Pilot scale investigation of infrared drying of paper

Heng-De Kuang, Jules Thibault, Rubie Chen, and Bernard P.A. Grandjean

ABSTRACT: This investigation considers the infrared (IR) heat transfer mechanism taking place in IR paper drying. A mathematical model was developed to calculate the IR energy density impinging onto the paper sheet, to evaluate the penetration of the IR rays into the paper sheet, and to calculate the IR absorption by the paper sheet. Experimental results, obtained with a pilot-scale machine using a gas-fired IR dryer, show that the evaporation rate generally decreases with time as the paper sheet passes through the drying section. A higher IR emitting surface temperature leads to a higher evaporation rate but to a lower drying efficiency. The paper temperature, measured under the operating conditions studied, is well below 100°C, and it can be effectively controlled by manipulating the blowing air velocity or the IR emitting surface temperature. The surface brightness of a paper sheet, dried with IR energy, can be lowered by about 1 point as the moisture content is decreased to about 0.1 g water/g fiber.

KEYWORDS: Drying, gas heaters, heat transfer, infrared dryers, infrared radiation, mathematical models, paper sheets, pilot plants.

Almost all paper and paperboard are dried with steam-heated cylinders. Auxiliary methods such as high-velocity high temperature air impingement and pocket ventilation systems have succeeded in improving the drying efficiency of steam heated cylinders. Another auxiliary method, which has been used over the last 50 years to increase the drying rate and the drying efficiency, is infrared (IR) radiation *(1)*. However, the use of IR heaters is quite limited. Indeed, in 1980, IR paper drying in American paper industries accounted for less than 3% *(2)*. During the last decade, the use of modern gas and electric IR heaters showed an increase, first in Europe and subsequently in North America. However, these applications were mainly used for coating drying or for moisture profiling, in combination with computer-aided automatic control. The use of IR heaters in the main drying section has not been reported. Comprehensive studies on the mechanisms involved in IR drying process are still limited. Among the few important works conducted during the last decade, Duffy *et al. (3)* used a static apparatus and a gas-fired IR heater to study the drying effect for several types of pulp laps and papers at different exposure distances. Drying rate curves were presented for pulp laps with high grammage; whereas, for light grade papers such as newsprint, only a few data were reported since the drying rate for the light grade papers was too rapid to be measured accurately. Instead of using a gas-fired IR heater, Coste and Charuel *(4)* used an electric IR heater. Heat and water distributions in the drying section were identified by balancing the mass and heat over the IR heater and the paper sheet. However, in both of these studies, drying was usually done under constant operation conditions. Effects of various operating parameters on the IR paper drying were not investigated.

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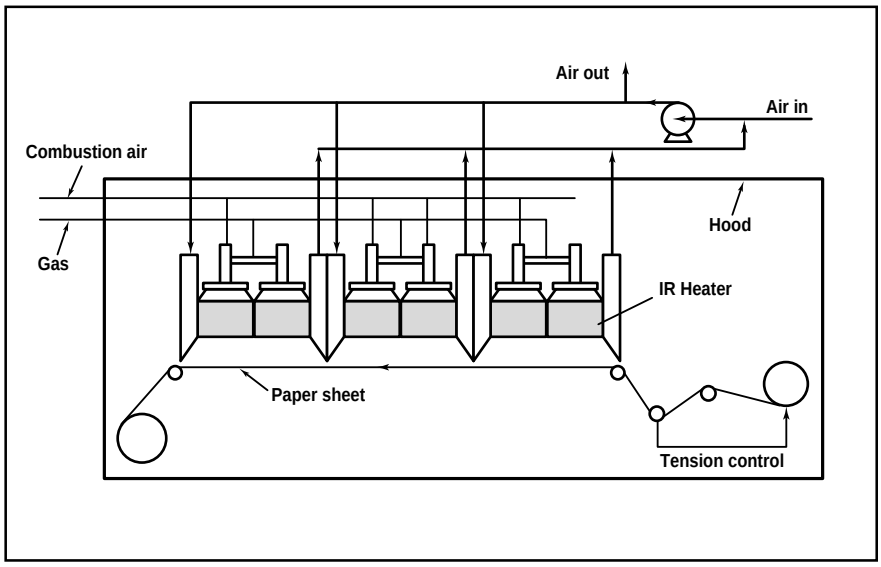
More recently, Lemaitre *(5, 6)* investigated the drying effect and energy consumption as a function of the initial moisture content using different IR heaters. Effects of paper color and grammage were also studied. Instead of performing an experimental investigation, Lampinen and Ojala *(7, 8)* developed models to calculate the IR heater efficiency. However, some heat and mass transfer mechanisms involved in a drying process were not considered.

Other publications on IR paper drying are concerned with coating drying *(9–12)* and moisture content profiling *(13–16)*. The general knowledge of IR applications in paper drying has also been reviewed *(17–19)*. However, the available information is still insufficient to allow an engineer to calculate the drying rate and the energy efficiency, to justify the installation of particular IR heaters on a paper machine, and to operate them properly. In order to better comprehend mechanisms involved in IR paper drying, a research program has been designed. The research program is comprised of both a theoretical study by mathematical modeling and an experimental evaluation of the efficiency of a gas-fired IR heater using a pilot scale machine. In this paper, an analysis of IR heat transfer is presented for a more accurate prediction of the energy absorption by the paper sheet, and hence to predict the possible drying efficiency using the limited information available in the literature. The experimental results concerning evaporation rate, drying efficiency and the effects of various operation parameters on IR drying will subsequently be presented. Finally, effect of a gas-fired IR drying on paper brightness will be briefly discussed.

Experimental

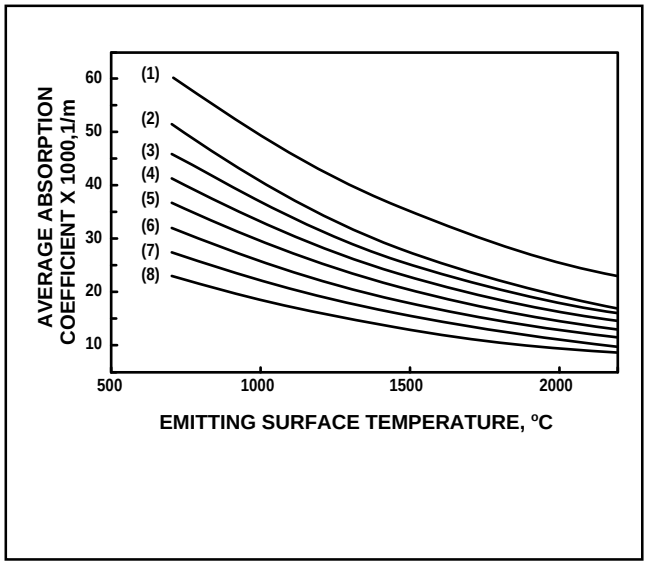
To evaluate the efficiency of gas-fired IR paper drying, a pilot-scale plant was constructed in our laboratory. This experimental system, depicted in **Fig. 1**, consists of a winding system, an IR with a nominal input power of 126 kW and an air circulation system. A reel cylinder, driven by a master motor, is used to provide a wide range of constant running speeds of the paper sheet. At the other end, a slave motor, with a paper tension sensor, controls the speed of the take off paper roll so that the paper tension can be kept constant throughout the winding operation. The exposure distance between the IR emitter surface and the paper surface can be adjusted in a range of 0.1-0.3 m. The gas-fired IR heater is composed of 18 emitter modules (Solaronics), arranged in a configuration of 6 rows by 3 columns. Each emitter has a porous ceramic surface with a width of 0.14 and a length of 0.21 m. Natural gas and combustion air are first mixed in the mixer tube of each emitter and then distributed into each combustion chamber. By varying the flow rate of natural gas, the temperatures of the ceramic emitting surface can be controlled at different levels thereby providing different IR energy spectra. In order to evacuate the gas mixture, which passes through the emitter surface after combustion, and the water vapor evaporated from the paper sheet, each two rows of emitters is surrounded by blowing and suction boxes. The evacuated gas mixture can be partially recycled to control the blowing air temperature.

1. Schematic diagram of the experimental IR drying system

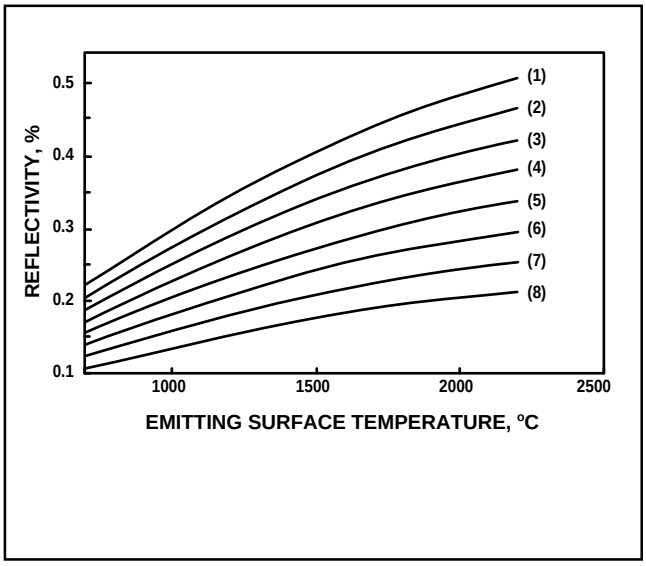


In the present study, the commercial newsprint used was obtained from a paper mill. It had an ovendry basis weight of 46 g/m^2. Prior to each drying experiment, the paper was rewetted by spraying an even layer of water on the paper sheet during rewinding. Then the roll of paper was kept covered overnight to allow the possible swelling of the fibers and to achieve an even moisture distribution within the paper sheet. A wide range of paper moisture content can be obtained by varying the speed of the paper sheet during rewinding. During a drying experiment, the speed of the paper sheet was kept constant in the range of 20–160 m/min. In most of the experiments, the distance between the emitting surface and the paper sheet was kept constant at 10.5 cm and the blowing air temperature was held at 130°C.

2. Average IR absorption coefficient as a function of IR emitting surface temperature: *1* solid fiber; *8* water; *2* to *7* paper with a porosity of 0.7 and moisture content of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 g water/g fiber, respectively



3. Reflectivity of a paper with a porosity of 0.7 at various moisture content as a function of IR emitting surface temperature: *1* dry paper; *2* to *8* paper with moisture content of 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 g and 1.4 g water/g fiber, respectively



Heat transfer analysis

In this investigation, it is assumed that the emitting surface acts as a gray body, and transmissivity of air between the emitting surface and the paper surface is unity since experimental measurement has shown that the humidity of the circulation air is in the range of 0.05–0.01 g/g dry air. Based on the absorption data of water vapor by Hottel and Egber *(20)*, the absorptivity of the humid air above the paper sheet in the usual emitting surface temperature is negligible. At the paper surface, the impinging IR rays either penetrate into the paper sheet or are reflected. Therefore a portion of the IR energy will be reflected back and forth between the paper sheet and the emitting surface. Its energy will be progressively attenuated due to the losses into surroundings and the absorption on both the emitting and the paper surfaces for each reflection. Summing up the energy absorbed from any primary beam and repeated reflections gives the energy density of the IR rays, penetrating into the paper sheet as follows:

$$I_t = F_{ip}\frac{A_i}{A_p}\frac{\left(1-R_{wp}\right)e_i\sigma T_i^4}{1-F_{ip}F_{pi}R_1R_{wp}} \qquad (1)$$

where F_{ip} and F_{pi} are the view factors between the IR emitters and the paper sheet. They can be calculated using the equation contained in Hsu *(21)*. In Eq. 1 R_i can be estimated as $(1-e_i)$, while R_{wp} is evaluated by the surface area weighted average of the reflectivities of water and dry paper:

$$R_{wp} = R_{dp}(1-\varepsilon S_t) + R_w\varepsilon S_t \qquad (2)$$

Within the paper sheet, the IR energy density is attenuated due to the internal absorption by water and fibers. The IR rays are considered to travel through the paper sheet in the direction normal to the paper surface. Bouguer's law is used to determine the energy density of the IR rays along its traveling path:

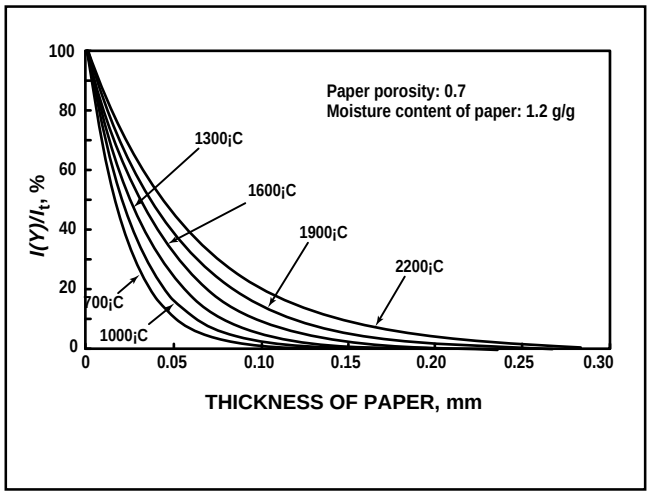
$$I(Y) = I_t e^{-\int_0^Y \bar{a}_{wp}dY} \qquad (3)$$

where Y is the coordinate representing the paper thickness with zero corresponding to the top surface of the paper sheet and $\bar{a}_{wp}$ is the average absorption coefficient of the wet paper sheet. In the present study, the average absorption coefficient is calculated using an average value of the absorption coefficients of water and solid fibers as expressed by the following equation:

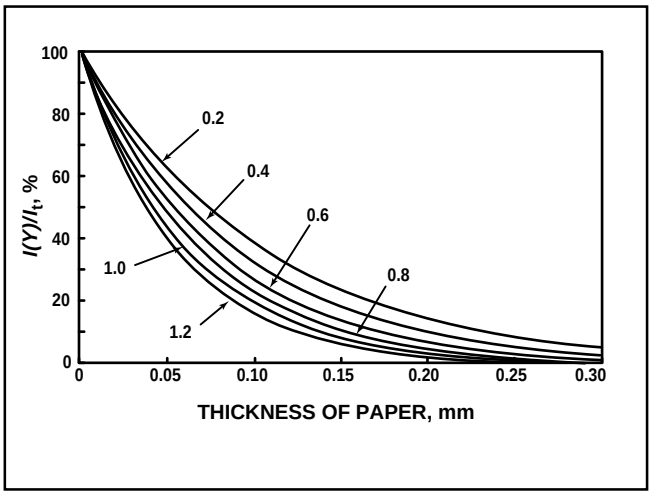
$$\bar{a}_{wp} = \varepsilon S\bar{a}_w + (1-\varepsilon)\bar{a}_f \qquad (4)$$

Literature information about the IR absorption and reflection by a paper sheet is quite limited. It comprises mainly absorption spectra that are usually determined for specific moisture content and paper sheet thickness. These spectra are not of great use for calculating the IR absorption for paper sheets under other operating conditions. In the present study, absorption spectra of water from Stephansen *(9)* and of paper from Ojala and Lampinen *(8)* were used to calculate the absorption at different emitting surface temperatures by integrating the corresponding absorption spectrum, weighted with monochromatic emissive power at the corresponding temperature. The computed absorption data were then used to calculate the generalized absorption coefficients of water

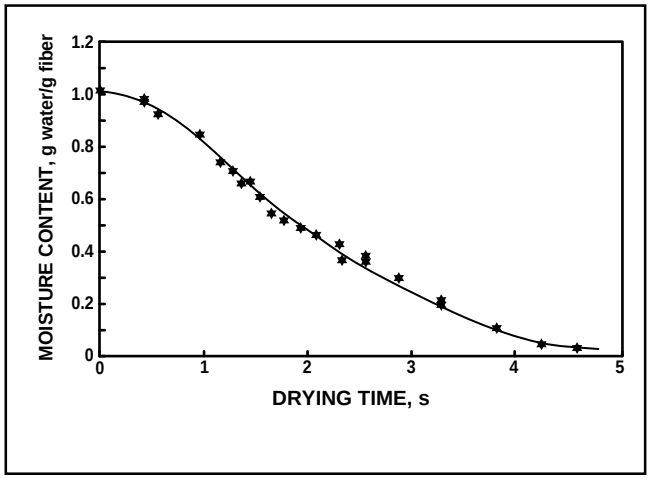
4. IR energy attenuation as a function of paper thickness at various IR emitting surface temperatures



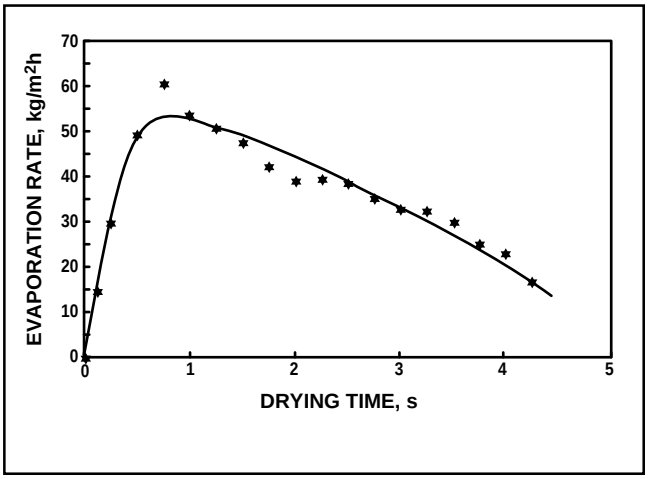
5. IR energy attenuation of a paper with a porosity of 0.7 at an IR emitting surface temperature of 2000°C and at various moisture contents of the paper sheet



6. Variation of moisture content as a function of drying time with an IR emitting surface temperature of 1030°C



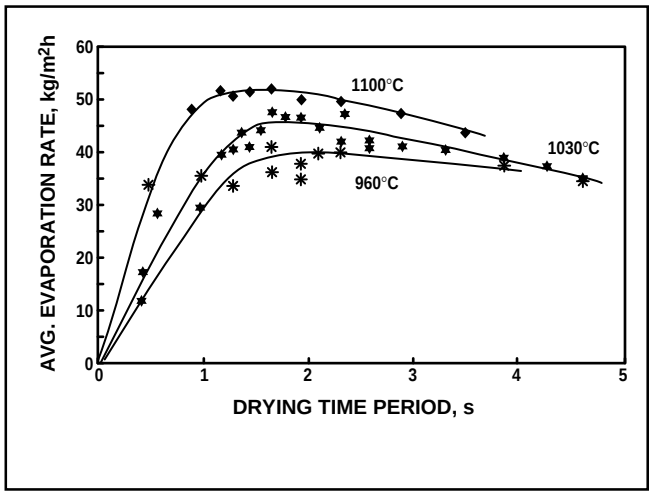
7. Variation of instantaneous evaporation rate as a function of drying time with an IR emitting surface temperature of 1030°C



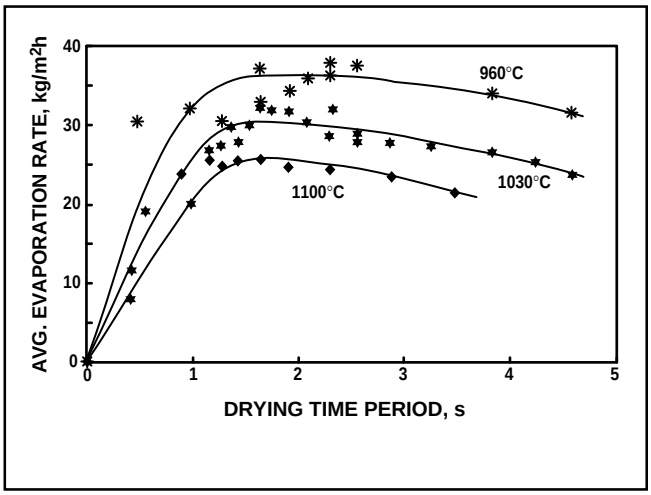
(a_w) and solid fibers (a_F) as functions of the IR emitting surface temperature. These generalized absorption coefficients (shown in **Fig. 2**) can be used to calculate the average absorption coefficients of the wet paper sheet ($\bar{a}_{wp}$) under various moisture contents and porosities. The porosity is a function of paper grammage and thickness. As an illustrative example, Fig. 2 also shows the average absorption coefficient of a paper with a porosity of 0.7 and with a moisture content varying from 0.2 to 1.2 g water/g fiber. On the other hand, the reflectivity of water surface (R_w) is 3–4% in the wavelength range of 1–15 μm for an incident angle of 0–60°. For IR paper drying, a reflectivity of 4% can be used for the water surface in the calculation of the reflectivities of wet paper sheet. For the reflectivity of dry paper (R_{dp}), the same method as for the absorption coefficient is used with the spectra published by Ojala and Lampinen *(8)*. **Figure 3** presents the reflectivity of dry paper as well as that of a wet paper sheet as a function of the emitting surface temperature, assuming a paper porosity of 0.7.

In IR paper drying, it is known that a higher emitting surface temperature leads to a greater penetration of the IR energy into the paper sheet. In this investigation, the IR energy attenuation within a paper sheet for different moisture contents, paper thickness and IR emitting surface temperature were calculated from Eqs. 3 and 4 and the data of Fig. 2. Choosing a paper porosity of 0.7 as an example, the IR energy attenuation at different IR emitting surface temperatures and different moisture contents as a function of

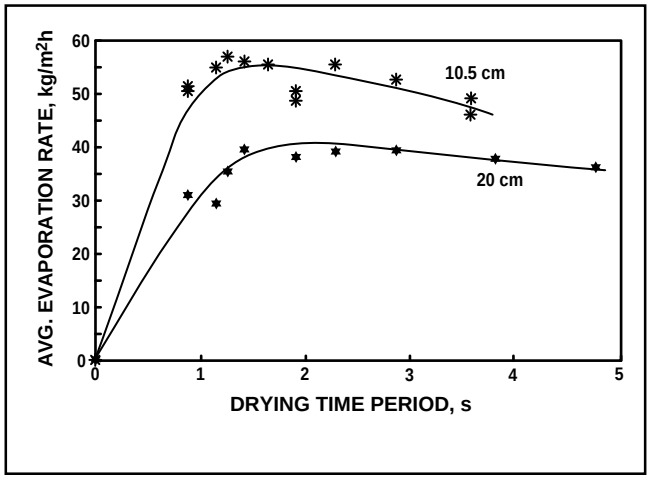
8. Variation of average evaporation rate as a function of drying time period in each passage of the paper sheet through the IR heater at three different IR emitting surface temperatures



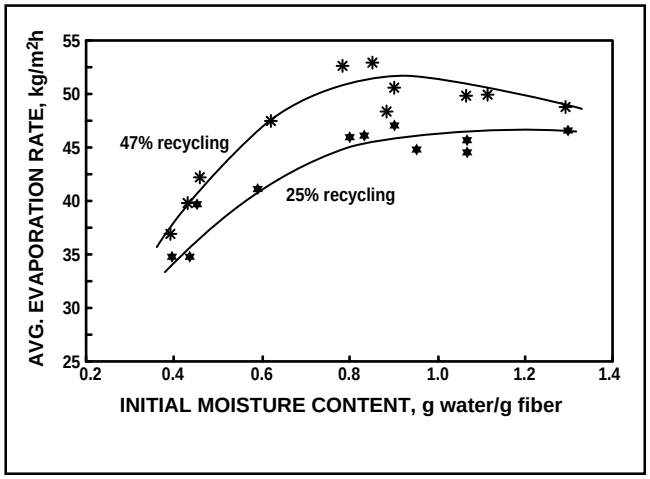
9. Variation of average drying efficiency as a function of drying time period in each passage of the paper sheet through the IR heater at three different IR emitting surface temperatures



10. Variation of average evaporation rate as a function of drying time period in each passage of the paper sheet through the IR heater at two different exposure distances (IR emitting surface temperature: 1100°C)



11. Variation of average evaporation rate as a function of initial moisture content of paper sheet at different air recycle ratios (IR emitting surface temperature: 100°C)



the paper thickness are illustrated in **Figs. 4 and 5**, respectively.

The most useful information is the absorption by the whole paper sheet and the efficiency of the IR heaters. The absorption by the whole paper sheet is the IR energy attenuation as it travels through the paper sheet. It is expressed by the Eq. 5:

$$q_a = I_t \left(1 - e^{-\bar{a}_{wp} L} \right) \qquad (5)$$

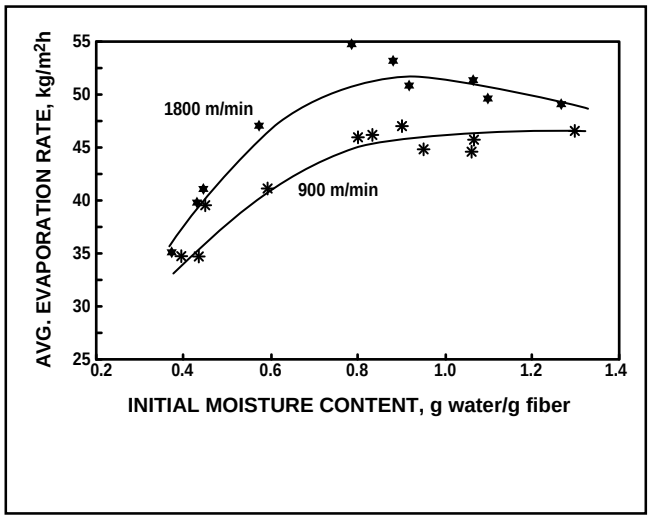
The efficiency of the IR heaters can be estimated by the IR energy absorption efficiency which is defined in the present study as the ratio of the IR energy absorbed by the paper sheet to the IR energy emitted from the IR heater, and expressed from Eqs. 1 and 5 as:

$$\eta_a = \frac{F_{ip} \left(1 - R_{wp} \right) \left(1 - e^{-\bar{a}_{wp} L} \right)}{1 - F_{ip} F_{pi} R_i R_{wp}} \qquad (6)$$

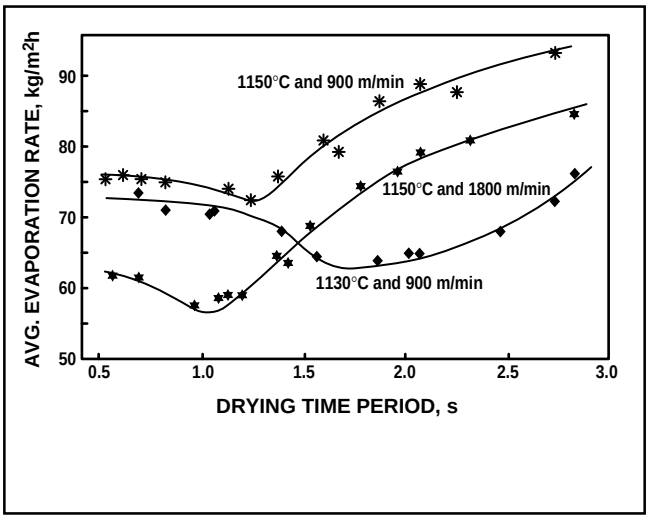
The reflection and the internal absorption of the paper sheet depend on the IR emitting surface temperature, the reflectivity of dry paper, the paper porosity and moisture content. Therefore, the IR energy absorption efficiency depends on the view factor between the IR heater and the paper sheet, the IR emitting surface temperature, the reflectivity of dry paper, the paper porosity, the paper moisture content, and the paper thickness.

With these equations, as well as the available absorption and reflection data, the absorptivity and the transmissivity of the paper sheet under different conditions can be calculated. It is also possible to estimate the variation of the IR absorption by the paper sheet and the

12. Variation of average evaporation rate as a function of initial moisture content of paper sheet at different blowing air velocities (IR emitting surface temperature: 100°C)



13. Temperature of the upper surface of paper sheet at different IR emitting surface temperatures and blowing air velocities



energy absorption efficiency as a function of the moisture content of the paper sheet, and as a function of the emitting surface temperature.

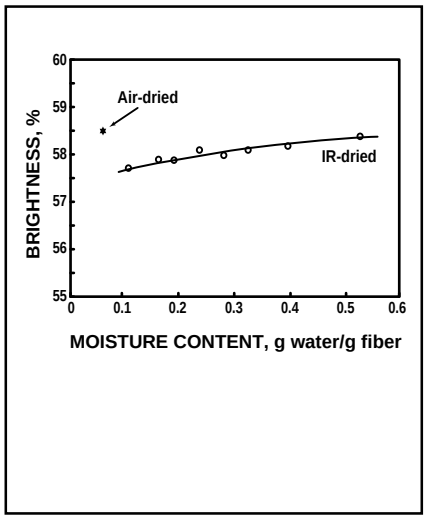
Experimental results and discussion

In order to establish a typical drying curve and to monitor the decrease of the moisture content during the drying process, the paper sheet was exposed to the IR radiation for different periods of time by passing the paper sheet through the IR heater at different speed. In each individual experiment, the initial moisture content of paper sheet and the other operating parameters were held constant. The moisture content of paper after drying was determined gravimetrically at the end of each exposure time. **Figure 6** shows a typical drying curve where the moisture content is plotted as a function of the drying time. This figure shows that the moisture content decreases rapidly. About 20% of the moisture content was evaporated with a drying time of 1 second, which corresponds to about 22% of the total drying time required to complete drying. In the case of steam cylinder drying, it has been reported that—for the same time period—only about 7% of the evaporation could be achieved *(22)*. Based on the decrease of the moisture content, the instantaneous evaporation rate was calculated graphically and it is presented in **Fig. 7**. The instantaneous evaporation rate is proportional to the slope of the drying curve in Fig. 6. Since this slope depends highly on the precision in the determination of the moisture content during drying, and a high precision is difficult to attain with a pilot scale plant, the instantaneous evaporation rates presented in Fig. 7 are therefore considered as an approximation of actual evaporation rates. However, despite this limitation, it is clear that, in general, the evaporation rate decreases throughout the drying except for the initial sharp rise.

It has been well accepted that IR radiation, when used at the later stage of conventional cylinder drying, can increase the drying rate, hence extending the constant drying rate period to the later stage of drying. In addition, previous experiments carried out on pulp laps with more than 700 g/m^2 have shown the distinct presence of a constant rate period by IR drying *(3)*. Therefore, one might expect the existence of a constant drying rate period in IR drying. However, if a constant rate drying is present when using IR radiation for papers such as newsprint, it is over a very short time span, as shown in Fig. 7. In this series of experiments, all operating parameters were held constant except the paper running speed. Therefore, the variation of the evaporation rate can be attributed mainly to the variation of the IR heat transfer to the paper sheet during drying. It has been found that wet materials almost always reflect less IR energy than dry materials. There are two principal reasons for the reduction of reflectivity upon wetting. One is the low reflectivity of the water surface. Another is the multiple internal reflections within the liquid layers between the solid surface and liquid surface. Throughout the drying process, the IR paper surface reflectivity increases until it assumes a constant value when the paper surface becomes completely dry. On the other hand, internal absorption decreases with decreasing moisture content as indicated in Eq. 4. Consequently, IR heat transfer to the paper sheet will decrease as the paper becomes drier. These are the main reasons for the absence of a constant drying rate period.

Drying experiments at different IR emitting surface temperatures

14. Brightness of paper versus moisture content of paper sheet after pre-drying with IR heater



were also carried out. For each IR emitting surface temperature, a series of runs were conducted using different paper running speeds. Results confirm the absence of a constant drying period in the drying process. In addition, to evaluate the drying effect at different IR emitting surface temperatures, average evaporation rates were calculated based on the moisture removal in each passage of the paper sheet through the IR heater. By measuring the gas flow rate for each emitting surface temperature, the average drying efficiency of the IR heater was also calculated. The average drying efficiency is defined as the ratio of theoretical heat required to evaporate the water to the actual heat consumed as the paper passes through the IR drying section. **Figures 8 and 9** show, respectively, the variation of the average evaporation rate and the average drying efficiency of the IR heater for three IR emitting surface temperatures. Higher IR emitting surface temperatures give higher evaporation rates, but lower drying efficiencies. As the emitting surface temperature increases, the IR energy increases very rapidly according to the Stephan-Boltzman law, and then higher evaporation rates were obtained. However, from Figs. 2 and 3, when the IR emitting surface temperature increases, the reflectivity of a paper sheet increases and the IR absorption coefficients result in a lower IR energy absorption efficiency as indicated in Eq. 6. Moreover, when the present gas-fired IR heater operates at higher emitting surface temperature, it has a lower transformation efficiency. These reasons explain the variation of the drying efficiency with the emitting surface temperature; therefore, the selection of the emitting surface temperature is a compromise between the evaporation rate and the drying efficiency, depending on particular circumstances and operational requirements.

Figure 10 shows the effect of the spacing between the emitting surface and the paper sheet on the average evaporation rate. Under the same operating conditions, a larger exposure distance results in a smaller view factor between the heater emitting surface and the paper sheet. Hence, a larger exposure distance has a lower IR energy density and should consequently lead to a lower drying rate. In Fig. 10, when the spacing is increased from 10.5 cm to 20 cm, a significant reduction in the evaporation was indeed observed. In an industrial application, the effect of paper-heater spacing would be greatly reduced due to the width of the running paper sheet, resulting in a view factor that is significantly higher. Nevertheless, this effect should not be ignored in the design and for any application of IR paper drying.

Further experiments were conducted to investigate the effect of air conditions on the drying rate. In these experiments, the paper sheet was first rewetted to different moisture contents and then dried at a constant paper running speed of 70 m/min. By adjusting the air valves in the air circulation system, two different blowing air velocities and two different air recycle ratios were used. The blowing air velocity was measured at the exit of the blowing slits of the IR dryer. The air recycle ratio is defined as the ratio of the flow rate reentering into the IR heater to the total gas flow rate leaving the circulation fan. **Figures 11 and 12** present the average evaporation rate as a function of the initial moisture content under different air conditions. It is indicated that a higher initial moisture content has a higher evaporation rate, except when the initial moisture content is higher than 1.0 g water/g fiber. In the latter case, a large amount of sensible heat is required to heat up the wet sheet to a point of significant evaporation. Figure 11 shows that a higher recycle ratio leads to a higher evaporation rate. Since the combustion waste gas of very high temperature and the evaporated water vapor are mixed and evacuated by the suction boxes of the IR heater, a higher recycle ratio implies a hotter and more humid air blowing into the heater. At a 25% recycle ratio, the temperature and the humidity of blowing air are around 100°C and 0.04 g/g dry air, while at a 47% recycle ratio, these values increase to 150°C and 0.09 g/g dry air, respectively. Air temperature and humidity have opposing effects with regard to drying. A higher air humidity reduces the water vapor concentration driving force for water vapor diffusion away from the paper sheet and produces a greater attenuation of IR energy in the humid air. However, results presented in Fig. 11 clearly indicate that the influence of the air temperature dominates over that of the air humidity. Figure 12 compares the evaporation rate under two blowing air velocities. A faster blowing air velocity leads to a higher evaporation rate. From the previous described heat transfer analysis, an increase in blowing air velocity has a negligible effect on the IR heat transfer to the paper sheet. Therefore, the increase of the evaporation rate shown in Fig. 12 is attributed primarily to the increase in convective heat

transfer. It should be noted that the convective heat transfer is increased due to the faster blowing air velocity in two ways: (a) an increase in the heat transfer coefficient, and (b) a decrease in the paper surface temperature, due to an increase in the mass transfer coefficient, resulting in a higher temperature driving force between the ambient air and the paper surface. The effect of the blowing air velocity would be more appreciable if the outlet air valve could be manipulated to give a higher blowing air temperature.

The difference in the evaporation rate, observed for different air recycle ratios and different blowing air velocities (Figs. 11 and 12), tends to diminish when the initial moisture content of paper is lower than 0.6 g water/g fiber. At such a low moisture content, water evaporation takes place mainly within the paper sheet and water becomes more difficult to remove. In addition, due to the hygroscopic properties of paper and the accumulation of the IR absorption at the paper surface, the temperature on the paper surface increases more rapidly in this stage of drying. As a result, the convective heat transfer is reduced and the effect of blowing air conditions on the drying rate diminishes.

In this study, an IR thermometer was used to measure the temperature at the top surface of the paper sheet as soon as the paper exits the IR heater. When the paper sheet enters the drying section, its temperature increases very rapidly. In less than half a second, the sheet surface reaches a temperature in excess of 60°C, depending on the operating condition. The results of the temperature variation as a function of the drying time are presented in **Fig. 13.** Following an initial rapid increase, the temperature of the paper sheet decreases slightly before increasing again. The rapid initial temperature increase is due to the large IR energy absorption combined with a relatively low evaporation rate resulting from the low water temperature in the early stage of drying. The temperature of the paper sheet continuously increases until the energy required for water evaporation equals the IR energy absorption. Subsequently, the temperature of the paper sheet decreases due to the decrease of the IR energy absorption during the drying process while the high evaporation rate persists. The sheet surface temperature decreases until reaching a minimum value where the surface of the paper becomes dry. It is hypothesized that when the water migration from the paper interior is not sufficient to compensate for the surface water evaporation, evaporation occurs within the paper sheet leaving a dried layer at the paper surface. It is the IR energy absorption by the top dried layer of the paper sheet that leads again to a rapid temperature increase of the paper surface in the final drying stage.

Figure 13 shows that an increase of the blowing air velocity from 900 to 1800 m/min results in a lower paper surface temperature, but does not change the shape of the temperature-time profile. At a higher blowing air velocity, both the heat and mass transfer coefficients are increased. However, from the previous heat transfer analysis, the major energy source of IR absorption by the paper sheet is not increased with the blowing air velocity. The increase of the convective heat transfer could not sustain the higher evaporation rate induced by the increase of the mass transfer coefficient. Instead, the temperature of the paper sheet has to decrease to give a lower driving force of water vapor concentration so that the energy consumed for water evaporation can balance with the heat transferred into the paper sheet. Figure 13 also clearly puts in evidence the influence of the emitting surface temperature on the paper temperature. The lower level of the temperature curve at a lower IR emitting surface temperature is an indication that less IR energy is transferred into the paper sheet in this case.

Effect of IR drying on paper brightness

During IR drying, the paper sheet is exposed to a heat source of very high temperature. The heat transfer and evaporation rates are much higher than those in conventional cylinder drying. To determine if the paper brightness is affected by such intense drying, an evaluation of the paper brightness was carried out. samples were first dried, with the IR heating system, from an initial moisture content (1.15 g water/g fiber) to different moisture contents of 0.11 to 0.53 g water/g fiber. Then, the samples were conditioned in a standard test atmosphere according to TAPPI Test Method T 402. To evaluate the effects of the operating conditions, different IR emitting temperatures, different exposure distances and exposure times were used. In addition, a sample was completely air-dried in the standard test atmosphere so that it can be compared with those pre-dried by the IR heater. **Figure 14** illustrates the variation of paper brightness. From this figure, it is seen that the brightness of the paper sheet decreases slightly with the decrease of the IR pre-dried moisture content regardless of the different emitting surface temperatures and the different exposure distances used in these experiments. Figure 14 also shows the brightness of the air-dried sample. As the sample is dried by IR energy to about 0.1 g water/g fiber, the brightness of the IR dried sample decreases about 1 point when compared with the air-dried sample.

Conclusions

A brief description of heat transfer from an IR heater emitting surface to a paper sheet has been presented. From this analysis, it is possible to

calculate the IR energy density impinging onto a paper sheet and to determine the penetration of IR rays into the paper sheet. The IR absorption by the paper sheet and the IR energy absorption efficiency of the IR heater can also be calculated. This simple method can be used to evaluate an IR drying system.

A series of experiments was performed with a pilot-scale drying system to evaluate the influence of various operating conditions on the drying rate when IR heaters are used. Experimental results showed that under normal operating conditions, a constant drying rate period is almost absent when newsprint is dried with IR heaters. A higher emitting surface temperature has a higher evaporation rate but a lower drying efficiency. Under the operating conditions, used in the present investigation, an increase of blowing air velocity and an increase of the air recycle ratio can improve the drying rate and efficiency. The temperature of the paper sheet exhibits a small decrease after the initial rapid increase and then a rapid increase at the later stage of drying. The paper temperature can be effectively controlled by manipulating the blowing air velocity or the IR emitting surface temperature. When the paper sheet is dried with the IR heater from 1.15 to 0.1 g water/g fiber, the brightness of paper sheet is reduced by about 1 point.

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Nomenclature

- A = area, m^2
- $\bar{a}_{wp}$ = average IR absorption coefficient, 1/m
- a = IR absorption coefficient, 1/m
- e = emissivity
- F_{ip} = view factor from emitters to paper sheet
- F_{pi} = view factor from paper sheet to emitters
- I = IR energy density, $J/s \cdot m^2$
- L = paper thickness, m
- q = IR absorption, $J/s \cdot m^2$
- R = reflectivity
- S = saturation, the ratio of void volume occupied by water
- T = temperature, K
- Y = coordinate in paper thickness direction
- ε = porosity, ratio of void volume in paper sheet
- η = IR energy absorption efficiency, %
- σ = Stephan-Boltzmann constant, $J/s \cdot m^2 \cdot K^4$

Subscripts

- dp = dry paper
- f = solid fiber
- i = infrared emitter
- p = paper
- t = sheet top
- w = water
- wp = wet paper
- a = absorption