# Physics and application of electric infrared emitters

## Drying of hydrophilic substrates and aqueous dispersion on their surface

**Drying paper and its coatings are the most energy-intensive process in paper production. Drying takes place either by conduction, convection or radiation. The latter is the most expensive of the three energies, but under certain boundary conditions it is the energy of choice, especially if you want to dry goods that are moist on the surface, so that conduction - drying on a drying cylinder - is ruled out. We are focusing here on radiation. This can be easily decarbonized, and efficiency can be increased compared to current application scenarios. Some facts about this are hardly known, but they have a significant influence on the quality of the finished paper and its raw material costs.**

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We shed light on some of the facts that are not known in detail to show papermakers the various options for optimizing their paper production. When drying coatings - especially functional coatings - drying control is crucial. However, temperature control in md is not expedient, especially because only the temperature of the surface can be recorded, not that of the initial sedimentation layer. However, temperature control in the z-direction is relevant.

When drying, it must always be borne in mind that over two thirds of the energy used to produce paper is used to dry the paper and the coating. Radiation is the most expensive form of energy, which is why the papermaker must be aware of how to optimize its use. The radiation used in the paper industry is infrared radiation, the wavelength of which is adjacent to visible light and spreads over a broad wavelength spectrum. Radiation of different wavelengths also has different effects on drying. Many of these facts also apply to the drying, profiling and preheating of substrates. We present these physical relationships in this article.

### 1 Drying

Drying in the paper industry is both simple and very difficult. The solvent of choice is water. We do not use other solvents in paper production, at most in subsequent steps such as printing. Water differs from many other solvents because it is bound to the material to be dried. This hydrogen bond towards the fibers as well as towards other water molecules must be overcome in addition to evaporation.

We must therefore concentrate on the interaction between water molecules and fibers or coating color components. We achieve this by stimulating hydrogen bonding and hydroxyl groups.

We achieve the excitation via the energy input. This must be large enough to separate water molecules from each other and separate them from the hydroxyl groups. However, drying is only complete when we have vaporized the water, i.e. moved it out of the material to be dried. We also must consider where the water has to move in order to minimize the amount of energy required.

Drying is therefore always a two-stage process - and the energy input is largely responsible for how and where the water leaves the dry material. Here we should work with physics, not against it.

### 1.1 Types of drying in papermaking

The papermaker has various tools at his disposal that enable him to remove the water from the paper. There is still a lot of water in the wire section. Only a very small amount of water is bound to the fibers via hydrogen bonding. Here, gravity, vibrations and centrifugal force are sufficient to remove most of the water, 90 % to over 99 % of the amount of water that comes out of the headbox with the fibers.

Excess, unbound water is pressed out in the press section - depending on the paper machine and paper grade, a further 0.2 % to 8 % of the total water is pressed out here. However, the paper then still contains 40 % to 60 % water. This is firmly bound to the fibers so that it cannot be removed either by gravity or by pressing.

This final step requires around 90 % of the total energy used for dewatering - to remove 0.2 % to 1.5 % of the total amount of water that was brought from the headbox onto the forming fabric.

This last bit of water is crucial when considering the cost of paper production. Basically, the water now needs another reason to leave the paper. The first choice is thermal energy: if the water is brought to the boil, it evaporates and leaves the dry material.

The papermaker mainly uses steam-driven drying cylinders. These transfer their energy to the surface of the paper by conduction and heat the depth of the paper by conduction. The first cylinders bring the paper to vaporization temperature. As soon as evaporation begins, the temperature of the surface of the cylinders and the paper remains the same - heating by energy input from the cylinder and cooling by evaporation enthalpy balance each other out.

When drying with drying cylinders, two facts must not be overlooked: the energy is transferred via the surface. If this happens too quickly, the surface can dry too quickly with heavier grammages and thus become a thermal insulator. Considerably more energy is then required for drying. At the same time, there is a risk of layer separation inside the substrate. At the end of the drying section, overheating is then required to remove the moisture from the center of the web through the overdried surface.

The second important point is that the vapor must be given space between the cylinders so that it can leave the substrate. Basically, cylinder drying is the most efficient way to separate the water from the fibers.

### 1.2 Drying of coating

However, drying cylinders are only suitable for drying relatively dry substrates - with one exception, the cast coating. They cannot be used for coating drying. Here the papermaker must resort to hot air - convection - and radiation. The moist coating is damaged by contact drying, resulting in undesirable surface marking. Coating drying must therefore first take place without contact.

When drying the coating, it must be considered that the substrate is hydrophilic and very absorbent. The liquid phase of the coating will preferentially move towards the substrate due to the capillary forces of the substrate and the hydrogen bonding. On the one hand, this is detrimental to drying because we then need considerably more energy, to slow down the movement of the liquid phase into the substrate, to detach the liquid phase from the fibers by overcoming the hydrogen bond, and to accelerate the liquid phase back to the surface.

We therefore waste valuable energy if we do not move the liquid phase towards the surface right from the start.

Secondly, we are damaging quality and our wallets: the customer only pays for the coating on the surface, not for coating components in the substrate. By controlling the heating of the coating in the machine direction, the papermaker tries to control the drying process in such a way that as little migration into the substrate as possible takes place. However, this usually leads to very long drying distances.

If drying is carried out correctly, the control by surface temperature in md is irrelevant.

However, it is important to control drying in the z-direction: the initial sediment layer must always be warmer than the surface. Otherwise, the water cannot be motivated to move towards the surface.

#### 1.2.1 Hot air drying

Drying the material to be dried can be achieved very energy-efficiently with hot air. The costs for this are more favorable than drying with cylinders, but a much larger drying section is required. Very dry hot air is blown onto the material to be dried. The relative humidity is so low that the partial vapor pressure of the water is low. It is higher in the material to be dried, so that the heated water moves to the surface, is evaporated and absorbed by hot air. The hot air turbulently disturbs the laminar boundary layer so that a lot of water can be absorbed into the air. At the same time, in modern hot air dryers the saturated air is discharged and replaced by new dry air, so that the gradient of the partial vapour pressure in the sheet always point towards the surface.

The major disadvantage of hot air compared to radiation is that, like cylinders, it only heats the surface. The heating of deeper layers, whether coating or paper, takes place through heat conduction within the material to be dried. Precise control of the energy input in the machine direction is therefore required. Less energy must be introduced into the coating (or the substrate) at the surface by convection than is transferred to the depth of the material by conduction. This is the only way to ensure that the surface does not become overdried, filmy or cornificated and thus transformed into a thermal insulator.

#### 1.2.2 Drying by radiation

Infrared radiation is the only type of heat transfer in paper production that can penetrate deep into the material to be dried. It stimulates the hydrogen bonding and the hydroxyl groups and thus leads to heating of the material. The disadvantage of infrared drying is that radiation is the most expensive form of energy. It must therefore be carefully weighed up when it is the better choice.

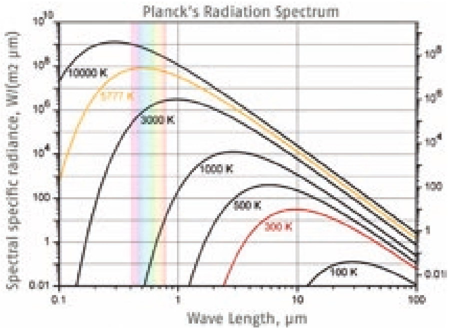


Fig. 1: Planck's radiation spectrum, with temperatures according to Stefan-Boltzmann and Wien's displacement law

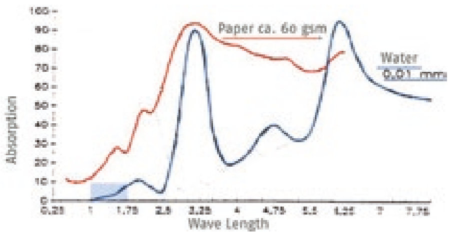


Fig. 2: Infrared reflection and absorption of paper and water

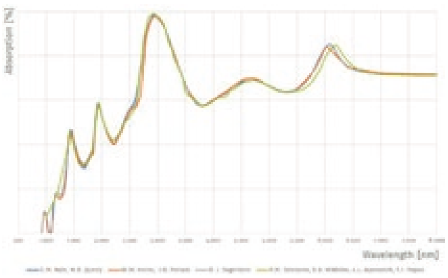


Fig. 3: Absorption of infrared radiation by water

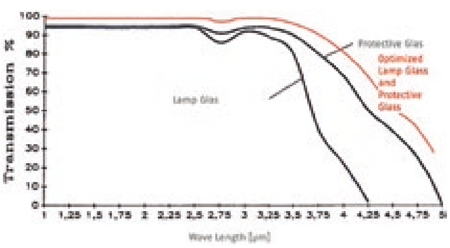


Fig. 4: Transmission of infrared radiation through lamp glass of conventional infrared lamps (black)[8] and optimized infrared lamps (red)

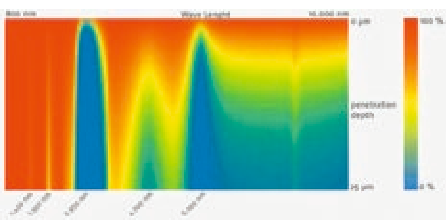


Fig. 5: Penetration and absorption of infrared radiation by water according to Lambert-Beer's law for wavelengths between 800 nm and 10,000 nm and penetration depths between 0 and 25 µm.[10]

Infrared radiation belongs to the electromagnetic spectral range and is connected to visible light at wavelengths between 0.78 µm and 1,000 µm, where the microwave range begins. According to ISO 20473, infrared is divided into three ranges: NIR Near infrared: between 0.78 and 3 µm wavelength, MIR Mid-infrared: between 3 and 50 µm wavelength, and FIR Far infrared between 50 and 1,000 µm wavelength.

We use various types of infrared emitters in the paper industry. The most common, because they appear to be cheap to operate, are gas-fueled emitters. Depending on the burner type they have their maximum output at wavelengths between 2.5 and 3.5 µm, i.e. in the transition from NIR to MIR. This corresponds to a blackbody temperature of 830 to 1,160 K. Conventional electrically operated emitters use lamps that have their maximum output in the near infrared at a wavelength of around 1.18 µm and have a blackbody temperature of 2,450 K.

Enhanced electrical emitters have their maximum power at a wavelength of 1.5 µm, corresponding to a blackbody temperature of 2,000 K.

The radiation intensity depends on the surface temperature to the fourth power, as can be seen in Fig. 1, Planck's radiation spectrum. In the seventies, it was assumed that electrically operated infrared radiators typically have a twenty-fold power density due to the more than doubled black body temperature, which means that a great deal of power can be used for drying in confined spaces.

However, this was a fallacy, as the conversion of energy into radiation is only the first step of several to dry the coating and substrate. It must also be considered that the emitted energy corresponds to the area under the corresponding curve in Fig. 1. One third of the radiation has a shorter wavelength, two thirds a longer wavelength.

*1.2.2.1 Absorption of the radiation*

For the papermaker, it is important how the radiation is converted into heat. This results from the absorption of the radiation through the excitation of the hydrogen bond. When radiation strikes matter, it is either transmitted, reflected or absorbed. Absorption means conversion into heat. What is therefore relevant for drying is how much energy is converted into radiation and how much of this radiation is converted into heat through absorption.

In 1991, Helmut Graab published an excellent, pioneering study on the infrared dryers known at the time.[1] A substantial part of that publication were the absorption graphs of water and coating base paper as a function of wavelength (Fig. 2).

For decades, the technical article created a myth about coat drying using infrared. Unfortunately, the absorption curve of radiation by water in the near-infrared range is incorrect. Dr Peter Fisera et. al.[2] published in 2008 that no energy is absorbed below a wavelength of 1.2 µm. Above 2.1 µm, however, 80 % of the radiation is absorbed within the first 20 µm. Ideally, the maximum radiation should be between 1.3 and 2 µm.[3] This peak is missing from the information available to Helmut Graab at the time. Precise measurements of the absorption of infrared radiation by water in solid, liquid and gaseous form were difficult to view publicly because they were only available in analogue form in very few libraries. Figure 3 shows the absorption curves of various measurements of the interaction[4, 5, 6, 7] between infrared radiation and water in solid, liquid and gaseous form.

At around 1.45 µm and 1.95 µm, the infrared radiation is very well absorbed by water in the near infrared. Significantly less than the peak at 2.95 µm and 6.1 µm. However, it should not be forgotten that these first two wavelengths correspond to a surface temperature of 1,500 and 2,000 K respectively - compared to around 1,000 K at 2.95 µm - and so the energy density is five to sixteen times higher. It can also be seen that hardly any infrared radiation is absorbed at wavelengths of 1.3 µm and shorter. The lack of knowledge about the absorption peak at 1.45 µm led to the assumption that, despite their high energy density, electric infrared radiators are fundamentally unsuitable for drying coating and paper.

The glass of conventional electric infrared lamps absorbs up to 6 % of the infrared radiation, the protective glass a further 5 %, as can be seen in Figure 4 (the red graph is not from the original graphic). This means that considerably less energy is available with electric emitters - up to 10% of the energy is absorbed by the glass - and at the same time considerably more energy is required to cool it. Also, radiation above 4 µm is largely absorbed by the glass of conventional lamps and does not contribute to heating the material to be dried but requires additional energy to cool the glass. Basically, with conventional electric lamps, losses of over 15 % must be expected compared to gas emitters, which do not reach the dry material but are destroyed in the lamp glass. With optimized infrared lamps, by comparison, less than 8 % is not absorbed by the dry material. Especially in the area of the absorption peaks at 2.95 µm and 4.7 µm, sufficient radiation is still transmitted through the glass. This means that more energy reaches the material to be dried and at the same time the energy required to cool the lamps is reduced. As a side effect, this leads to significantly improved work safety, as the lamps are cold to the touch in less than 2 seconds after being switched off.

*1.2.2.2 Penetration of the radiation*

What is relevant for energy-efficient drying is not only how much original energy is absorbed by the material to be dried, but where. If only the surface of the material to be dried is heated, the deeper regions must be heated by means of heat conduction. And this must be done faster than heating the surface to avoid film formation on the surface of the coating or keratinization of the sheet surface.

Radiation, however, has a high energy density and transfers this very quickly to the dry material. The speed of heat conduction within the substrate is considerably slower at 0.3 mm/s[9] or 0.58 W/m*°C.

The penetration of the radiation is described using Lambert-Beer's law. For aqueous media, the penetration and absorption can be seen in Figure 5. It can be seen that in the near infrared, the radiation penetrates deeply and is hardly absorbed. The peaks at 1.45 µm and 1.95 µm can be recognized, where the radiation is slightly converted into heat in the upper layers of the line. However, over 90% of the radiation goes into the substrate and prefers to heat it. Above a wavelength of around 2.5 µm up to 3.5 µm, the hydroxyl groups absorb the radiation within the first few µm and only heat the surface of the coating or the substrate. The situation is similar for the peak at 6.1 µm. For the relevant absorption peaks, the penetration depth with the corresponding absorption is precisely determined in Figure 6.

This means that with gas fired IRs the radiation films the surface very quickly because the heat conduction within the coating brings the energy into the depths much more slowly than new energy is introduced into the surface.

Gas-fueled infrared heaters have their maximum output at a wavelength between 2.5 µm and 3.5 µm, depending on the type of burner. The majority of the radiation is converted into heat within the first 5 µm. Heat conduction within the coating is much slower, so that the initial sediment layer remains cool for a long time, while the surface is the hottest layer of the coating. Drying starts at the surface and pushes the liquid phase of the coating into the substrate. And with it the binder and the fines of the coating. With barrier coatings, the barrier polymer is forced into the substrate, where it does not form a barrier, but only causes high costs.

*1.2.2.3 Temperature differential*

In their investigations into the migration of binder, Philippe Bernada and Denis Bruneau measured the delay in the heating of the sediment layer compared to the surface of the layer (Fig. 7). They measured the temperature[12] of the coating on the surface and in the sediment layer and applied a vacuum to the sediment layer. The thickness of the coating was 1 cm, i.e. 10,000 µm, to achieve sufficient temporal resolution. At the same time, they had to turn the electric emitters down so far that they could set a temperature of 50°C to 160°C, i.e. a radiation maximum at 7 µm to 8 µm. As a result, over 90 % of the energy introduced was absorbed in the uppermost 10 µm.

This led to an extreme migration of the liquid phase into the substrate. And only 30 to 120 minutes later did the initial sediment layer reach the same temperature as the surface of the coating. Despite the low energy input, the problem is that the surface was heated more by radiation than the energy could be transferred to deeper layers by conduction. This experiment was not really helpful for its original objective - investigating binder migration - but it does illustrate very well what happens during coating drying when energy is introduced into the surface faster than it is transferred in the material to be dried by heat conduction. This is exactly the result of drying with gas-powered infrared dryers or high-performance hot air hoods.

In 1995, Kuang, Thibault, Chen and Grandjean investigated the attenuation of the energy of infrared radiation for different wave-

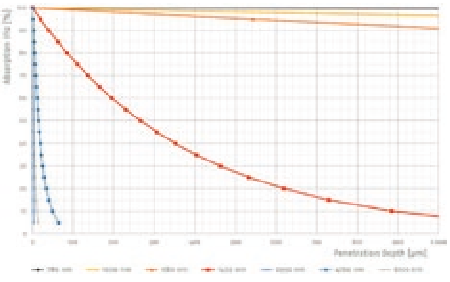

Fig. 6: Penetration and absorption of selected wavelengths of infrared radiation by water according to Lambert-Beer's law for wavelengths between 780 nm and 6,100 nm and penetration depths between 0 and 1,000 µm.[11]

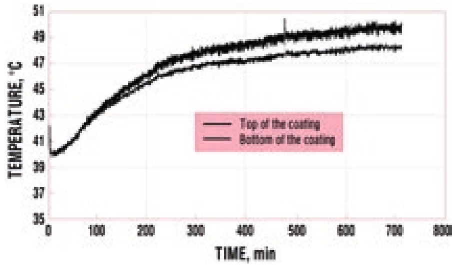


Fig. 7: Development of the temperature of the surface and the initial sediment layer during drying with infrared radiation at 60°C without dewatering the initial sediment layer

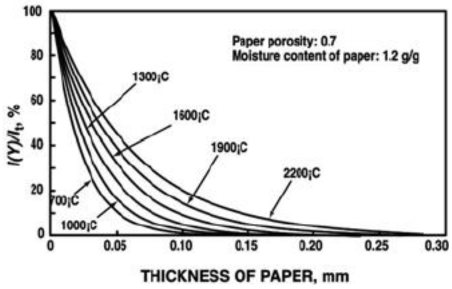


Fig. 8: Attenuation of the energy of infrared radiation as a function of the thickness of the sheet for different temperatures of blackbody radiators

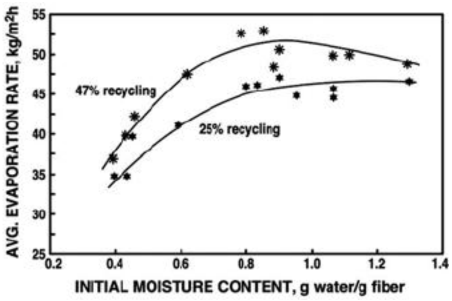


Fig. 9: Change in evaporation rate as a function of the original paper moisture content at different air speeds at a black body temperature of 100°C[15]

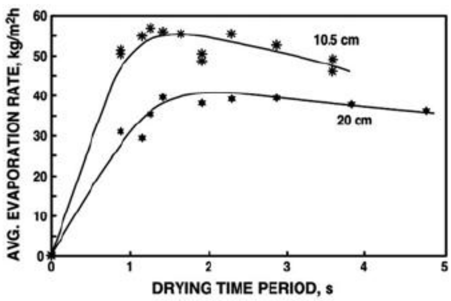


Fig. 10: Change in the average evaporation rate as a function of the distance of the emitter from the paper surface at a blackbody temperature of 1,100°C[16]

lengths corresponding to given blackbody radiators as a function of the paper thickness (Fig. 8).[13] They found that at 2,200°C, corresponding to a wavelength of around 1.2 µm of an electrically operated infrared radiator, the radiation was attenuated the least, i.e. penetrated very deeply, as would be expected according to Lambert-Beer's law. The radiation was only absorbed at a depth of 300 µm.

However, there is a deviation here from Fig. 5 and Fig. 6, where we assumed water as the medium. The fibres in the paper also have many hydroxyl groups, but these act in a slightly different way (see Fig. 2). For the graphs corresponding to 700°C and 1,000°C, which are typical for gas-fueled infrared emitters, the radiation is already completely converted into heat in the first 120 µm.

In his above-mentioned work, Helmut Graab noted that the temperatures found after the radiator in electric high-temperature radiators were not the same as those found in gas-fueled low-temperature radiators. He assumed that his results refuted Björnberg's measurements.[14] However, Björnberg had found that at shorter wavelengths, the radiation penetrates deeper into the paper and for this reason the temperature of the web surface gives no indication of the energy absorbed by high-temperature radiators. This corresponds to the theory of Lambert-Beer's law. As postulated by Björnberg, this surface temperature is irrelevant - if you dry properly with high-temperature radiators. With gas-powered low-temperature radiators, on the other hand, measuring the temperature is essential because drying takes place from the outside in, and the temperature after each dryer can be used to set how much binder is driven into the substrate.

In the case of high-temperature emitters, a distinction must be made between those NIR emitters with maximum power at 1.18 µm and the enhanced eNIR emitters with 1.45 µm. The latter have only 50 % of the power loss of NIR emitters, in which almost half of the radiation is emitted at wavelengths shorter than 1.3 µm, which does not interact with the hydrogen bonds and hydroxyl groups - i.e. is not converted into heat.

*1.2.2.4 Mass transport of the water*

Evaporation is the first part of the drying process. The important second step is the mass transport of the vaporized water from the material to be dried, be it coating or paper. And even more important is the direction in which this mass transport takes place. This defines how much energy must be used in total.

Ideally, we vaporize the water on the coating or web surface. Once we have succeeded in penetrating deep into the substrate with the radiation, the water moves to the surface. As soon as the water vaporizes there, it extracts the vaporization enthalpy from the surface and cools it. Although directly under the radiator, the surface becomes a wellness oasis for the water. However, only until the laminar boundary layer is saturated with vapor and the partial vapor pressures in the surface and the laminar layer are equal. Then evaporation stops and the water remains in the dry material.

Turbulent disturbance of the laminar surface layer with warm, dry air considerably reduces the partial vapor pressure above the sheet, so that large quantities of water can be evaporated. Figure 9 shows the research by Kuang, Thibault, Chen and Grandjean on how the evaporation rate is enhanced by higher velocities of cooling air - the faster the laminar layer is turbulently disturbed, the more water is evaporated. And the cooler the surface becomes.
They also found that the evaporation rate increases the closer the radiator is to the surface (Fig. 10). A smaller distance results in higher shear forces, which lead to an increase in turbulence. And turbulence is the natural enemy of laminar boundary layers. This reduction in distance also shows that the disturbance of the vapor-saturated boundary layer is essential for good drying, as this leads to substantial cooling of the surface - not due to increased air velocity, but due to increased evaporation rate.

*1.2.2.5 Direction of mass transport*
If infrared drying is carried out in such a way that the water begins to evaporate as soon as the radiation is introduced, the surface is kept cool by the enthalpy of evaporation. If, at the same time, the wavelength of the radiation is selected so that most of the absorbed energy is converted into heat deep in the substrate, a temperature gradient is obtained between the initial sediment layer and the surface of the coating. The water always moves to where it is cooler and leaves the coating at the surface. This dries last when the substrate and the coating are depleted of water. There is no premature cross-linking or filming on the surface.
The liquid phase of the coating, binder and fines penetrate the substrate only as far as the capillary forces of the porous substrate allow.
Ideally, emitters with a radiation maximum between 1.5 and 2.0 µm wavelength are used for this purpose. Here, considerably less energy is lost in a wavelength range that does not excite hydrogen bonding or hydroxyl groups. At the same time, it is still in a range in which the radiation penetrates sufficiently deep into the substrate.
By heating up the substrate, the correct infrared radiation prevents the liquid phase of the coating from slowing down, which then has to be released from the fibers of the substrate and accelerated back towards the surface. All that is needed is the energy for vaporization.

## 2 Application cases

These theoretical advantages of eNIR dryers for coat drying, profiling, substrate drying and preheating can also be recognized in practice. Several examples show that the theory of drying physics precisely describes the practice of drying.

### 2.1 eNIR-Booster for pre-coat drying

One board machine is equipped with an online coating machine, each with two coating heads for the top and back pre-coats and the corresponding top coats. The drying of the precoats consisted of two NIR dryers with a wavelength of 1.18 µm, followed by two hot air hoods. Basically, the optimum concept for many years with immobilizing of the initial sediment layer, followed by very favorable drying for the main load of evaporation. The infrared drying system consisted of 2 rows of 28 modules with 30 kW electrical power each. The typical precoat was run with an application solids between 69 % and 71 % and the typical application weight was 13 g/m². Originally designed for a production speed of 400 m/min, production was now at 700 m/min.
The cardboard factory wanted more freedom:
1. Increase the weight of the precoat to 20 g/m², or
2. Increase in production speed to 1,000 m/min, whereby the latter should only be fully utilized together with a rebuilding of the top coat drying system.
There were various proposals for rebuilding the machine at a cost of between USD 18 and 25 million. One envisaged the use of gas-fueled infrared radiators, another the addition of hot-air hoods. Both involved relocating the reel, the two top coats and the second pre coat.
A third envisaged the exclusive use of hot-air hoods, in which case the factory hall would probably have had to be extended.
The customer decided to replace the emitters at a cost of just under USD 1 million. eNIR emitters were used, whose radiation maximum is at a wavelength of 1.4 µm. At 24 kW, the replacement emitters had 20 % less power than the original emitters, but an 80 % higher specific evaporation power was guaranteed, enabling the customer's targets to be achieved. Figure 11 shows that with the NIR emitters, the cardboard was slightly wetter than the raw cardboard after pre-coat drying.
After the conversion to eNIR dryers, it was possible to evaporate more water from the cardboard during the reference runs than with the standard configuration. After pre-coat drying with eNIR, it was considerably drier than the raw cardboard. It must be taken into account that at such low moisture levels, the energy required to remove the water from the fibers of the substrate is considerably greater. However, it also shows that deep penetration of the radiation into the substrate considerably improves the coating level, preventing excessive penetration of the liquid phase into the substrate and thus considerably reducing the energy required for coating drying. Figure 12 shows how an optimal selection of the wavelength effectively prevents the penetration of the liquid phase of the coating into the substrate and thus prevents the migration of binder and fines. It can be seen that eNIR is much more effective on the rougher cardboard side with higher capillary forces, as the substrate has been heated up much more overall. On this side of the board you can see that the previous infrared emitters were clearly overdriven - they had only been designed for a speed of 400 m/min - and at 700 m/min were unable to prevent the latex, starch and fine fraction of the pigment from migrating into the substrate. At the same time, the previous NIR emitters were unable to cool the top of the coating, as vaporization only took place under the hot air hoods. The temperature differential between the surface of the coating and the

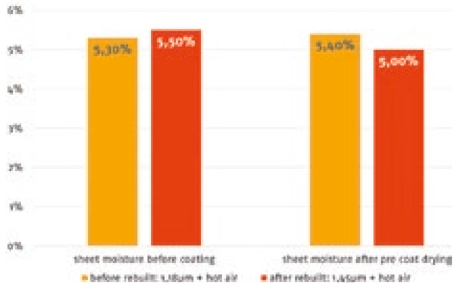


Fig. 11: Change in the moisture of the base board and the board after pre-coat drying with NIR emitters and eNIR emitters[17]


Fig. 12: Change in the specific evaporation rate as a function of the capillarity of the substrate depending on the wavelength of the emitter[18]

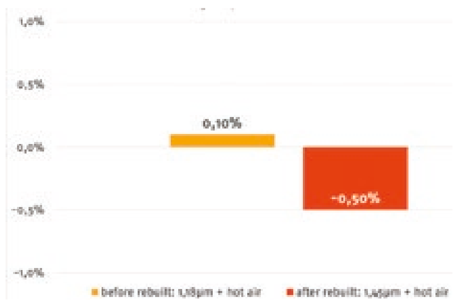


Fig. 13: Change in water content as a function of the wavelength of the emitter[19]

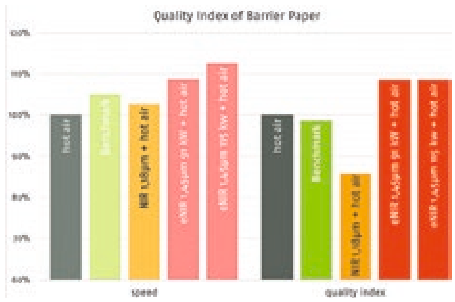


Fig. 14: Standardized production speed and synthetic quality index of a barrier coating with hot air hoods compared to booster plus hot air hoods for drying the coating[20]

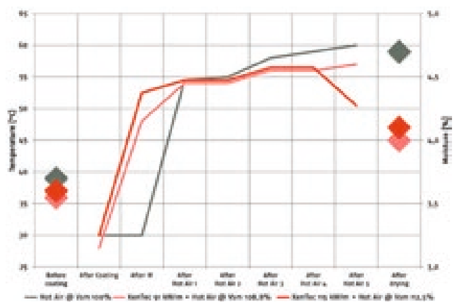

Fig. 15: Temperature curve and moisture of a barrier coating with hot air hoods compared to a booster plus hot air hoods for coating drying[21]

initial sediment layer was basically non-existent, which also meant that mass transport to the surface was not achieved.
The optimized eNIR emitters were able to do this much better despite a nominal 20% less power. Sufficient radiation was converted into heat in the substrate. This means that much less energy is required to vaporize the water.
Questions regarding the optimization of the pre and topcoat formulations cannot be answered here. However, experienced developers know how the costs of the pre coat, but especially the topcoat, can be reduced if the coating hold out is improved as much as in this case. Of course, this also leads to a decarbonization of raw materials.
Figure 13 clearly shows this: with NIR emitters, the cardboard had 7.39 kg/m/h more water than the substrate after pre-coat drying. When drying with eNIR at the same power, it had 65.04 kg/m/h less – so the right wavelength saves a considerable amount of energy.

### 2.2 eNIR-Booster for barrier drying

A paper mill produces various speciality papers on an offline coating machine, one of which has a barrier made of high-molecular PVOH. Several coatings are applied to both sides, the last one being a barrier on the top side, which is dried with five hot air hoods. Grades with this barrier are coated at a very low production speed. Due to the low production volume, the high contribution margin per ton is counteracted, as fewer tons are now produced per hour. An eNIR emitter is installed between the coating head and hot air hoods, with a reflector on the back to reduce radiation losses. An installation space in md of 0.5 m is sufficient for this to enable a speed increase of 20 % to 30 %.
A row of emitters with an output of 160 kW per meter width will be installed. Prior to this, tests had been carried out with NIR emitters with 200 kW per meter width. However, these did not achieve the minimum requirement of a 5 % increase in output because the paper quality dropped too much and the paper would no longer be saleable. Figure 14 shows the increase in speed by 8.8 % and 12.5 % respectively, with enhanced paper quality.
The increase in production was achieved by heating the substrate with simultaneous vaporization during irradiation. Figure 15 shows that despite the very high energy input from the eNIR emitters, the surface temperature is lower than with pure drying using hot air hoods. The enthalpy of vaporization guarantees a low surface temperature and positive temperature differential movement of the water to the surface. The barrier is achieved with a single coat, as no water evaporates and leads to pinholes. The lower temperature curve and lower humidity allow further speed increases that are not possible with NIR or gas-powered dryers.

### 2.3 eNIR-profiling

Profiling with eNIR dryers enables a considerable increase in paper machine performance. Compared to profile correction with water, radiation is considerably more expensive. However, the paper machine must evaporate the applied water. This requires

between 0.5 % and 3 % of the drying capacity, so that production is reduced by 2 % to 10 %. If profiling is carried out with infrared, the paper can be fed to the dryer considerably moister, increasing production by 3 % to 15 % compared to profiling with water. The additional production compensates for the higher energy costs.
The thermographs in Fig. 17 show the influence on the moisture profile and temperature of the sheet. Without profiling (on the left in the picture), the temperature hardly varies, which is equivalent to an acceptable moisture profile thanks to the built-in profile control with water atomization. When the test system was switched on (thermography on the right in the picture), the paper machine moved forwards by 3.5 %, at the same time the irradiated strip heated up and was still around 9°C warmer at the reel. The edge was 2.4 percentage points drier, with around 5 % moisture instead of 7.5 % in the rest of the web.
With profiling across the entire width, the production speed can be advanced by around 10 % to 14 %. The moisture profile can be brought from +/-2.1 % to +/-0.2 % with just under 320 kW/m. Although the moisture content is very low, and thus more energy is required to evaporate water from the fibers, the specific evaporation rate for this recovered paper-based paper was 0.48 kg/kW. With an energy input of 155 kW/m, production can be increased by 12 %. At 0.30 €/kWh, costs of 2.82 €/t arise in this case. The additional contribution margin per additional ton produced is considerably higher, meaning that the use of electricity instead of water pays for itself very quickly. Typically, such projects amortize within 3 to 18 months thanks to the efficient eNIR emitters.

### 2.4 eNIR-preheating

The properties of eNIR emitters can be seen very clearly from the thermographs taken during a test to preheat heavy cardboard. For one test, the top side of a 600 g/m² and 1,000 µm thick cardboard was preheated with 160 kW/m eNIR radiation. Figure 18 shows the structure and the temperature change on the top side of the web, Figure 19 shows the underside. It can be seen how the temperature reaches the opposite side with a delay. The temperature change and speed of the temperature change correspond to the findings of Dr Peter Fisera.[23] It can be seen that even at a very low speed of 25 m/min, it takes around 1.2 s for the heat to reach the underside.
The introduction of energy and the heating of the substrate in the z-direction are very clearly recognizable. You can clearly see that the web is heated throughout its entire depth. When preheating with eNIR emitters, the web is irradiated from above and below in order to achieve perfect flatness. This distributes the temperature very evenly in the z-direction. And while the surface of the web is cooled by evaporation, the temperature in the center of the web remains high. As a result, the water moves towards the cylinder surface, the surface remains moist and therefore a very good temperature conductor. This increases the vaporization rate of the cylinders. The cost of the expensive energy of infrared radiation is offset by the significantly increased vaporization rate of the drying cylinders. These cylinders are

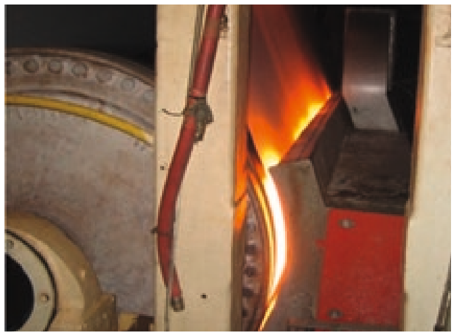

Fig. 16: Space-saving installation of an eNIR emitter with curved infrared lamps adapted to drying cylinders for optimum energy input into the web. Moist areas can be recognized, where the lamps shine with higher power

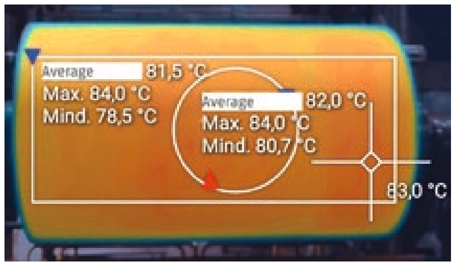


Fig. 17: Thermographs of an operating test for profiling at 0 % power

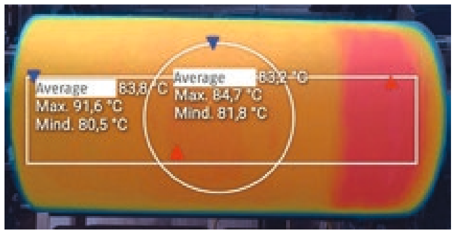


Fig. 18: Thermographs of an operating test for profiling at 100 % power. The machine only accelerated by 3.5 %, not the expected 10 % to 14 %. The leading edge is almost 9°C warmer[22]

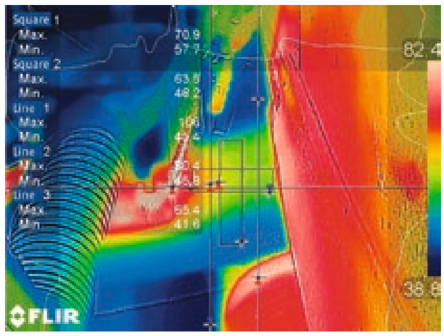


Fig. 19: Thermography of an emitter on the top side of the web between the press and the dryer section for preheating the cardboard[24]

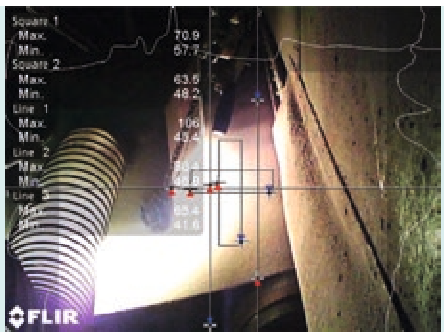


Fig. 20: Visible image of an emitter on the top side of the web between the press and the dryer section for preheating the cardboard

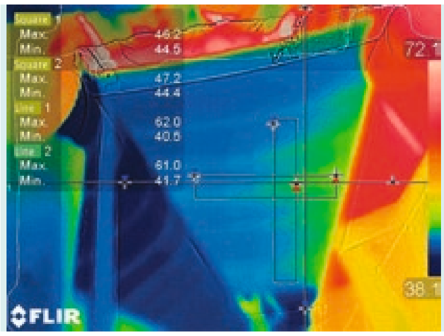

Fig. 21: Thermography of the non-irradiated underside of the web between the press and the drying hood for preheating the cardboard. It can be seen that the heating of the cardboard reaches the underside with a time delay. The reverse side is heated by just under 3°C.[25]

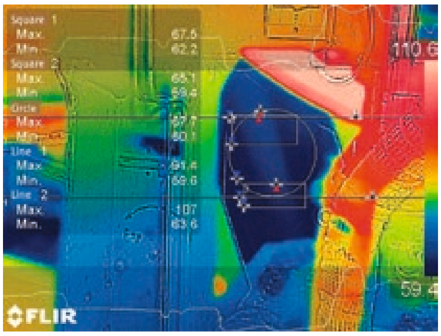

Fig. 22: Thermography of the non-irradiated underside of the web between the 2nd and 3rd cylinder. Even after several cylinders, it can still be seen that the rear side in the irradiated area is up to 8°C warmer than the non-irradiated web.

used for drying from the position of the emitters and do not have to bring the web to evaporation temperature. Figure 19 clearly shows that after the emitter, the irradiated underside is around 3°C warmer than the normal web; before the third cylinder, the temperature difference is already 6°C. The efficiency of the cylinders is significantly increased at the preheated point.

## 3 Summary

The first and most important step in coating drying is to increase the application solids content and reduce the difference between the application and immobilization solids content. The latter considerably reduces the amount of infrared radiation, the former the total energy required for drying. Fundamental work was carried out here by Dr Manfred Baumeister.

There are several descriptions of infrared radiation in paper production, but these only partially stand up to scientific scrutiny. Scientific findings based on physical laws confirm the penetration depth of targeted radiation in the z-direction.

Optimum coating and barrier drying takes place from the initial sediment layer. This is achieved by heating the substrate with rapid immobilization of the initial sediment layer and cooling of the coating surface. This results in a positive temperature differential from the sediment layer to the surface with rapid upward water transport. Migration into the substrate is reduced to an absolute minimum. Similarly, drying from the inside out also occurs during profiling, preheating and drying of substrates. The quality of the paper is maximized, energy consumption is minimized and raw material costs can be reduced to a minimum.

This can only be achieved with electric infrared dryers. An eNIR dryer has significantly lower conversion losses and typically evaporates twice as much water as an NIR emitter for the same amount of energy.

Electric infrared emitters can be powered by renewable energy. This represents a further advantage, as it allows a significant part of the drying process to be decarbonized. The savings potential with eNIR emitters is considerable. www.wolfheilmann.eu

**Sources:**

1 Helmut Graab, Zanders AG: Einfluss der Strahlertemperatur von Infrarotstrahlern auf die Trocknungsleistung, Wochenblatt für Papierfabrikation 19/1991

2 Dr. Peter Fisera, Andritz AG; Tim Klemz, Compact Engineering: Infrared Dryers as a tool in the press section, Pulp and Paper Technical Association, Proceedings of PacWest Conference, Jasper, 2008

3 Magnus Pettersson, University of Lund: Heat Transfer and energy efficiency in infrared paper dryers, 1999

4 MG.M. Hale and M. R. Querry, Optical constants of water in the 200nm to 200µm wavelength region" Appl, Opt,, 12, 555-563, (1973)

5 W, M, Irvine and J, B, Pollack, Infrared optical properties of water and ice spheres, Icarus, 8, 324--360, (1968)

6 D, J, Segelstein, "The complex refractive index of water," University of Missouri-Kansas City, (1981)

7 V, M, Zolotarev, B, A, Mikhilov, L, L, Alperovich, and S, I, Popov, Dispersion and absorption of liquid water in the infrared and radio regions of the spectrum, Optics and Spectroscopy, 27, 430--432, (1969)

8 Helmut Graab, Zanders AG: Einfluss der Strahlertemperatur von Infrarotstrahlern auf die Trocknungsleistung, Wochenblatt für Papierfabrikation 19/1991

9 Dr. Peter Fisera, Andritz AG; Tim Klemz, Compact Engineering: Infrared Dryers as a tool in the press section, Pulp and Paper Technical Association, Proceedings of PacWest Conference, Jasper, 2008

10 Wolf Heilmann: Physik und Anwendung elektrischer IR-Strahler, Fachausschuss COAT des Vereins Zellcheming

11 Wolf Heilmann: Trocknung von Barrierestrichen, Wochenblatt für Papierfabrikation 9/2019

12 Philippe Bernada, Denis Bruneau: Modeling binder migration during drying of paper coating, TAPPI Journal, Vol. 79; No. 9, September 1996

13 Kuang, Thibault, Chen, Grandjean: Pilot scale investigation of infrared drying of paper, TAPPI Journal, Vol. 78; No. 7, July 1995

14 T. Björnberg: Electric infrared drying – new drying method and practical experiences, TAPPI Coating Conference Proceedings 1987

15 Kuang, Thibault, Chen, Grandjean: Pilot scale investigation of infrared drying of paper, TAPPI Journal, Vol. 78; No. 7, July 1995

16 Kuang, Thibault, Chen, Grandjean: Pilot scale investigation of infrared drying of paper, TAPPI Journal, Vol. 78; No. 7, July 1995

17 Zheng Lin, Ningbo Zhonghua Paper; Wolf Heilmann; Tim Klemz, Compact Engineering: Optimised Coat Drying in a board machine, Wochenblatt für Papierfabrikation, 7/2014

18 Zheng Lin, Ningbo Zhonghua Paper; Wolf Heilmann; Tim Klemz, Compact Engineering: am angegebenen Ort

19 Zheng Lin, Ningbo Zhonghua Paper; Wolf Heilmann; Tim Klemz, Compact Engineering: am angegebenen Ort

20 Wolf Heilmann: Trocknung von Barrierestrichen, Wochenblatt für Papierfabrikation 9/2019

21 Wolf Heilmann: Trocknung von Barrierestrichen, Wochenblatt für Papierfabrikation 9/2019

22 Wolf Heilmann: Kosteneffiziente Trocknung mit teurer Energie, Herbsttagung der Regionalgruppe Süd des VPM und Zellcheming, 11/2022

23 Dr. Peter Fisera, Andritz AG; Tim Klemz, Compact Engineering: Infrared Dryers as a tool in the press section, Pulp and Paper Technical Association, Proceedings of PacWest Conference, Jasper, 2008

24 Wolf Heilmann: Kosteneffiziente Trocknung mit teurer Energie, Herbsttagung der Regionalgruppe Süd des VPM und Zellcheming, 11/2022

25 Wolf Heilmann: Kosteneffiziente Trocknung mit teurer Energie, Herbsttagung der Regionalgruppe Süd des VPM und Zellcheming, 11/2022