of sheet curl. The recommended location of a single gas-fired dryer is such that it will counteract the natural curl present in the sheet due to the serpentine fabric run in the first five dryer cans.

PILOT-SCALE EVALUATION

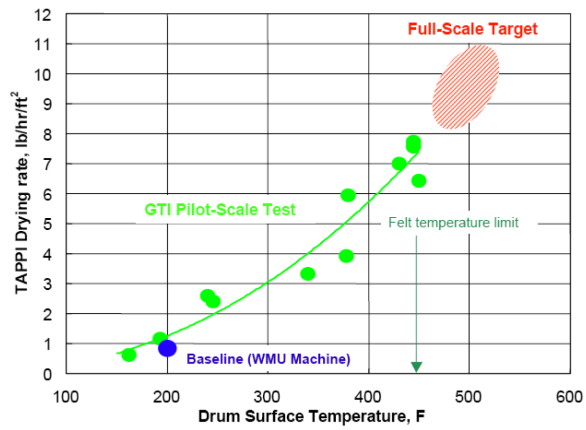
Figure 2 shows the pilot machine at WMU, a Fourdrinier paper machine capable of manufacturing 0.6-m papers and boards at speeds up to 50 m/min. The dryer section consists of a first and second section separated by a size press with eight and five dryer cans, respectively, as shown in **Fig. 3**.

We selected steam drums No. 3 and No. 7 for baseline evaluation. Drum No. 3 was selected as the most thermally loaded drum in the drying section, and drum No. 7 was selected for evaluation of GFPD performance at lower inlet moisture levels. The baseline test measured the drum surface temperatures and paper moisture profiles across the paper web at different heat input levels. The obtained information became benchmark data for a comparative analysis with the gas-fired retrofit test results.

During the pilot-scale test the GFPD drum was installed in the same two locations as for the baseline test. The drum was placed in the dryer No. 3 position to test at 45% inlet solids and in the dryer No. 7 position to evaluate the GFPD performance at 60%–90% solids. The instrumentation of the paper machine for the GFPD test was the same as during the baseline test except for steam pressure and temperature measurements at drums No. 3 and No. 7. An advanced air/gas flow management and mixing system, equipped with high accuracy vortex flow meters and a portable gas analyzer, controlled and monitored flame stoichiometry and exhaust emissions.

Pilot-scale evaluation indicated an increased drying rate in GFPD of approximately 4-5 times over the average value measured for a steam-heated dryer, as seen in **Fig. 4**. However, the maximum operating temperature of the felt material limited GFPD drying rates.

2. WMU pilot-scale paper machine dryer section without GFPD installed (top) and with GFPD installed (bottom).

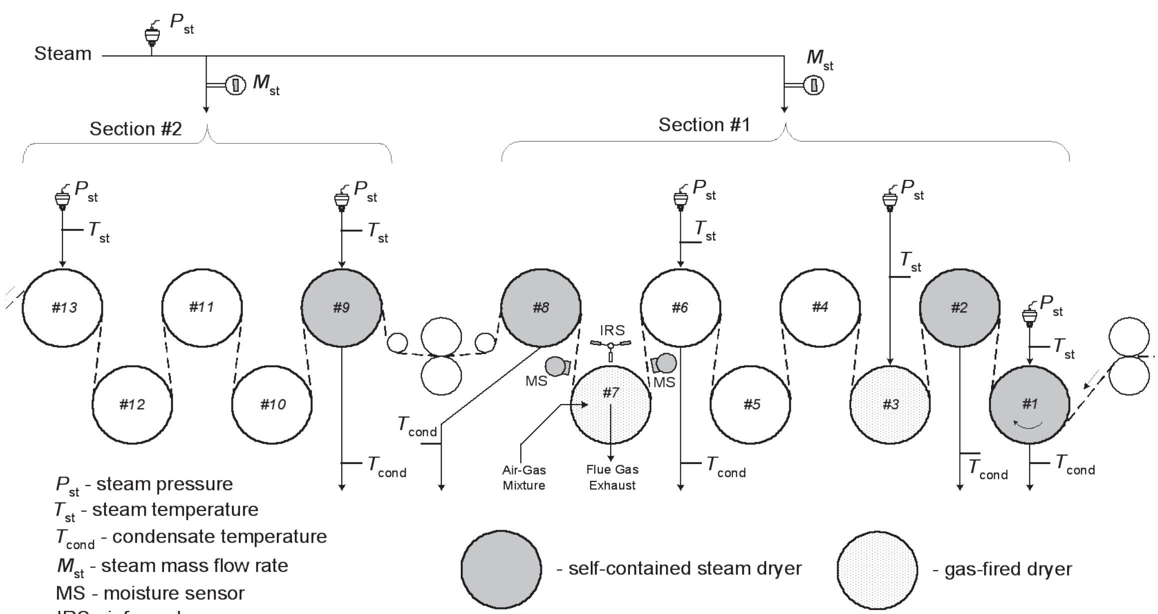


4. Effect of drum surface temperature on the drying rate at 45% sheet solids.

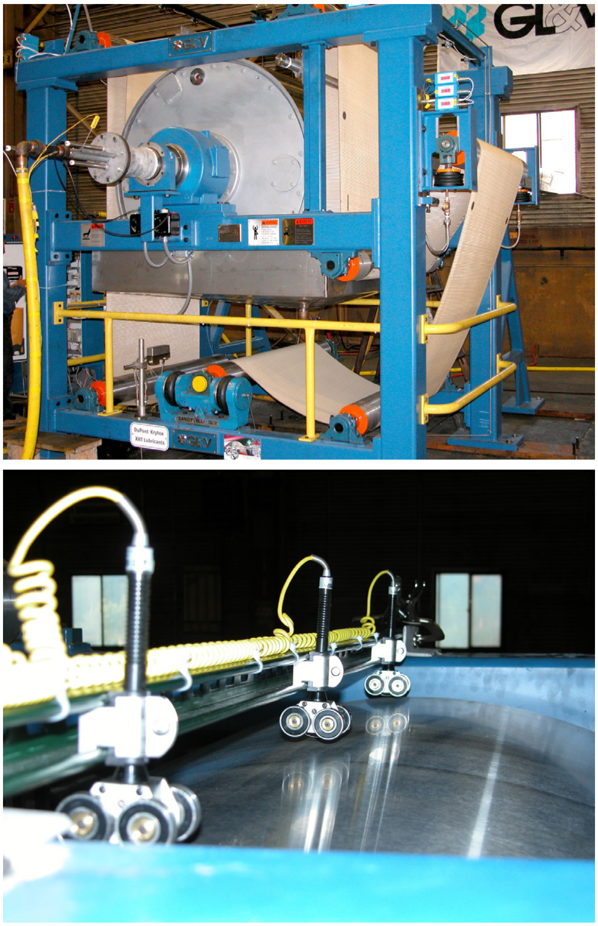
FULL-SCALE EVALUATION

Detailed analysis of the previous pilot-scale GFPD evaluation showed the strong potential of this technology for further improvement of the papermaking process. Furthermore, a careful review raised the following technical issues associated with the high-temperature operation and combustion system ignition, which had to be resolved before installing the first commercial unit:

- Reliable bearing operation at the elevated temperature;
- Protecting the high voltage ignition wire to provide a reliable ignition by delivering the spark into the correct spot of the gas-fire burner;
- Availability of felt fabric able to operate at the 260°C–320°C level without melting or stretching significantly;



3. Process and instrumentation diagram for GFPD testing at WMU.



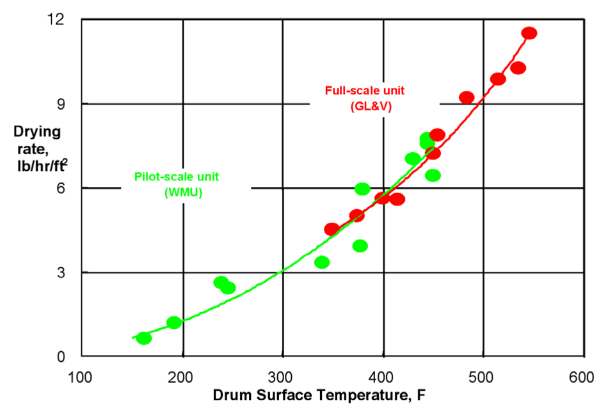
5. ***Full-scale GFPD trial unit: (top) overview of GFPD and (bottom) contact thermocouples for drum surface temperature measurement.***

• Ability of the multi-zone combustion system to locate the air/gas mixers (outside of the drum or inside the drum) that link to the location of the appropriate control valves and programmable logic controllers (PLCs).

With industrial partners and paper industry support, the project team successfully resolved the issues for the full-scale trial and showcase. The full-scale trial unit was designed, engineered, fabricated, and installed at GL&V. This unit, shown in **Fig. 5**, enables the technology to be extensively evaluated and provides a demonstration facility for U.S. papermakers.

Three infrared (IR) temperature sensors, located across the drum (one in the center and two on the periphery), provided surface temperature measurements. Since IR sensors are very sensitive to the surface emissivity, the contact K-type thermocouples mounted on the movable crossbar confirmed the IR readings (Fig. 5). All surface temperature sensors were continually displayed to complement the data acquisition system.

The combustion was stable and complete. The NOx emissions slightly exceeded those expected due to higher combustion temperatures. However, the emissions were still



6. ***TAPPI drying rate vs. drum surface temperature.***

lower than those produced by the majority of steam production facilities.

The TAPPI drying rate of the full-scale GFPD trial system was estimated as approximately 55 kg/m²•h (11 lb/ ft²•h) with the system operating at drum surface temperature of 290°C (550°F). **Figure 6** shows the TAPPI drying rate at the elevated drum temperature, which complements the set of results obtained earlier for the pilot-scale unit evaluated at WMU's pilot paper plant.

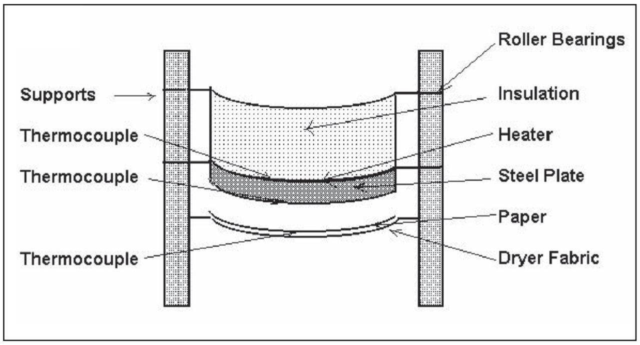
Successful commercialization of the GFPD can help the paper industry increase the production of dryer-limited paper machines by 10%–20%, resulting in significant capital savings for both retrofits and new capacity. A corresponding increase in energy efficiency from 65%–85% would provide large energy savings.

Laboratory results with high-temperature drying

In addition to the process design considerations in installing a GFPD, we determined the effects of high-temperature drying on the heat transfer rates and paper properties. The optimum location for the GFPD depends on the effect of high-temperature drying on the rating rates, essentially the paper-shell contact coefficient, and the resulting paper properties. Different studies on the effect of temperature on drying rates found that the paper-shell contact coefficient might increase, decrease, or remain the same [6-12] with respect to increasing shell temperatures. Drying-induced curl is the paper property of highest concern when shell temperatures increase. The following experiments address both the effect of shell temperature of the drying rates and paper properties.

Experimental

Figure 7 illustrates the simulated heat transfer into the paper during the drying process of a typical paper cylinder. The experimental system consisted of a heated steel platen, a dryer fabric, and thermocouples. Data were collected using three type E thermocouples and a data acquisition system manufactured by Computer Boards Inc. (Mansfield, Massachusetts,



7. Experimental paper drying system.

USA). The thermocouples were located in the paper, at paper-heater interface and at the heater shell interface. The paper, placed on the dryer fabric and a one-half inch 304 stainless steel plate, was heated by a thermal-heating pad manufactured by Heater Designs (Bloomington, California, USA).

The system simulated heat transfer on a paper dryer cylinder. The curvature of the metal shell used in these experiments was that of a 2-m diameter dryer cylinder. The fabric tension in these experiments was 1.1 kN/m, which is within the range recommended by TAPPI [15] for newsprint machines (0.5 kN/m–1.7 kN/m).

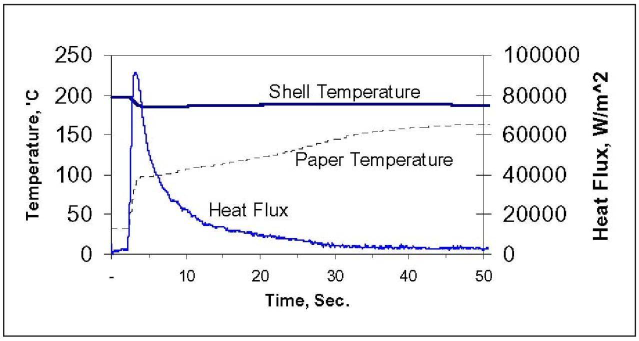
To calculate the paper-shell contact coefficient, it was necessary to determine heat flux and the paper and shell temperatures at the interface. The heat flux was calculated through an explicit model, described by Dewitt [7], using the rapid temperature changes recorded by the three thermocouples. We obtained the shell and paper temperatures from thermal couples embedded at the paper-shell interface.

To obtain representative drying curves, we used a Noble and Woods handsheet machine to make handsheets from both softwood lap pulp and softwood lap pulp once-recycled. In addition to type of pulp, our other control variables were basis weights of 60g/m², 120g/m², and 180g/m² and shell temperatures of 100°C, 150°C, and 200°C. The lowest temperature, 100°C, corresponds to the average cylinder temperature used on conventional cylinder dryers producing newsprint [9]. The highest temperature, 200°C, is representative of the gas-heated dryer surface temperature. The wet handsheets were weighed before and after drying to check moisture content and the amount of evaporated water.

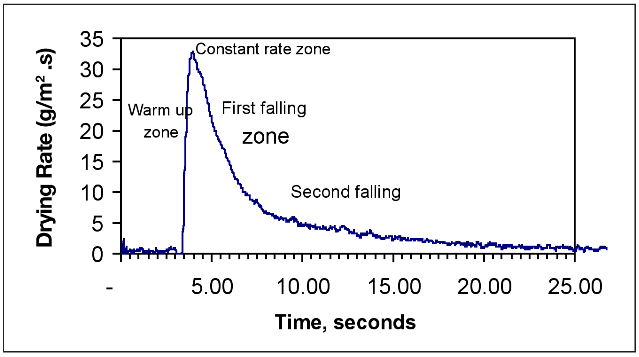
EXPERIMENTAL RESULTS

Handsheets from virgin pulp and recycled paper were dried from 60% moisture content. **Figure 8** shows the typical heat fluxes determined and shows the temperature changes of the heated platen, paper, and heat flux into the sheet.

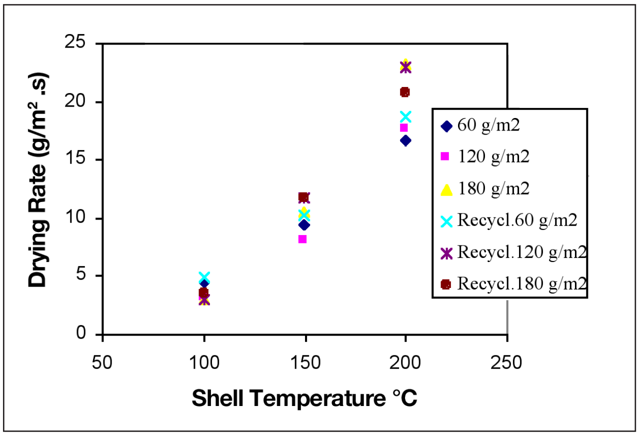
Figure 9 shows the typical drying rate data obtained from both virgin and recycled pulp. The first period is the warm-up period in which the drying rate increases continuously, followed by the constant rate period. In our study, the constant rate period lasts for less than a second in all the drying experiments. The next period is the first falling period. The moisture



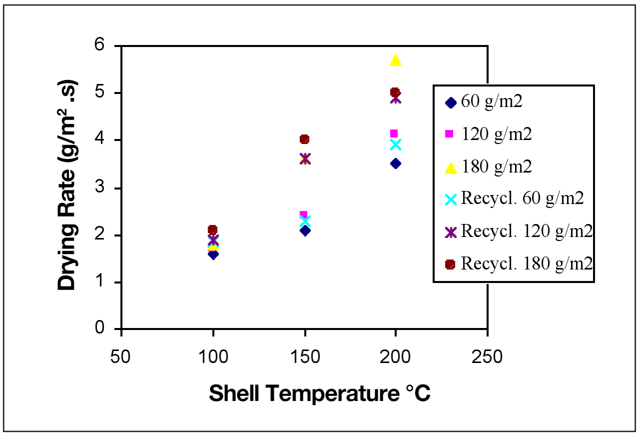
8. Temperature profiles and heat flux during drying.



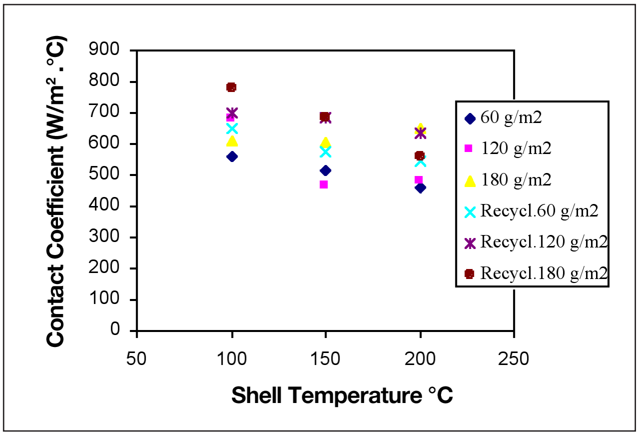
9. Typical rate with 40% initial solids, 180g/m² and 200°C shell temperature using either virgin or recycle pulp.



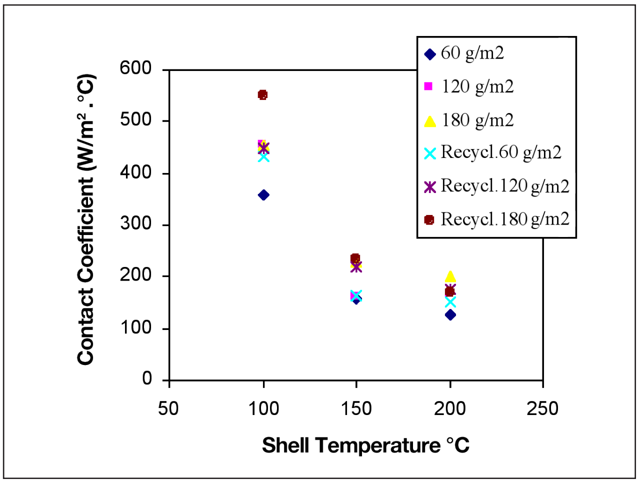
10. Effect of shell temperature and basis weight on the average drying rates for virgin pulp in the first falling rate period.



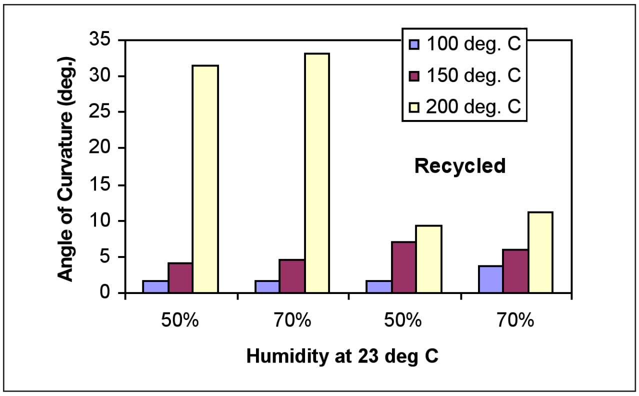
11. Effect of shell temperature and basis weight on the average drying rate in the second falling rate period.



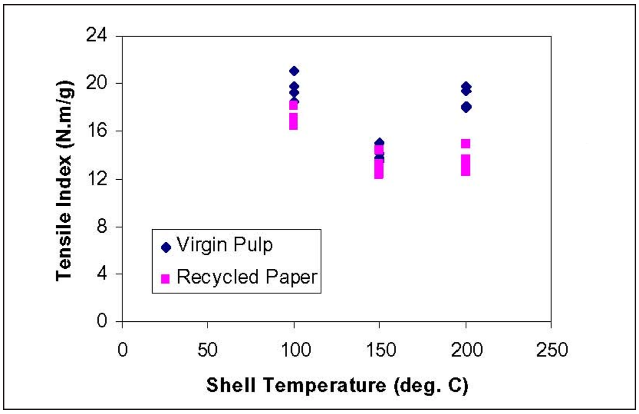
12. Effect of shell temperature and basis weight on the contact coefficient for virgin pulp and recycled pulp in the first falling rate period.



13. Effect of shell temperature and basis weight on the contact coefficient for virgin pulp and recycled pulp in the second falling rate period.



14. Effect of shell temperature on paper curl at 180 g/m² for virgin and recycled pulp.



15. Effect of shell temperature on tensile index for 180 g/m² virgin lap pulp and recycled lap pulp.

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, which causes the web temperature to increase. During the last period, the bound water zone, physicochemical bonds hold the remaining water. These bonds are difficult to break, which causes the drying rate to decrease.

Since the constant rate period is very small and most of the sheet drying occurs in the first and second falling rate periods, the analysis focuses of the effect of average drying rates within these periods. **Figure 10** shows the effect of shell temperature and basis weight on the first falling drying period. There is a linear relationship between the shell temperature and the average drying rate. There were no differences in the drying rates between the virgin and recycled pulp and the basis weight did not significantly affect the drying rate.

Figure 11 shows the effect of shell temperature on average drying rate in the second falling period for virgin pulp and recycled paper. The drying rate increases as the shell temperature increases. There is an increase in the drying rate with the basis weight and no difference between virgin and recycled pulp.

The major resistance to heat transfer from shell to paper is the paper contact coefficient. **Figure 12** shows that the contact coefficient remains constant during the first falling rate period with an average value of 600 W/m²°C. For both virgin and recycled pulp, the contact coefficient in the first falling period is independent of the shell temperature and basis weight.

Figure 13 shows the effect of high surface temperature and basis weight on the contact coefficient for virgin pulp and recycled paper in the second falling rate period. 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.

Physical properties

To study the effect of the high-temperature gas-heated driers on paper curl, we cut the papers dried with different shell temperatures into 15 cm x 15 cm sheets and cycled them between 50%–70% relative humidity. The angle of curvature of the edge rise and the distance between the edge and the midpoint of the strip determined curl. The dried papers curled away from the heated surface toward the side dried last. **Figure 14** shows different paper curl at high temperatures for virgin pulp and recycled paper. The curl increases when shell temperature increases and the tendency for paper to curl is lower with recycling treatment. All drying occurred with the sheet heated on one side only, which created considerable curl. Although these results show the direction of curl and the effect of shell temperature, the actual curl on a commercial machine would be much less.

To study the effect of high-temperature drying on paper quality, we measured tensile strength for all dried samples. **Figure 15** shows that the shell temperature does not affect the paper strength; therefore, the high surface temperature causes no deterioration in the paper structure or paper quality. The recycled paper has a slightly lower tensile strength than original paper, which results from lost strength of interfiber bonding during recycling.

DISCUSSION

The pilot machine trials and construction of the commercial prototype gas-fired dryer demonstrate the commercial feasibility of this new GFDT, while the laboratory study examines two critical aspects of paper drying: the effect of temperature on heat transfer rates and the effect on paper curl. The study also helps determine the ideal location of a gas-fired, high-temperature dryer. With a gas-fired dryer, the shell temperature can be as high as 300°C, which results in a ΔT of approximately 200°C, and a drying rate 3 to 4 times that of a steam heated cylinder. The pilot machine trials, prototype, and laboratory data support the conclusion that with a gas-fired dryer, heat transfer rate, and therefore drying rate, can increase by three times the conventional drying rate. This increase per dryer can add a 2%–4% increase in the drying rate for each high-temperature dryer added. With several gas-fired dryers, the total capacity can increase by 10%–20%.

The laboratory data shows that the paper-shell contact coefficient is independent of temperature in the constant rate period and first falling rate period, but decreases with an increase in shell temperature during the second falling rate period. The implication of this finding is that the ideal location of a high-temperature cylinder is in the middle of the drying chain. If it is placed too close to the wet end, it is likely that a vapor barrier will form between the drying and the paper, reducing the heat transfer rate. If it is placed too close to the dry end, it will be located in the second following rate zone and the heat transfer rate and drying rate will not increase as fast and the shell temperature will increase.

Both the original pulp and the recycled pulp showed similar behavior with regard to the effect of the shell temperature on this contact effect. However, the contact coefficient for the recycled pulp is 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.

As expected, the high temperature and especially one-sided drying affect the curl tendency of the paper. In all cases, the paper tends to curl toward the side dried last and less curling occurs with recycled pulp; however, the curl results when all heat is transferred from one side of the paper. In a commercial operation with two or more high-temperature dryers, curl should not be a problem. Usually a commercial board has an inherent curling tendency and proper placement of the high-temperature dyer could counter this tendency. However, such an installation would not allow curl to be controlled and once the machine situation changed due to factors such as furnish changes or machine speed, a negative interaction between the high-temperature dryer and sheet curl could return. Therefore, two high-temperature dryers, which would allow any curl already present or caused by the high-temperature drying to be controlled, are recommended.

CONCLUSIONS

1. Each gas-fired high-temperature dryer is anticipated to increase the drying rate by 2%–4%. This estimated increase in the overall drying rates results from an increase in temperature driving force for drying in a typical drying chain.
2. The paper-shell contact coefficient is not affected by shell temperature in either the constant rate zone or in the first following rate zone, but decreases with increasing temperature in the second following rate zone. The decrease is present with both types of pulp.
3. The optimal location for installing a high-temperature dryer is near the middle of the dryer chain and never at the beginning or end of the chain.
4. At least two high-temperature dryers should be installed together. This will not only guard against increases in curl, but will allow curl to be controlled by adjusting the relative temperatures of the high-temperature dryers. **TJ**

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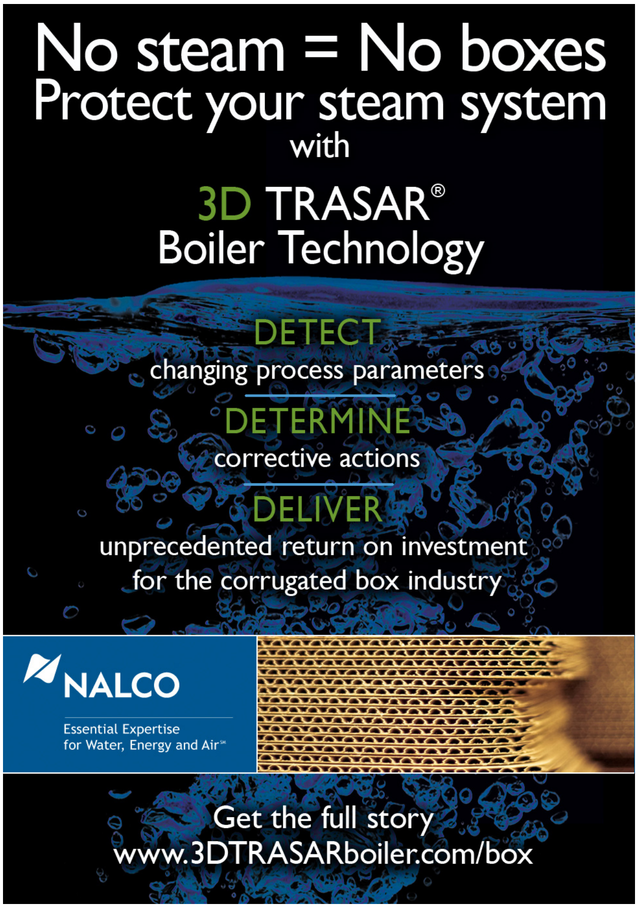


INSIGHTS FROM THE AUTHORS

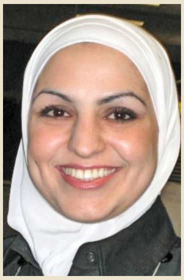
Our goal in researching the gas dryer system developed by GTI was to confirm its potential for decreasing the capital cost for a new dryer capacity, thereby increasing the production rate for dryer-limited machines and increasing drying efficiency.

At WMU, we have conducted numerous studies on drying efficiency and mechanisms for heat transfer from the internal drying shell into the paper, so this project was a natural complement to our previous research.

In our study we faced the challenge of translating our laboratory research into production machine systems, but by comparing the laboratory data to pilot and actual production data, we found assurance that our conclusions were accurate and our estimates correct. We were pleased to discover just how well the data from laboratory tests corresponded to production machine data. We appreciated the cooperation and synergy among government, university personnel, and industrial research, production, and fabrication teams.

Mills can use the gas fired drying system to increase production on dryer-limited machines and to control curl in finished paper. A decrease in the price of natural gases decreases drying costs associated with this technology and results in more favorable economics.

Our next goal is to partner with mills that are interested in installing this technology.



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