# Experimental evaluation of electric infrared dryers

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## Abstract

*Infrared (IR) dryers are widely used in the paper industry for drying coated paper grades. However, there is limited knowledge regarding the efficiency of IR dryers. This study was undertaken to investigate the radiation efficiency and the total efficiency of electric IR dryers. Radiation efficiency was measured in the laboratory and on an industrial machine. The results indicate that radiation efficiency increases with increasing power and is just above 60% at full power. Total efficiency—the fraction of supplied power that ends up in the paper web—was measured on a small off-machine coater. The results indicate a total efficiency of approximately 40%. Problems and experimental techniques are discussed, and recommendations for future evaluations are presented.*

## Introduction

Infrared (IR) dryers are widely used in the paper industry, mainly for drying of coated paper and for correcting moisture profiles. IR dryers are small units with very high heat flux, which makes them easy to retrofit on existing machines. The high heat flux is obtained without contact, which is a major advantage in drying of coated paper. In addition, dryer output in the cross-machine direction (CD) is easily controlled, which makes IR dryers useful in correcting moisture profiles. When considering installed power, drying of coatings is the most common application of IR dryers in the paper industry. The size of IR installations has increased in recent years, and installed power of 10 MW or more is no longer unusual. Indeed, the upper range of IR dryers in the paper industry is currently 30–40 MW *(1)*.

Two types of IR dryers are widely used in the paper industry: gas-fired medium-wave dryers and electrically heated short-wave dryers. These two dryer types are quite different in design and operating principle. Short descriptions of both dryers and their application in the drying of coatings are given by Hagen *(2)*.

Considering the size of modern installations and the fact that IR drying of paper is an established technology, there is surprisingly little known about the energy efficiency of IR dryers. Most papers on the subject present estimates rather than results from measurements and experience. The situation is not improved by the fact that most of the estimates are provided by suppliers who state high efficiencies for their dryers and low efficiencies for all other dryers.

The radiation efficiency of an IR heater is the fraction of supplied energy—fuel or electricity—that is actually converted into radiation. The radiation efficiency can be thought of as an upper limit for the efficiency of the heater working in a dryer. Losses of radiation are inevitable, and energy not converted into radiation is normally used only to a small extent in the dryers. There are a few published works dealing with the radiation efficiency of gas-fired IR heaters, e.g., Speyer *et al. (3)*, who measured maximum radiation efficiencies in the range 25–54% for various commercial heaters. Measurements on electric IR heaters are scarcer. Yetman *(4)* measured the radiation efficiency of several IR heaters, most of them gas fired, using a pyrometer taking 121 readings over a 1.314-m hemisphere. Among the heaters tested was an electrical short-wave heater giving a radiation efficiency of 44–46%, which was the highest result in these trials. Graab *(5)* measured the radiation efficiency of an electrical IR dryer using a simple calorimetric method. The measured efficiency was 62%. Evin *(6)* used a more elaborate calorimetric method to determine the radiation efficiency of a short-wave IR heater with a white ceramic reflector. The measured efficiency was 48%. Bédard and Brunet *(7)* report measurements from a test rig for IR heaters where the radiation efficiency for a short-wave IR heater was determined as 76–78%.

Radiation efficiency is an interesting parameter when comparing different heaters or when developing new heaters. However, it is of little value when choosing or designing an IR dryer for a paper machine. Papermakers need to know how much of the energy supplied to the IR heater actually ends up in the paper web. There is a clear need for measurements on commercial paper machines or on pilot machines.

Lemaitre and Glise *(8, 9)* investigated gas-fired and electric IR radiators on a pilot paper dryer. Efficiency was defined as the energy consumed in evaporating moisture and increasing temperature compared with the supplied power. For unbleached uncoated paper, efficiency was within the range 30–50% for both the gas-fired and the electric dryer. For both dryers, the efficiency increased from about 30% (at 10% initial moisture content) to just below 50% (at 30% initial moisture content). The gas-fired dryer produced the same result for bleached paper. For the electric dryer, however, the efficiency for bleached paper was approximately 10–15% lower over the whole range of initial moisture content, for an overall efficiency of 20–35%. When drying coated paper, the efficiency was a bit lower for both types of dryers. At an initial moisture content of 15%, the efficiency was 25–30% for the electric dryer and 30–35% for the gas-fired dryer.

Stenström and Johansson *(10)* evaluated the efficiency of an industrial gas-fired IR dryer in terms of fuel consumption, radiation flux, web moisture reduction, and web temperature. The radiation efficiency was 35–39%, and the total efficiency—based on evaporation and temperature increase—was approximately 28–31%. Unfortunately, there was a rather poor accuracy in the measurements of moisture reduction, and the radiator was working at a high excess air ratio that impeded radiation and thus reduced the total efficiency. Evin *et al. (11)* present results from pilot machine trials comparing the efficiency of a ”classical” dryer with that of a new design. For the classical dryer, the total efficiency, based on evaporation and temperature increase for a bleached paper, was 20–35% at moisture contents in the range 8–33%. The result for the new design was somewhat higher, with efficiencies of 27–43% for moisture contents in the range 14–31%.

The present work was undertaken to further investigate the efficiency of electric IR dryers. Lab-scale measurements were carried out to investigate the radiation efficiency of an electric IR heater as a function of supplied electric power. Additional measurements were conducted on an industrial off-machine coater to investigate the fraction of supplied energy that is actually absorbed by the web using different back-reflector alternatives.

## Lab-scale investigation of radiation efficiency

A small electric short-wave IR heater designed for paper drying was studied. The heater was 15 × 40 cm and used 12 tungsten halogen lamps rated at 2 kW each. Inside the heater, the lamps are mounted in front of a flat gold-coated reflector and protected by a glass sheet made of water-free quartz. The components of the IR module are cooled convectively with air supplied by a small fan attached to the unit. The principle layout is illustrated in **Figure 1**.

The IR module was mounted horizontally, facing an open water-cooled tray measuring 1 × 1.5 m, as seen in Fig. 1. The tray was painted inside with a matte black color. During the experiments, water flow through the tray was 5-cm deep. Since water absorbs virtually all IR radiation and the black bottom absorbs most of the visible radiation, the tray absorbs almost all radiation emitted from the IR heater. Thermocouples were inserted into the cooling water supply and exit pipes to measure the temperature increase and thus, together with the flow rate of the water, the radiation efficiency. During these measurements, the distance between heater and water surface was reduced to only 2 cm, thus effectively reducing losses of radiation.

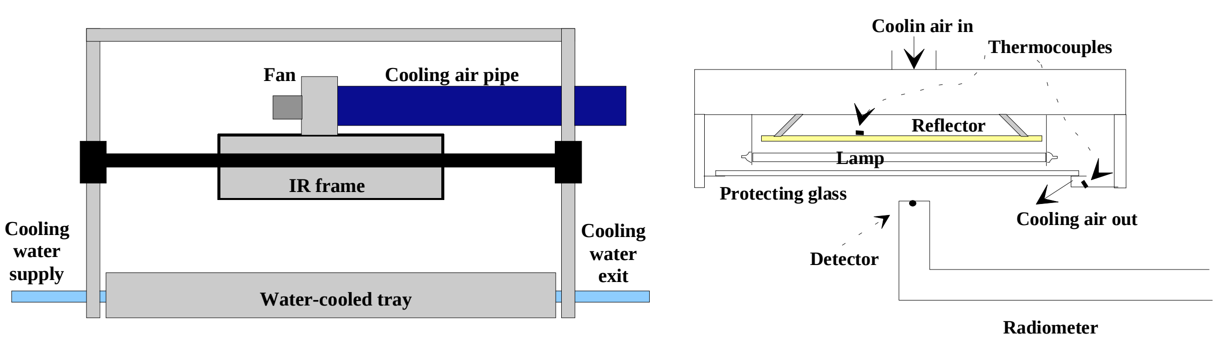


**Figure 1.** *Lab-scale setup; left, the IR module in holder with water-cooled tray; right, cross section of the IR module with the radiometer*

The radiation was also measured using a radiation heat-flux probe, a 2π-radiometer from Lands Instruments International Ltd. The instrument is indicated to the right in Fig. 1. At the top of the instrument is an ellipsoidal cavity, as illustrated in **Figure 2**. Radiation from 2π steradians falls into the cavity, is reflected by the gold-coated walls, and is finally absorbed by the blackened detector at the bottom. The detector involves a differential thermocouple that measures the heat flux. A calibrated nitrogen purge is used to avoid convective heat into the cavity, and the entire instrument is cooled with large flows of cooling water. The instrument measures the radiation intensity at the location, not the intensity emanating from any surface. Note that no optical components limit the spectral range of measurement. The accuracy of the instrument is estimated by the supplier to be within ±3%.

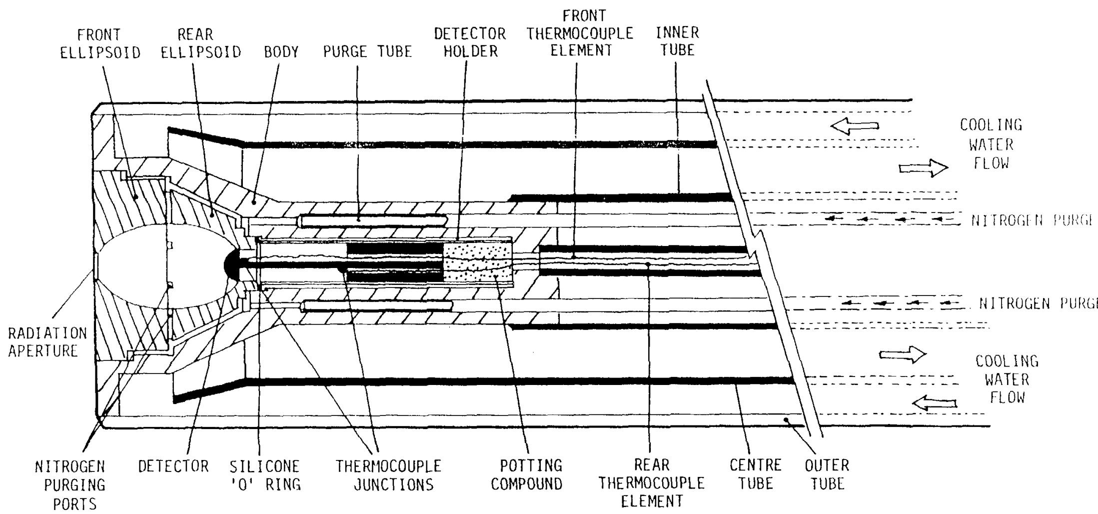


**Figure 2.** *Operating principle of the 2π-radiometer*

The total power emitted by the IR module was determined by using the radiometer to measure the intensity at 63 different points in front of the heater, 1.5 cm from the protecting glass. This scanning procedure was repeated for six different levels of electric power input in the range 4.8 kW to the maximum power 19.2 kW. As an example, **Figure 3** shows the intensity distribution under the heater at maximum power supply. Integration of the intensity distribution under the IR frame gives the total power converted to radiation at the different power levels.

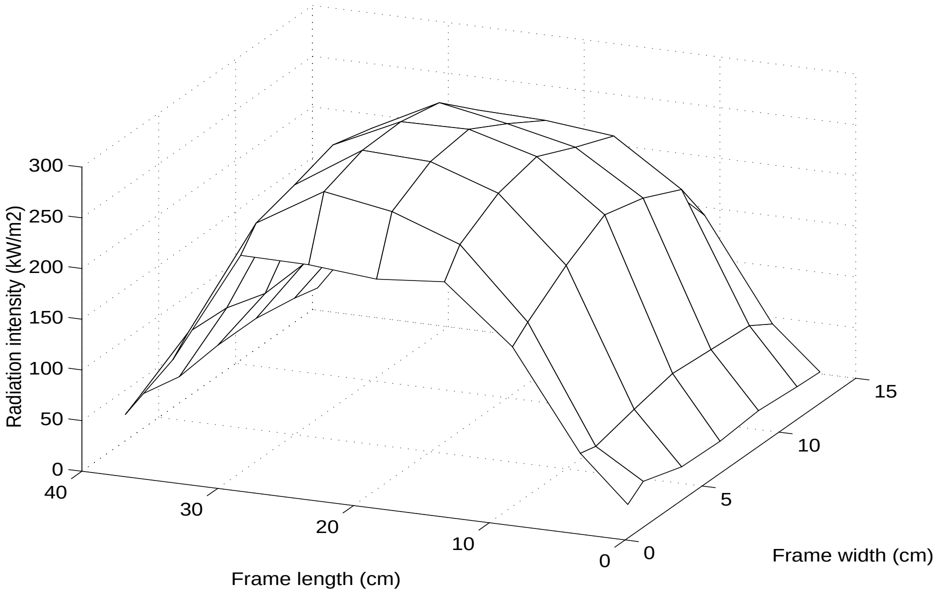


**Figure 3.** *Radiation intensity distribution 1.5 cm from protecting glass at full power*

The intensity distribution in Fig. 3 clearly shows the influence of the edges of the heater. In the length direction of the frame, this is the same influence as on a full-scale heater, but in the width direction, this is not realistic. A full-scale heater is several meters wide and the edges, important in these measurements, will hardly affect the result at all. Thus the measurement on this small heater will indicate a lower efficiency than would be encountered with a large-scale heater. Using the intensity measured at 7.5 cm from the edge in the width direction as an indication of the intensity under a full-width heater gives an estimate of the efficiency of a full-scale heater.

The efficiency of the heater as measured by the radiometer and with the calorimetric method is illustrated in **Figure 4**. The estimated efficiency of a full-scale IR heater is also indicated. The line is based on intensity measurements in one point at 20 different power levels and scaled to the careful measurement of the efficiency to give a trend of the efficiency at different power levels. During all these measurements, the flow and temperature of the cooling air were also measured, and the total energy balance of the heater evaluated. Approximately 10% of the supplied energy was missing in the total energy balance.

The results presented in Fig. 4 show that the radiation efficiency is dependent on the electric power applied. The efficiency increases from 38% to 55% when increasing the electric power from 4.8 to 19.2 kW. The calorimetric method is in good agreement with the radiometer results for powers below 14 kW. Above 14 kW, the efficiency no longer increases according to the calorimetric method. During theses measurements, however, there was visible evaporation from the water surface due to local overheating, which explains the difference at higher power. The estimates for a full-width heater indicate a maximum efficiency of 60–62%.

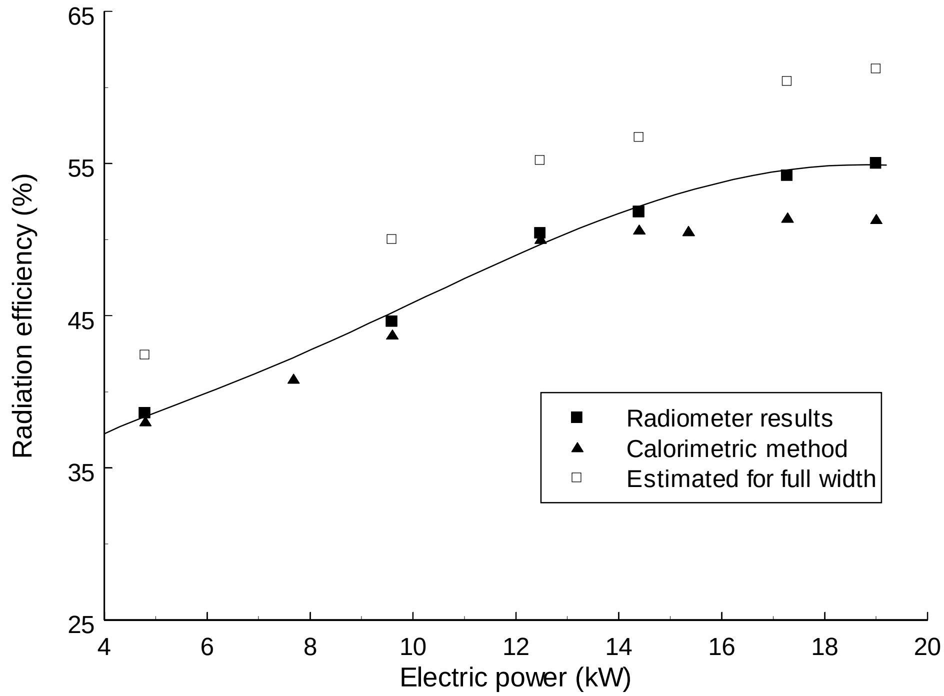


**Figure 4.** *Radiation efficiency for lab-scale heater*

## Industrial measurements

The fraction of supplied power that actually ends up in the paper depends on the radiation efficiency of the IR heater and the paper quality. Most paper qualities are rather transparent to short-wave IR radiation. To improve the overall efficiency, electric IR dryers use back reflectors to redirect transmitted energy back to the paper web. The choice of back-reflector technology may thus also be important for the total efficiency of an installation. Most electric IR dryers use a passive ceramic back reflector. Ojala and Lampinen *(12)* showed that the efficiency of the system increases with increasing back-reflector temperature. This has encouraged the development of an electrically heated back-reflector system—a co-radiator system—as described, e.g., by Peltoniemi *(1)*. The general idea is that the efficiency of the additional energy supplied to the co-radiator is supposed to be very high.

### Experimental

In order to investigate the efficiency of electric IR dryers and compare different reflector alternatives, measurements were undertaken on a small off-machine coater at Klippan Finpappersbruk in Sweden. During normal operation, the machine is used to apply and dry coating on wrapping papers at approximately 60 m/min. The machine uses IR as the only source of energy supply to the web. **Figure 5** shows a schematic layout of the machine, which has a width of 1.8 m. The IR module includes tungsten halogen quartz lamps at a rated power of 3 kW, a gold-plated parabolic reflector, and protecting glass made from water-free quartz.

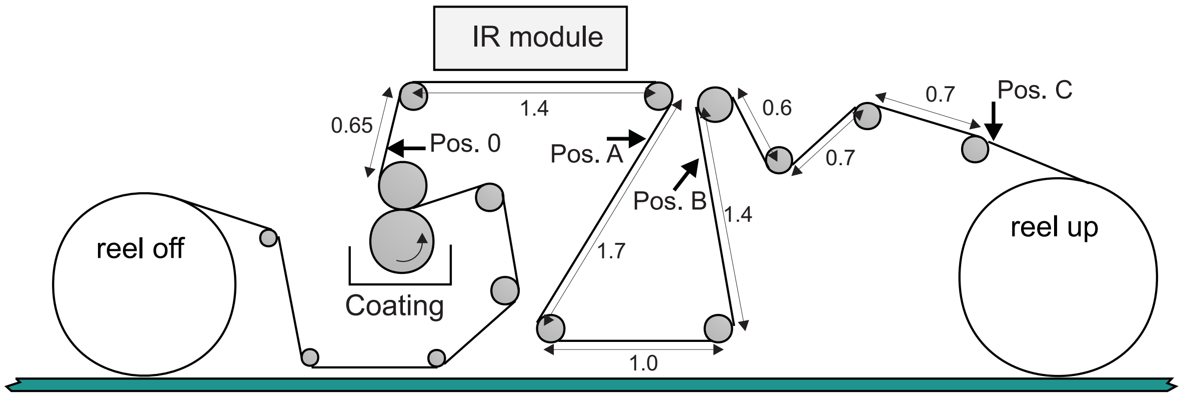


**Figure 5.** *Schematic layout of the off-machine coater (distances given in meters)*

During the measurements, three different back-reflector alternatives opposing the IR module were used simultaneously on the machine. One-third of the machine width was left empty; one-third was equipped with a ceramic back reflector; and one-third with a co-radiator. This is illustrated in **Figure 6**.

Measurements were obtained at various machine speeds within the range 50–110 m/min. Two different coating formulations were used, one based on $CaCO_3$, clay, and latex (solids content of 57%) and another based on clay and PVA (solids content of 20%). It was not possible to control the amount of applied coating on this machine. The base paper was 85 $g/m^2$ with moisture ratio 0.05 made from bleached TCF (totally chlorine free) sulfate pulp. The experiments included measurements on electric power consumption, cooling air flow and temperature into and out from the IR module, machine speed, coating temperature and dryness, applied coat weight, and web moisture ratio at the reel off and at the reel up.

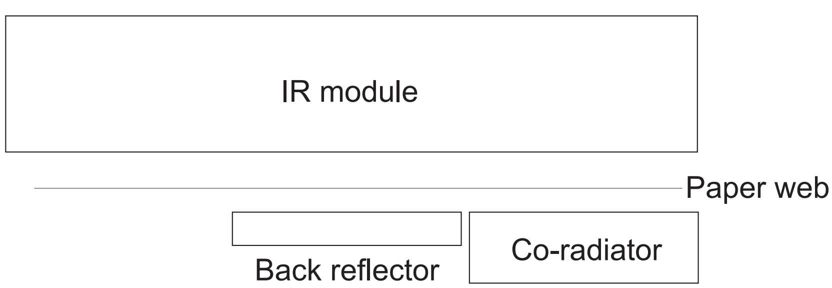


**Figure 6.** *Three different back reflector alternatives used at the same time*

The machine speed was measured by mill staff using a wheel, connected to a tachometer, running with the web. The dryness of the coating was measured by mill staff using standard equipment. The applied coat weight was determined as the difference between the ovendry basis weight of the base paper from the reel off and the ovendry basis weight of the coated paper at the reel up. The total basis weight of the paper at the reel off and reel up was also measured, allowing determination of the moisture ratio at both positions. All these measurements were conducted by mill staff. Unfortunately, procedures changed a bit as staff changed. During some of the measurements, six samples were taken from each section of the machine width, during some trials only one.

The temperature of the web was also measured at the reel off and in the positions 0, A, B, and C in Fig. 5. Web temperature was measured using a device originally developed to measure cylinder surface temperatures. This device, now manufactured by SWEMA, is based on ideas and prototypes presented by Stenström *et al. (13)*, who estimated the accuracy as ±2°C.

The radiometer was also used to measure the radiation intensity distribution under the IR module.

## Evaluation

The fraction of supplied energy transferred to the web is a heat-transfer efficiency and will from now on be called the total efficiency, $\eta_{tot}$. In order to estimate the total efficiency, it is necessary to consider all effects of the transferred energy.

Energy absorbed by the paper web under the IR module increases the temperature of the web, creating a driving force for the evaporation of moisture. Thus energy is used for evaporation and temperature increase. Evaporation requires not only the latent heat of water but, at low moisture ratio, also energy for breaking the bonds between water and cellulose, i.e., the heat of sorption. Furthermore, the elevated temperature of the paper will lead to convective losses to the cooler surrounding air in the draws before reeling up. Thus, all supplied energy will appear as latent heat of evaporated water, heat of sorption, sensible heat, and convective losses from the web. Total efficiency is calculated according to Eq. 1. (All variables are defined in the Nomenclature section at the end of this paper.)

$$\eta_{tot} = \frac{Q_{lat} + Q_{sorp} + Q_{sens} + Q_{conv}}{P_{el}} \qquad (1)$$

From measurements of moisture ratio and applied coat weight, the evaporated mass of water is easily calculated as the difference between the water in the web at the reel up and the sum of the water in the web at the reel off and in the applied coating. The latent heat of the evaporated water is then obtained by multiplication by the latent heat of water, as given by Eq. 2. Note that the units consistently used are W/m machine width, a convenient unit for use with IR dryers.

$$Q_{lat} = V_b \left( m_b \cdot x_{off} + m_c \cdot x_c - \left( m_b + m_c \right) x_{up} \right) \Delta H_{vap} \qquad (2)$$

It is well known that during drying, the last few percent of moisture is considerably harder to remove than the average moisture. This experience is partly due to internal transport limitations in the material and partly because the last water is actually bonded to the material with physical and chemical bonds. This means that the equilibrium partial pressure of water vapor in the structure is actually lower than the partial pressure of pure water. This reduction in vapor pressure is described by the sorption isotherm of the material. The sorption isotherm gives the relative humidity, $\psi$, with which the material is in equilibrium at various moisture contents. Evaporation requires that the bonds be broken, which in turn requires additional energy. Evaporation will require not only the latent heat of water but also the heat of sorption.

Thermodynamic theory gives a relation between the sorption isotherm, $\psi$, and the heat of sorption, $\Delta H_{sorp}$. This relation, known as the Clapeyron–Clausius equation, is given in Eq. 3, where $T$ is the absolute temperature.

$$\left(\frac{\partial \ln \psi}{\partial T}\right)_x = \frac{M_w}{RT^2}\Delta H_{sorp} \qquad (3)$$

The sorption isotherm for paper is not very well investigated when compared with other materials like wood, textiles, and some foodstuffs. However there are a few different sorption isotherms available in the literature. Heikkilä *(14)*, Karlsson and Soininen *(15)*, Paltakari and Karlsson *(16)*, Harrman and Schulz *(17)*, and Lampinen and Toivonen *(18)* have all presented correlations for the sorption isotherm for paper. All these isotherms are illustrated at 60°C in **Figure 7**. While the curves are similar in general shape, there are rather large differences among the curves. These differences are probably due to both differences among the various types of paper and experimental error.

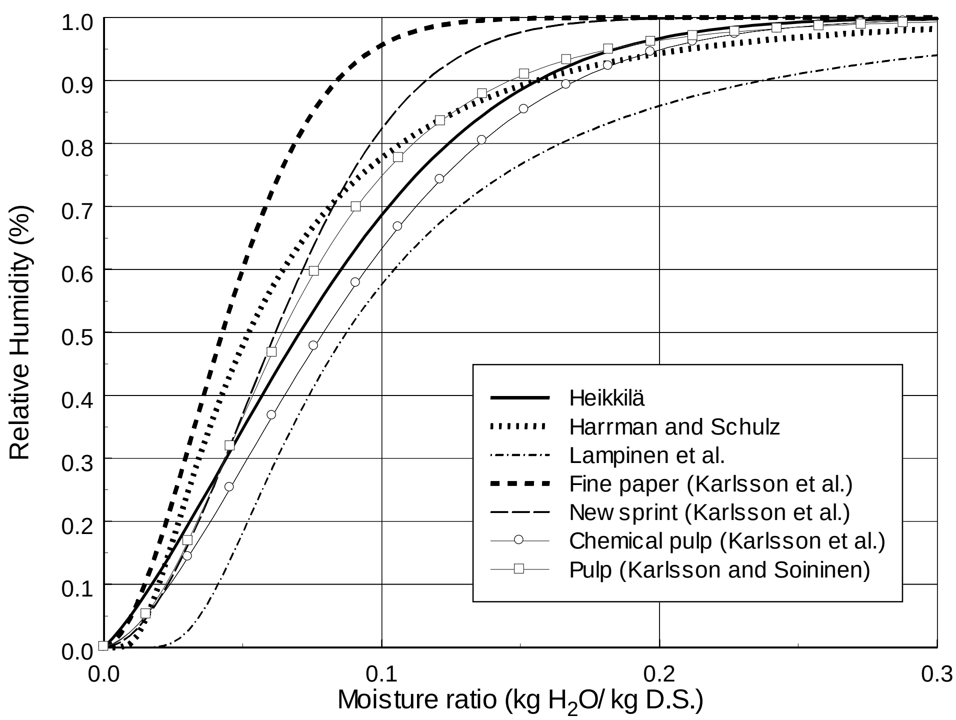


**Figure 7.** *Sorption isotherms for paper at 60°C*

Application of Eq. 3 to the sorption isotherms gives the heat of sorption shown in **Figure 8**, which also includes an experimental fit by Lampinen and Toivonen *(18)*. Isotherms that give an erroneous influence of temperature have been disregarded. At lower moisture content, most of the curves approach infinity, including the experimental curve by Lampinen and Toivonen. An interesting point is that similar isotherms give very different heat of sorption. Obviously, the general form of the fitted equation is important for the resulting heat of sorption, which of course is unfortunate.

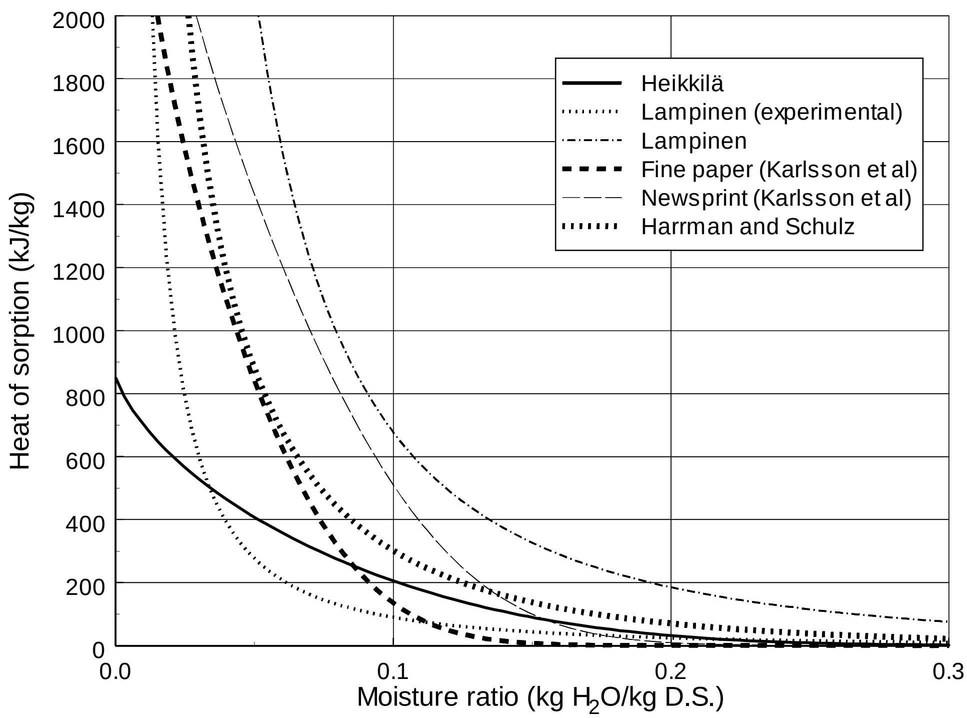


**Figure 8.** *Heat of sorption at 60°C calculated from the sorption isotherms in Fig. 7 and the experimental correlation by Lampinen and Toivonen (18)*

A heat of sorption approaching infinity is of course physically unrealistic. The last fractions of water removed from the paper have hydrogen bonds to the cellulose fibers. The energy of a hydrogen bond is generally in the range 20–30 kJ/mole *(19)*, which corresponds to 1100–1700 kJ/kg for water. A limiting heat of sorption much higher than this is not realistic. The only curve in Fig. 8 that is even close to realistic at lower moisture content is the calculated results from the isotherm used by Heikkilä *(14)*. It has a limiting heat of sorption of approximately 850 kJ/kg at 60°C and 1600 kJ/kg at 25°C. This matches the hydrogen bond energy. The conclusion is that the isotherm used by Heikkilä *(14)* is the best suited for calculations on paper.

During drying, the moisture content is decreasing, which calls for integration of the heat of sorption from the initial to the final moisture ratio to obtain the total additional heat needed. For all experiments, the total heat of sorption is calculated according to Eq. 4, which will give a negative value (heat released) if the paper has a higher moisture ratio at the reel up.

$$Q_{\text{sorp}} = V_{\text{b}} \cdot m_{\text{b}} \int_{x_{\text{off}}}^{x_{\text{up}}} \Delta H_{\text{sorp}} dx \quad (4)$$

Heikkilä *(14)* measured the sorption isotherm for nine different coating formulations and showed that the heat of sorption of the coating can be neglected when evaluating drying of coated paper. That conclusion is applied in this work.

The increase in web temperature and the associated increase in sensible heat is calculated from the difference in temperature at the reel up and the reel off and the temperature of the coating, as given by Eq. 5.

$$\begin{aligned} Q_{\text{sens}} = {} & V_{\text{b}}\left(T_{\text{up}} - T_{\text{off}}\right)\left(m_{\text{b}} C\text{p}_{\text{fiber}} + m_{\text{b}} x_{\text{up}} C\text{p}_{\text{water}}\right) + V_{\text{b}} m_{\text{c}} C\text{p}_{\text{c}}\left(T_{\text{up}} - T_{\text{c}}\right) \\ & + V_{\text{b}} m_{\text{c}} C\text{p}_{\text{water}}\left(x_{\text{up}}\left(T_{\text{up}} - T_{\text{off}}\right) + x_{\text{c}}\left(T_{\text{off}} - T_{\text{c}}\right)\right) \end{aligned} \quad (5)$$

Equation 5 implicitly assumes that all evaporation occurs at the temperature at the reel off, $T_{\text{off}}$. For thermodynamic consistency, the latent heat of water, $\Delta H_{\text{vap}}$, in Eq. 2 must then be taken at $T_{\text{off}}$. During all experiments, $T_{\text{off}}$ was in the range 22–26°C. For all evaluations, $\Delta H_{\text{vap}}$ was taken at 25°C.

The heat lost due to convective cooling of the web per meter of machine width is estimated according to Eq. 6. The assumption is that all evaporation occurs on the coated side of the paper. Therefore, the corrected heat-transfer coefficient has been used on one side and the uncorrected heat-transfer coefficient on the other side. The heat-transfer coefficient is evaluated from standard Nusselt correlations for parallel flow past a flat plate, treating each distance between two guiding rolls in Fig. 5 as individual surfaces. Measurement of web temperature at different positions facilitates estimation of web temperature on each surface. Correction of the heat-transfer coefficient for simultaneous mass transfer is outlined by Krischer and Kast *(20)*.

$$Q_{\text{conv}} = \sum_{\text{surfaces}} \left(h^{*} \cdot L \cdot \left(T_{\text{web}} - T_{\text{air}}\right) + h \cdot L \cdot \left(T_{\text{web}} - T_{\text{air}}\right)\right) \quad (6)$$

## Uncertainty analysis

The estimation of uncertainty is based only on the uncertainty in the latent heat of evaporated moisture, $Q_{\text{lat}}$. The uncertainty is estimated as the sum of the uncertainty in each variable multiplied by the absolute value of the partial derivative of the efficiency with respect to that variable, as indicated in Eq. 7.

$$\begin{aligned} \delta\left(\eta_{\text{tot}}\right) = {} & \left|\frac{\partial \eta_{\text{tot}}}{\partial V_{\text{b}}}\right| \delta\left(V_{\text{b}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial m_{\text{b}}}\right| \delta\left(m_{\text{b}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial x_{\text{off}}}\right| \delta\left(x_{\text{off}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial m_{\text{c}}}\right| \delta\left(m_{\text{c}}\right) + \\ & + \left|\frac{\partial \eta_{\text{tot}}}{\partial x_{\text{c}}}\right| \delta\left(x_{\text{c}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial x_{\text{on}}}\right| \delta\left(x_{\text{on}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial \Delta H_{\text{vap}}}\right| \delta\left(\Delta H_{\text{vap}}\right) + \left|\frac{\partial \eta_{\text{tot}}}{\partial P_{\text{el}}}\right| \delta\left(P_{\text{el}}\right) \end{aligned} \quad (7)$$

Most of the terms in Eq. 7 relate to basis weight and moisture content of the base paper and the coating. These variables were calculated from the measurements by mill staff on wet and ovendry basis weights. As mentioned previously, the routines at the mill changed during the measurements. For the experiments including six samples from each section of the machine, the mean was calculated and the uncertainty was estimated from the standard deviation and Student's *t*-distribution for a confidence of 95% according to Eq. 8.

$$\delta(x) = t \cdot \frac{\sigma_x}{\sqrt{N}} \qquad (8)$$

For the measurements with only one sample, the 95% confidence in uncertainty was estimated as $\pm 2\sigma_x$ using the standard deviation from the measurements with six samples.

It is clear that there will be additional contributions to the uncertainty from the heat of sorption, the sensible heat, and the convective losses. However, it is hard to accurately estimate these uncertainties. Since the heat of sorption contributes less than 1% to the overall efficiency for most measurements, it is safe to conclude that even though the curves in Fig. 8 are very different, the addition to the uncertainty in efficiency will be less than 1%. It is also easy to estimate the influence of the uncertainty in sensible heat to less than 0.4% of the total efficiency. The correlations for the heat-transfer coefficient are based on more ideal conditions than present in a paper coater. The uncertainty in convective losses is probably more important, at most 3–4% of total efficiency.

## Results

The total efficiencies for the ceramic reflector and for the co-radiator are shown in **Figure 9**. The results without any back reflector were also evaluated but were surprisingly high. The reason is evident from the machine design illustrated in Fig. 5. Radiation transmitted through the paper sheet will not all be lost. The web actually passes under the IR module both before the coater and again after the IR drying. Transmitted energy will have a good chance to be absorbed anyway. The results are thus far from typical for an installation without back reflector and are not presented here.

The first most striking thing about the results in Fig. 9 is the large uncertainties. The uncertainty is almost entirely due to the large uncertainty in applied coat weight, which results in an uncertain amount of evaporated water. The standard deviation in applied coat weight was approximately 1 g/m$^2$, which is important when considering that the total coat weight was 6–10 g dry solids/m$^2$. This is especially important in combination with the low solids content of one of the coatings. It is clear from Fig. 9 that the situation would have been much improved if six samples had been taken during all the experiments. Given the large uncertainty due to problems in measuring the amount of evaporated water, the approximations made in the uncertainty estimation seem reasonable.

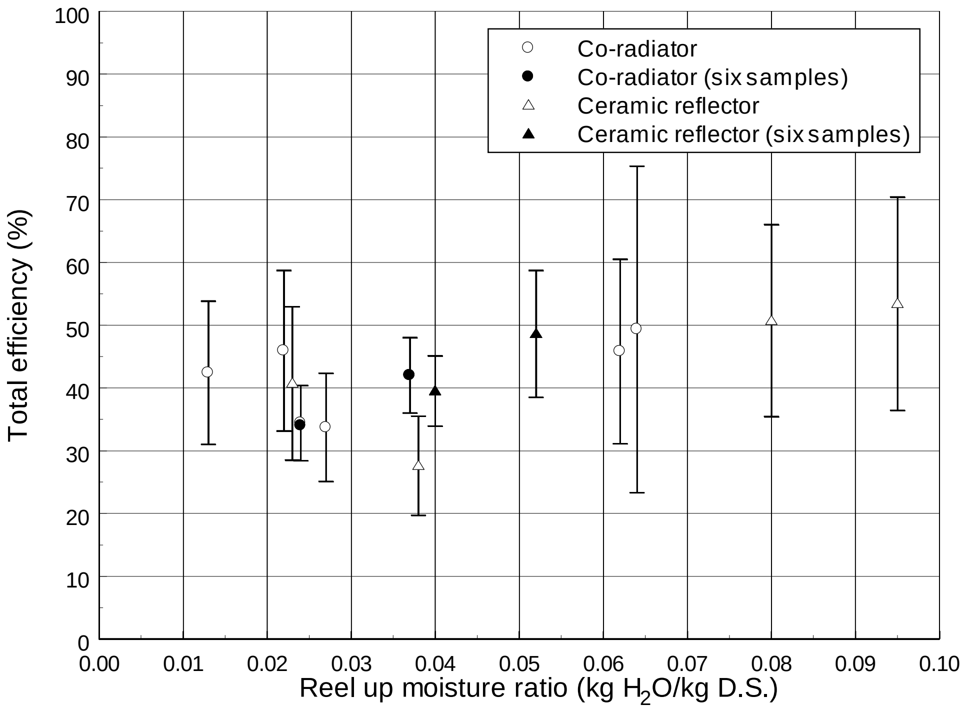


**Figure 9.** *Total efficiency from measurements with reflector arrangement (black symbols represent results based on six samples)*

The results in Fig. 9 indicate that the efficiency of the electric IR dryer seems to be in the range 30–50%. Actually, a horizontal line at 40% would cross the error bar of all measurements except one. If the error bars are ignored, there seems to be some trend with efficiency increasing slightly with increasing moisture ratio. It is worth noting that some of the experiments resulted in very low moisture ratio at the reel up. Unfortunately, it is not possible to detect a definite difference between the two reflector alternatives. A difference in efficiency of 5–7% would not be visible in the measured data due to the large uncertainties and spread in results.

One possible explanation for the small difference between the two alternatives and the spread in results, apart from the general uncertainties, is the radiation transmitted in the section without a reflector. As illustrated in **Figure 10**, the transmitted radiation will not only heat the section immediately underneath but also spread to the sections with the back reflector and the co-radiator. This will result in overly high efficiencies for all alternatives, but the increase will of course be more important for the ceramic back-reflector alternative. Another effect is that the moisture ratio of the samples varies depending on where in the width direction of the zone it was taken, thus increasing the spread in results.

The radiation intensity under the IR module in the dryer was measured using the 2π-radiometer, and the integration resulted in a radiation efficiency of 62%. Even though the heater is from another supplier than the lab-scale unit, the similarity in design explains the similar radiation efficiency.

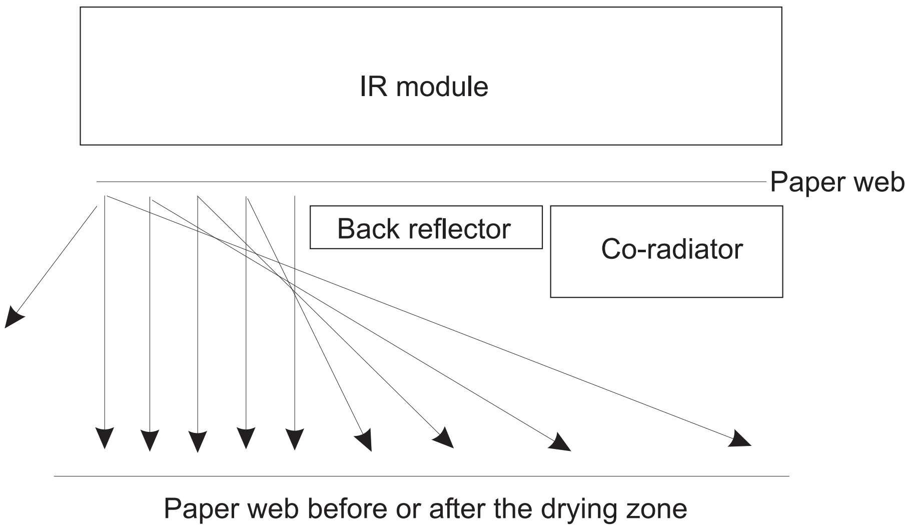

**Figure 10.** *Transmitted radiation spreads sideways*

The measurements on cooling air provided the most consistent result from the industrial measurements. For all experiments, 45–48% of the energy supplied to the IR module was carried off with the cooling air. Thus, the net radiant flux leaving the module cannot be more than 52–55%. The difference from the radiation measurement is due to the paper reflecting part of the radiation back to the heater. Allowing for some percent of radiation losses from the dryer and convective losses from the back reflector, it is hard to imagine a total efficiency much higher than 45%. Thus some of the points in Fig. 9 must definitely be questioned.

All discussion of efficiency so far is based on the electricity supplied to the IR module and the co-radiator. For operation of the system, the cooling air fans also require some power input. The rated power of the cooling air fans was such that if introduced in the energy balance, the efficiency of the dryer would be significantly reduced.

## Conclusions

The radiation efficiency of two different electric IR heaters has been evaluated. The maximum efficiency seems to be somewhat above 60%. The radiation efficiency is clearly dependent on the level of electric power applied, with efficiency increasing with applied power. Comparison of measurements using a radiation heat-flux probe and a simple calorimetric method indicates that rather accurate results for the radiation efficiency can be obtained without sophisticated equipment. Edge effects significantly reduce the measured efficiencies on small heaters, resulting in lower efficiency than a full-size heater.

Industrial measurements indicate that approximately 40% of supplied electricity ends up in the paper web. The uncertainty in these measurements was significant mainly due to a considerable spread in the measurements of applied coat weight. The extent of this uncertainty made it impossible to distinguish between the two reflector alternatives investigated. The results indicate total efficiencies a bit higher than literature data, but considering the uncertainty, the difference is not conclusive. Furthermore, the literature data do not contain uncertainty estimates.

The most consistent result was that 45% of the energy supplied to the IR module was lost with cooling air. For IR dryers with closed air systems, simple measurements on the cooling air will give an indication of how much energy is available for drying. Normally, additional losses of 5–10% will probably be encountered.

Future evaluations of IR dryers could benefit from experience gained in this study.

- Conduct measurements on a machine where the applied coat weight can be controlled. The moisture content and the applied coat weight must be measured accurately.
- Take multiple samples to reduce uncertainty of measurements.
- Measure moisture content and temperature of the web as close before and after the dryer as possible. If the distances are short, convective losses can be ignored, but if the distances are several meters, some estimate of the convective heat transfer is needed. For all temperature measurements close to an IR dryer, the effect of radiation must be carefully considered.
- If the final moisture ratio is moderately low, above 0.05 kg $H_2O$/kg dry solids, the heat of sorption can be ignored.

Finally, there is a clear need to increase knowledge on sorption isotherms and the heat of sorption for paper.

## Nomenclature

| | | |
|---|---|---|
| $Cp$ | specific heat | J/(kg·°C) |
| $h$ | convective heat transfer coefficient | W/(m$^2$ ·°C) |
| $h^*$ | heat transfer coefficient corrected for mass transfer | W/(m$^2$ ·°C) |
| $L$ | characteristic length | m |
| $m$ | dry basis weight | kg/m$^2$ |
| $M_w$ | molecular weight of water | g/mole |
| $N$ | number of samples | … |
| $\eta_{tot}$ | total efficiency | … |
| $P_{el}$ | electrical power consumption per width meter | W/m |
| $Q_{conv}$ | heat flux corresponding to convective cooling of web | W/m |
| $Q_{lat}$ | heat flux corresponding to evaporation of water | W/m |
| $Q_{sens}$ | heat flux corresponding to web temp. increase | W/m |
| $Q_{sorp}$ | heat flux corresponding to the heat of sorption | W/m |
| R | gas constant | J/(mole·K) |
| $T$ | temperature | °C or K |
| $t$ | Student's *t*-distribution | … |
| $V_b$ | machine speed | m/s |
| $x$ | moisture ratio | kg $H_2O$/kg dry solids |
| $\delta(i)$ | uncertainty in variable $i$ | (same as $i$) |
| $\Delta H_{sorp}$ | differential heat of sorption | J/(kg $H_2O$) |
| $\Delta H_{vap}$ | latent heat of vaporization | J/kg |
| $\psi$ | relative humidity | … |
| $\sigma_i$ | standard deviation in $i$ | (same as $i$) |

**Subscripts**

| | | | |
|---|---|---|---|
| air | air | off | at reel off |
| b | base paper | up | at reel up |
| c | coating | water | Water |
| fiber | dry matter of paper | web | paper sheet |

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