TAMPERE POLYTECHNIC
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FINAL THESIS

Henri Keski-Orvola

THE CONTEMPORARY DRYING OF PAPER AND PAPERBOARD COATINGS

Thesis Supervisor	Dr. Tech. Ulla Häggblom-Ahnger
Commissioning company	Tampere Polytechnic
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ABSTRACT

This work studies the drying of coating color, its effect on paper and paperboard properties and the trends of drying layouts. The purpose was to offer a compact information package based primarily on literature and studies for those interested in the subject. Several studies concerning the drying of paper coatings have been made, expressing that energy and investment costs can be decreased without losing anything in paper quality and slowly the studies are having an effect on drying layouts. We will be seeing less infrared dryers on coating machines in the future, their main task changing from drying to moisture profiling, while air drying will increase its popularity.

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TIIVISTELMÄ

Työssä käsiteltiin päällysteen kuivatusta, sen vaikutusta paperin ja kartongin ominaisuuksiin sekä kuivatusjärjestelmien trendejä. Tarkoituksena oli tarjota tiivis tietopaketti aiheesta kiinnostuneille käyttäen lähteinä pääasiassa kirjallisuutta ja alan tutkimuksia. Useita tutkimuksia on tehty paperin päällysteen kuivatukseen liittyen ja on ilmeistä että energiassa ja investointikustannuksissa voidaan säästää heikentämättä lopputuotteen laatua. Vähitellen tulokset ovat vaikuttamassa käytännössäkin, tulemme näkemään päällystysyksiköillä vähemmän infrakuivaimia niiden pääasiallisen tehtävän muuttuessa varsinaisesta kuivauksesta kosteusprofiilin säätöön ja ilmakuivainten käyttö tulee laajenemaan entisestään.

FOREWORD

Short and sweet: I’d like to thank my thesis supervisor Dr. Tech. Ulla Häggblom-Ahnger for encouraging me and pushing me through the process. Also, I want to express my gratitude to all my friends and close ones for not pushing me..

Henri Keski-Orvola
Tampere 2007

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1 INTRODUCTION

The process of coating paper and paperboard consists of different phases. The first one is the application of the coating color, where a surplus of coating color can be applied with different coating methods. The second is the metering of the coating. The third one is the drying of the coating and the fourth is finishing, e.g. calendering.

The focus of this thesis work is on the drying of coating colors. Other topics closely related to the subject are treated with that in mind. The work consists of covering the basics of what coating color is, why it is used and what happens to it as it is dried, the drying equipment and the use of that equipment in practice, i.e. coating machines.

2 COATING

Coating is performed primarily to enhance the printing qualities and visual properties of paper and paperboard in the most economical way. Depending on the grade produced, which defines what kind of characteristics are wanted, there may be 0-3 layers of coating per side. One layer usually has 10-15 g/m^2 of coating. /1, p.14; 2/

Especially in the food industry, but also in other industries too, coatings can be used to make the surrounding paperboard package more durable and thus protects the primary product from external threats. This work, however, only deals with aqueous pigment coatings. Plastic coatings that require the evaporation of water or solvent are dried with similar methods to normal pigment coatings. /1, p.14; 3, p.178; 4, p.195-196/

2.1 Effects of coating on paper/paperboard properties

- Decreased ink absorption
- Improved smoothness
- Improved gloss
- Improved opacity and possibly brightness
- Increased surface strength and decreased dusting
- Decreased mechanical strength (compared with papers at the same basis weight)
- Decreased stiffness (comparing with papers at the same basis weight)

Figures 1 and 2 show how the coating covers the paper surface, balancing the variations in the base paper. However, flaws in the base paper cannot be completely hidden by coating or during finishing. This is why a successful end product of coated paper requires success both in the production and coating of the base paper. /1, p.19, 581; 2/

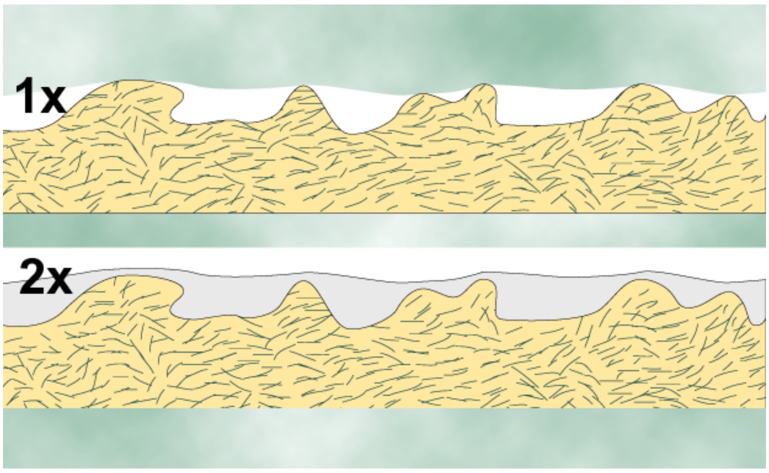

Figure 1. Single and double coating of paper /2/

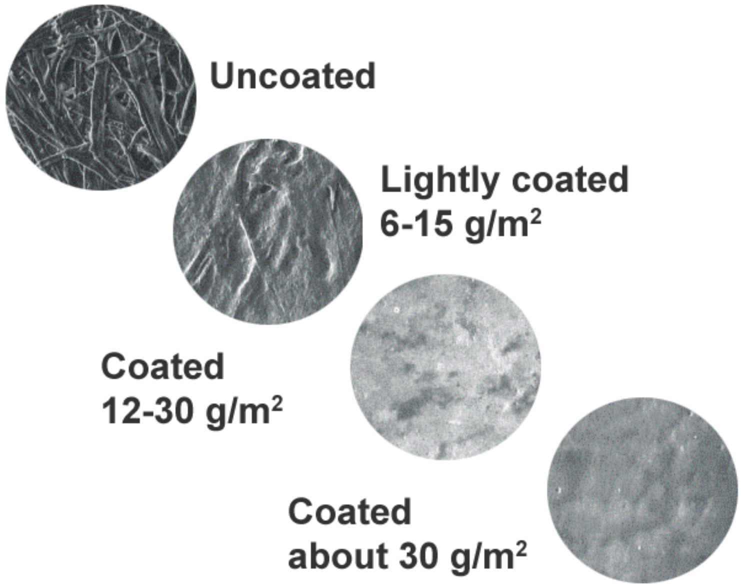

Figure 2. The effect of coating on the surface of the paper /2/

The pore size in the coating layer is considerably smaller than that in the paper/board, thus improving the printing properties of the board due to its minimal bleeding and absorption of printing inks. /2/

2.2 Coating components

Coating color consists of several components, the most important being the pigments. Kaolin clay and calcium carbonate are the most common ones, representing mineral pigments, but also synthetic pigments are used. In dry coating, pigments form 80%-95% of the coating by weight and about 70% by volume.

Different pigments have different kinds of characteristics, which define the most sensible combination of pigments to be used. Brightness, density, size distribution, price and particle shape are the most important ones, and they affect the rheological properties and the structure of the coating color, as well as the optical and printing properties of a coated paper. /1, p.14, 61/

Pigment type and pigment particle size distribution (PSD) affects the drying capacity, and it's commonly believed that pigments with narrow PSD increase energy costs. The belief is based on the fact that coating colors which contain narrow PSD pigments can't reach dry solids contents as high as coating colors with broader PSD pigments. /5/

Binders function as a glue between pigment particles and the base paper. They (A) bind the particles to the base paper, (B) bind particles to each other and (C) fill partly the voids between pigment particles to create a porous structure. The functions are portrayed in figure 3. Usually a combination of two different binders is used and the amount is about 5%-20% of the coat weight when dry. The most common binders are starches, latexes, CMC (carboxy methyl cellulose) and polyvinyl alcohol. /1, p.14, 189/

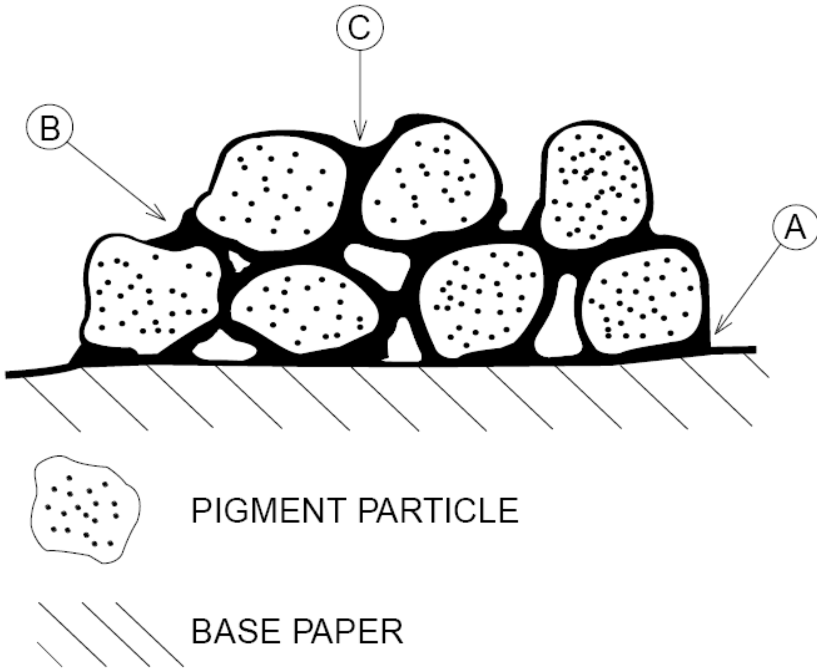

Figure 3. Functions of binders in the coating layer /1/

Thickeners can be added to adjust the rheology and water retention of the coating color. A thickener which has good binding properties can be called a co-binder. Thickeners slow down the speed at which the base paper absorbs water from the coating. There are also other various additives used in coating colors, but they have a minor effect in terms of drying. /1, p.15, 219-221/

2.3 Coating recipes

The components mentioned in the previous section are mixed with water to produce a coating color. A normal dry content for a coating color when applied to the paper is around 60%. Below are two examples of coating recipes, which are suitable for different base paper grades and printing methods. The sum of pigments has to be 100% and the other values are the dry amounts of certain components relative to the dry amount of pigment.

WF-color:		**%**
Fine clay HC 90		30
Ground fine carbonate	HC 90	70
SB-latex		12
CMC		0.8
Hardener		0.1
Lubricant		0.5
Optical brightener		0.2

LWC-color:	
Fine clay HC 90	70
Ground fine carbonate	30
SB-latex	8
Starch	4
Hardener	0.3
Lubricant	0.5

If LWC is to be printed in rotogravure, starch should be replaced with CMC. Also, the binder amounts are usually lower and in many cases, the carbonate would be replaced with talc. Rotogravure printing requires better smoothness and surface strength is less important than with offset printing. With board grades, more $CaCO_3$ is generally used than with paper. /1, p.17-18, 591; 3, p.185; 6, p.171; 7/

The amount of water in the coating color is the most crucial attribute in terms of drying since it dictates the requirements for a drying section. Increasing the coating color solids content reduces the production costs, because less water is needs to be evaporated. Also, higher solids content may allow an increase in running speed if drying capacity is limited. One study revealed that starch could be used a lot more than it is nowadays, since especially in the first coating layer of a double-coated paper (or paperboard), the visual shortcomings of starch compared to latexes won't become apparent. Starch's advantage is its price, while latexes' prices are influenced by the price of oil, which is going up all the time. /8/

2.4 Coating methods

The most common methods to coat paper are blade and film coating (figure 4). Coating color is applied to the paper in excess and the desirable coat weight is achieved by metering. The figure also illustrates the difference in the coat weight; with blade coating, the overall thickness of the paper is stable, whereas with film coating, the thickness of the coating remains stable and doesn't depend so much on the base paper's unevenness. /2/

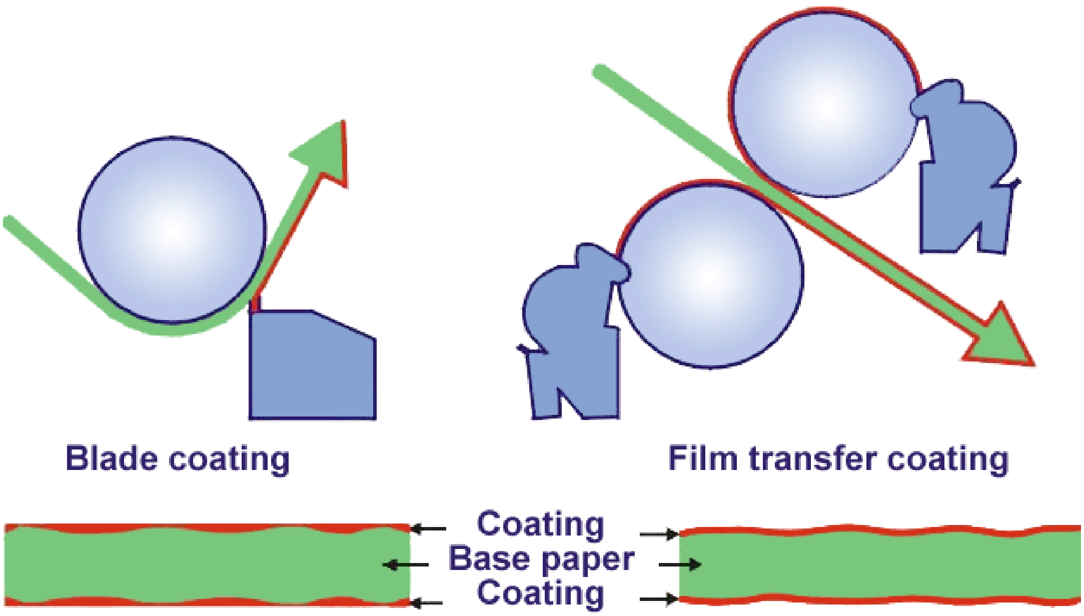

Figure 4. Blade coating vs. film coating /2/

3 DRYING EQUIPMENT

Heat transport always goes from a warm body to a cooler one and is accomplished by the three classic systems of conduction, convection and radiation. An example of heat being transferred by conduction is the can or drum of the conventional paper machine dryer, where good contact is obtained with the felts. Convection is used in two ways, natural and forced. Natural is where gas moves upwards or downwards depending on its temperature (which causes the difference in densities), but it is too slow for industrial purposes. Forced convection is used when a flow of steam is transported with blowers and fans to transfer heat (air drying). Radiation doesn't use a carrier as convection does. Instead, a hot object emits electromagnetic waves which then disturb the molecules in the object they reach. IR-dryers are an example of transporting heat by radiation. /9, p.110/

3.1 IR drying

Electromagnetic energy exists in all wavelengths ranging from 10^{-16} µm (cosmic wave) to 10^{6} µm (electric power waves). Infrared energy falls in the invisible light range, which is between 0.7 µm and 100 µm, after visible light (range 0.4 µm – 0.7 µm). Each material absorbs radiation best at a specific wavelength. Water itself has two absorption maximums at 2.9 and 6.1 µm and figure 5 shows how LWC paper absorbs radiation. The composition of the material always defines how much of the radiation it absorbs. /1, p.543-545; 6, p.165; 10; 11/

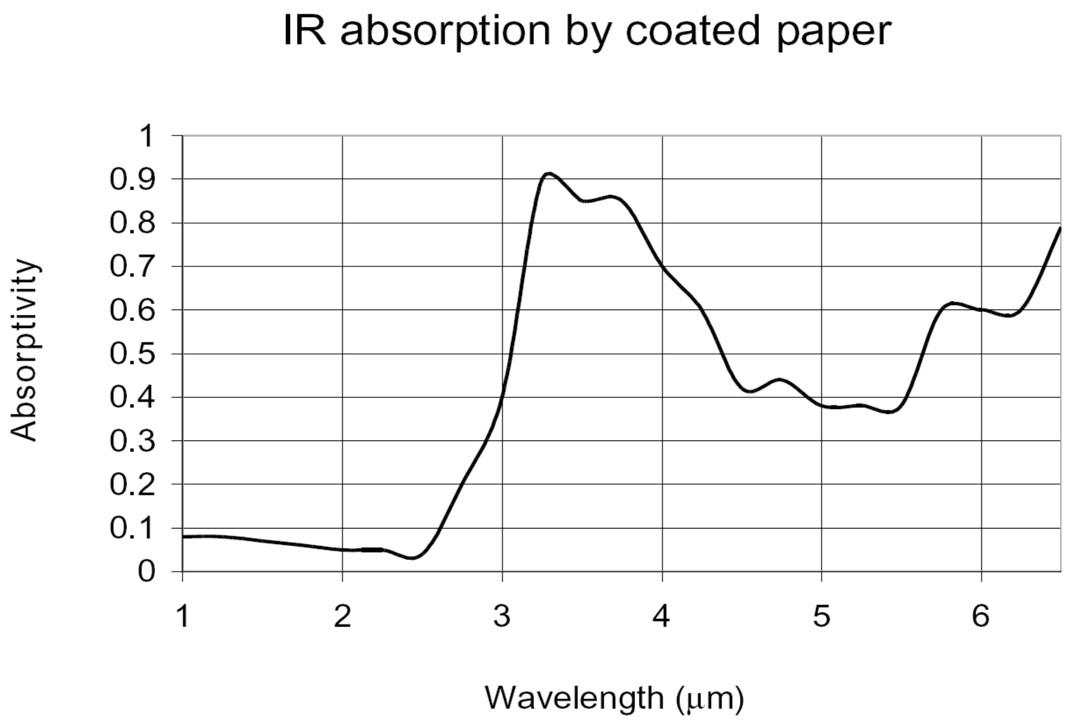

Figure 5. Spectral properties of a coated LWC paper /1/

Infrared energy is radiated from any material that is warmer than its environment and the net radiation flow is always from the higher temperature to the lower. In the paper industry, this fact is used by heating a reflector either electrically or by gas. The reflector then emits thermal radiation to the paper web, where a portion is absorbed, a portion penetrates and a portion of the radiation is reflected back. Radiation of a shorter wavelength penetrates the web with less difficulty, and is absorbed more evenly in the z-direction, while longer wavelength-radiation is absorbed more effectively and thus doesn't penetrate the web as much. /1, p.543-545; 2; 6, p.165; 11/

The emission spectrum of an emitter (radiator) depends on the temperature, as does the power output of the emitter. Because of this, it's not practical to design an emitter with an emission spectrum peak around the 2.9 μm, which would be optimal for heating water. Figure 6 shows how the amount of energy transferred would decrease if the emission spectrum peak would be at 2.9 μm. Also, it shows how the increase of temperature increases the radiation efficiency. The peak wavelength of emission of an infrared heater can be calculated by Wien's Displacement Law:

$$\lambda = \frac{C}{T_K}$$

λ = the peak wavelength [µm]

C = Wien's displacement constant, ≈ 2898 K·m

T = The temperature of the emitter [K]

It should be noted that an emitter gives off its radiation across a wide spectrum of wavelengths and the peak is where a high percentage of the radiated energy is given off. /1, p.544; 3, p.119-120; 10/

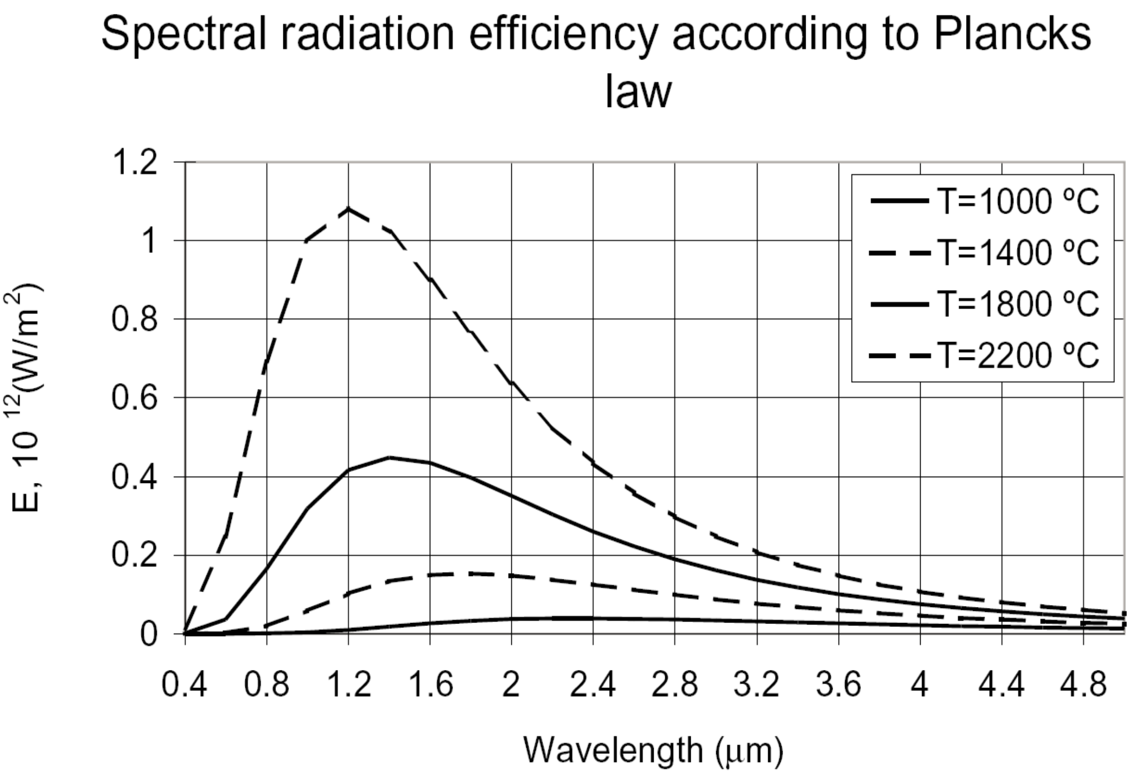

Figure 6. Emission spectrum of a black body in vacuum /1/

3.1.1 Electric IR dryers

An electrical IR radiator is usually basically a halogen lamp with a tungsten filament. Fine tungsten wire is surrounded by halogen gas, which is housed in a quartz tube about 1 cm in diameter. These tubes (usually 7-9 of them) are stacked next to each other, creating detachable modules 14-15 cm wide with a reflector behind the tube and a protective quartz cover in front. The modules form a line about 20-50 cm high and as wide as the web is. The power is controlled by adjusting voltage. /1, p.545-546; 2; 6, p.166/

Figure 7. Infrared dryer /2/

The tungsten filament can reach high temperatures, up to 2260°C and operates at a peak wavelength range from 0.8 µm to 2 µm. Close to 50% of the radiation emitted by the lamp is directed to a ceramic reflector behind the radiator. The reflector absorbs the IR energy and heats to almost 900°C and then reradiates energy with a peak wavelength of 2.5 µm. A part of the radiation goes through the paper web, which is why it is quite common to use a reflector also behind the web. To achieve very high densities, it's possible to set lamps on both sides of the web. Since some parts of the halogen lamps and reflectors can't endure high temperatures, plenty of cooling air has to be guided to them to prevent damage to the system; this also helps to reduce the risk of fire. The quartz cover absorbs some of the radiation depending on how clean it is kept. /1, p.545-546; 6, p.166; 9, p.119/

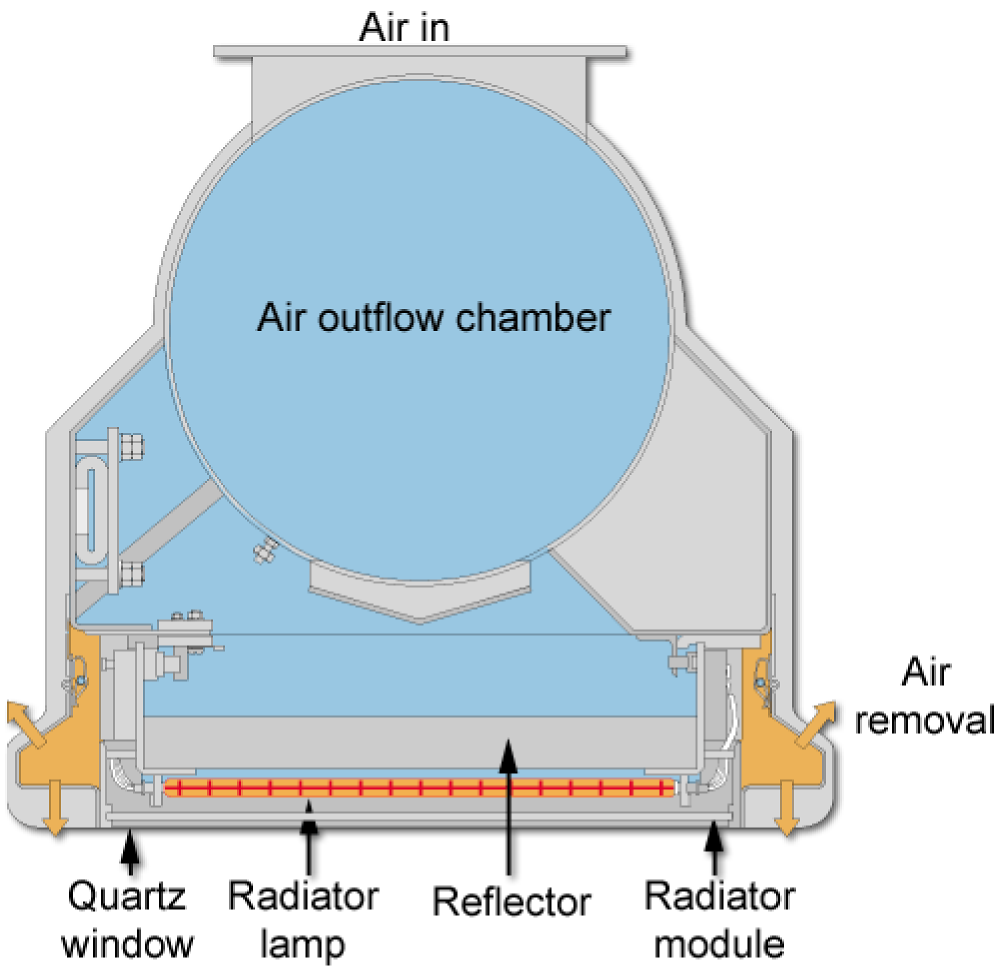

Figure 8. Electrical IR dryer /2/

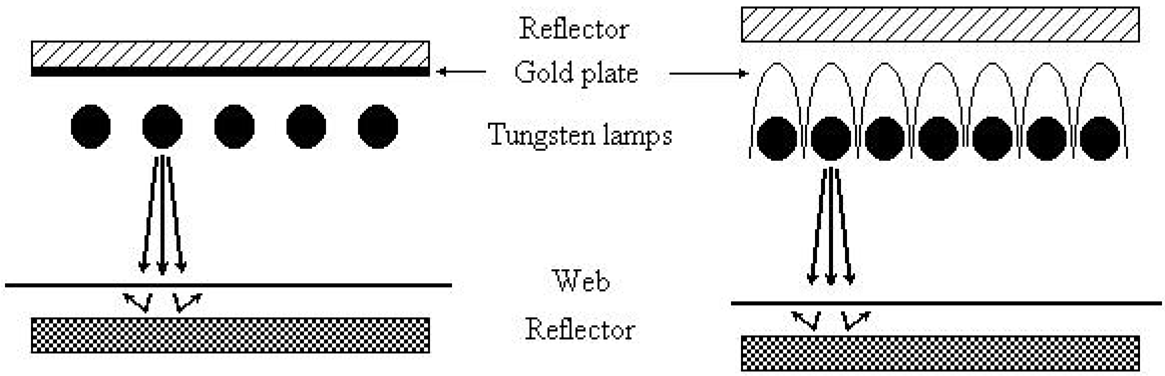

Figure 9. Lamp layouts

There are different ways to set the lamps, figure 9 shows two of them. On the right, parabolic reflectors surround the lamps, protecting them from each other and making it possible to install them closer to each other or to use a more powerful lamp. /12/

3.1.2 Gas IR dryers

A common gas-fired emitter has a ceramic plate heated from 600°C up to 1200°C. The fuel gas is a mixture of liquid propane and butane or natural gas mainly consisting of methane. Fuel gas and air are mixed and the pressure is equalized before they enter the burning area through nozzles or porous material. There are various types of emitters, although they use the same principle; the mixture of gases is ignited and the flame burns on the surface of a ceramic block. Between the block and the web, there is a metal (or ceramic) screen that absorbs over half of the radiation that leaves the ceramic plate. The metal screen heats and reradiates energy around a peak of 2.046 µm, which is only 0.007 µm longer than the peak of the energy the ceramic plate emits, but it is still notable with respect to absorption in water. The wavelength being relatively long, there is no need to use a reflector behind the web. /3, p.195; 6, p.167-169; 9, p.119/

The controlling of gas IR dryers is performed by switching the burners on and off using a magnetic valve. The valve has an on/off cycle of 6 seconds, which can be adjusted so that if it’s closed for 3 seconds, it will be open for 3 seconds, and the burner operates at 50% of its full capability. The output range available is between 3 and 100%. Also, the amount of gas burnt can be adjusted. /1, p.547-548; 2/

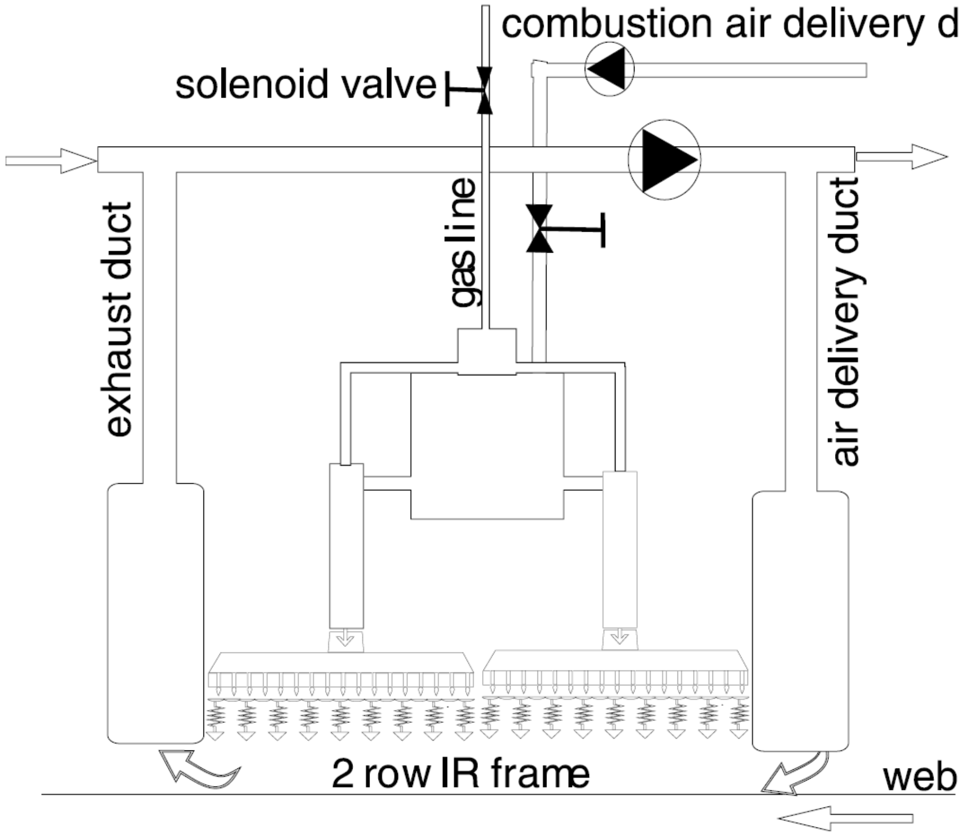

Figure 10. Principles of a gas IR dryer /1/

3.2 Air drying

These days there are two main types of air dryers in use. With air flotation dryers, hot air is blown from both sides of the web and the web floats in a state of equilibrium between the two opposing forces created by the pressure of the flowing air. With single-sided air impingement dryers, the web is supported by rolls and the air comes from only one side of the web, thus being better if the drying of only one side of the web is more appropriate. /1, p.548-549/

3.2.1 Air flotation drying

The air flotation dryer consists of two opposite dryer boxes, to which the air is fed from the drive side. Normally the main fan is after the heat source (draw-through system), which keeps the nozzle velocity at a constant level. 80-90% of the return air is recirculated and the rest comes from the machine room or from outside, but then it has to be preheated. Since the recirculating air takes the vaporized water with it from the dryer, the air has to be dried before it can be used again. /1, p.549-552; 6, p.162-163; 11/

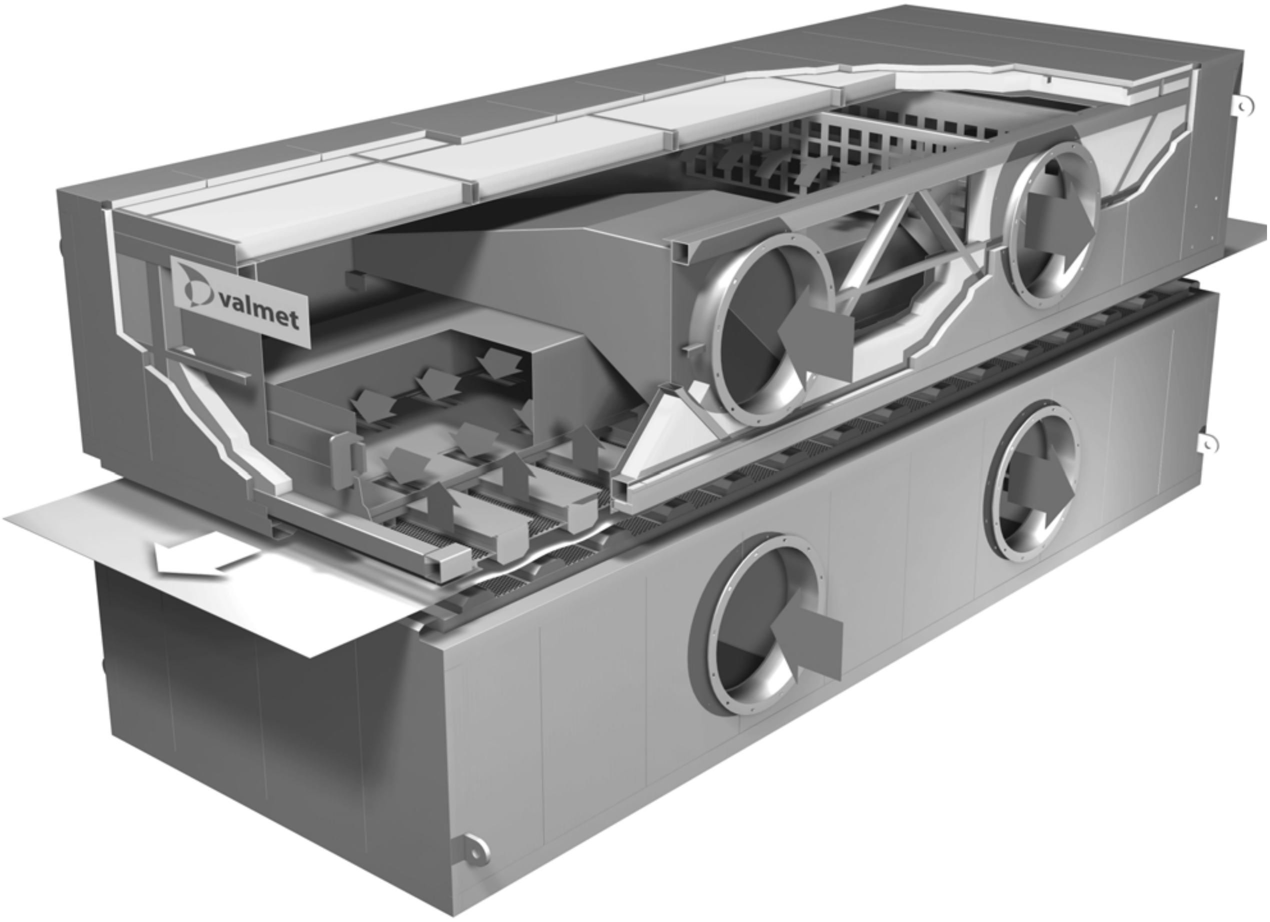

Figure 11. Air flotation dryer presenting air flows /1/

Air dryers are usually heated with in-line gas burners or steam coils, the choice being made considering the required drying air temperature, energy prices and investment costs. With steam-heated dryers, a temperature of 160-185°C with a steam pressure of 10-15 bars is typical, the steam pressure defining the maximum temperature. Using gas burners to heat the air, higher temperatures can be achieved, typically up to 300-350°C, which can be a great advantage when controlling the impingement temperature. /1, p.549; 9, p.113-117/

The operator controls the supply air temperature, and also (although it’s not common practice) it’s possible to control the nozzle velocity, usually even the velocity is controlled automatically either by adjusting the inlet vane in front of the circulation fan or the rotation speed of the fan. A velocity too high can cause binder migration even with the air being at room temperature, whereas with a low velocity heat won't be transferred well enough. /2; 6, p.163; 9, p.117/

Air velocities are usually around 40-60 m/s and the air is directed onto the paper with specially designed nozzles (slots or holes). The most efficient heat transfer is obtained with impingement nozzles, which direct the air perpendicularly to the sheet. In this way, air penetrates the barrier layer of air and vapor effectively, promoting more rapid drying. Figure 12 shows different kinds of nozzle technologies by Metso Paper. PowerFloat is a combination of normal flotation nozzles and impingement nozzles, providing a high evaporation rate. The others will be described more accurately. /2; 9, p.113-114, 11; 13/

The first flotation dryers used airfoil nozzles (Coanda nozzles, Figure 13). An airfoil nozzle consists of a single slot with a curved orifice and a flat support area next to it, which makes the air flow following the curved portion of the orifice and along the flat support area of the airfoil (Coanda effect). The air-jet flow will tend to maintain the web position with a fixed distance from the airfoil. The stabilizing effect is a result of a clear repulsion force to the web from a short distance, while a negative pressure, which increases as the distance to the web increases, draws the web towards the nozzle. The air flow can be against or parallel to the web travel direction, the latter being less effective but more stable, allowing better runnability. Nowadays foils are normally used for light paper grades requiring gentle drying. /1, p.553; 6, p.161; 13/

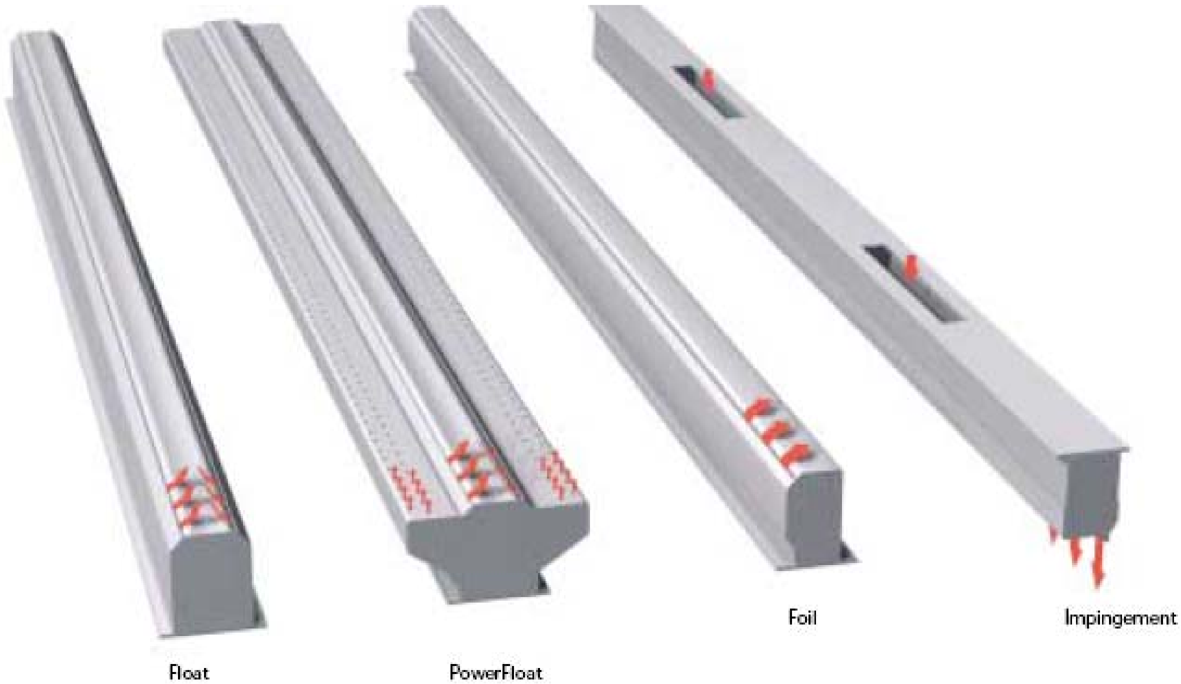

Figure 12. Nozzle technology /13/

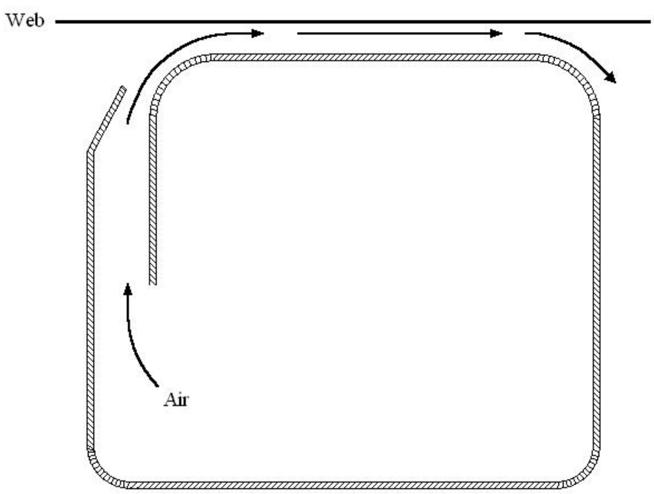

Figure 13. Coanda nozzle

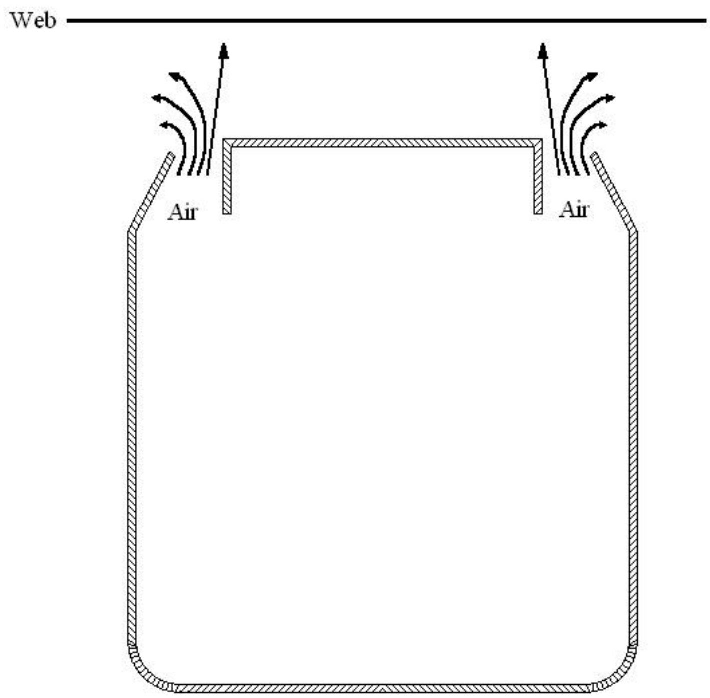

Figure 14. Float nozzle with airflow

With a float nozzle (also called air bar design or overpressure nozzle, figure 14), there is a flat support surface in the middle and two slots for the air to exit through. The air is made to converge towards the center, which creates a pressure pad along the air bar top. This design subjects the web to a continuous positive force, which pushes the web away from the nozzle. To achieve a stable operation, the air bars are staggered on both sides of the web. Figure 15 shows how the web forms a sine-wave path as it runs through the dryer, reducing wrinkling and enhancing web stability by reducing the tendency for the edges to touch the nozzles by eliminating the edge curl. /3, p.195; 6, p.161; 9, p.115; 13/

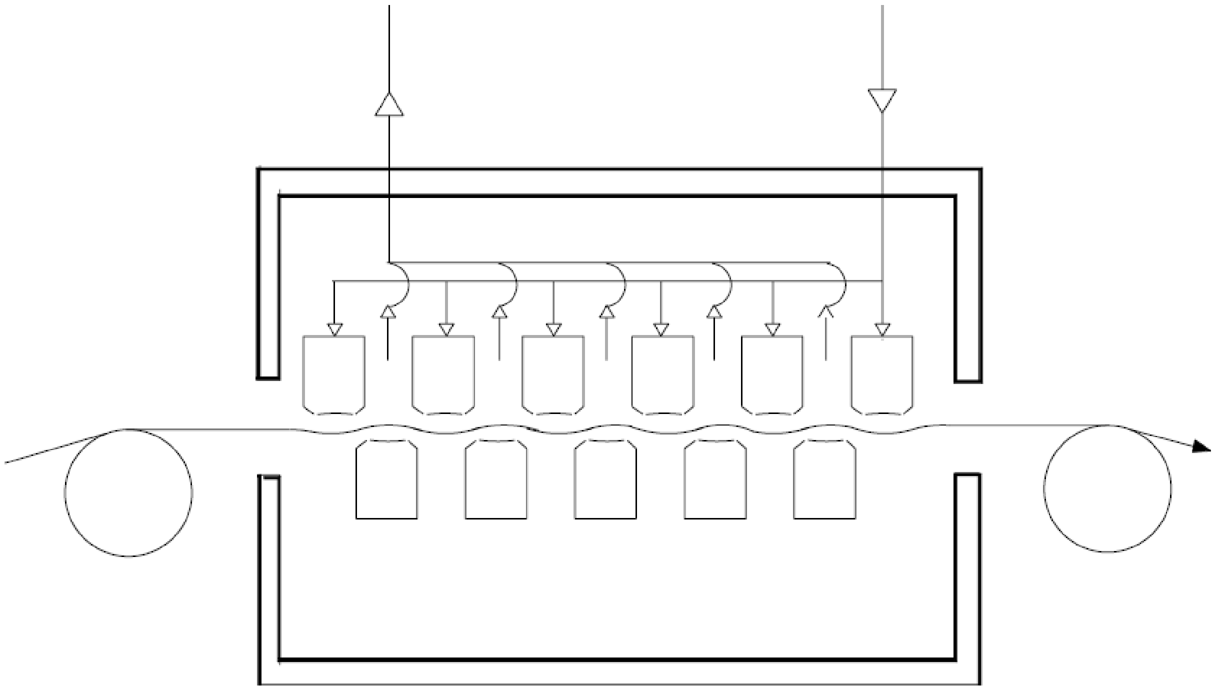

Figure 15. Air flotation dryer /1/

3.2.2 Single-sided impingement drying

Where the drying of paper coatings is concerned, this method has been made obsolete by flotation drying, but when drying coated board and in some converting processes where the drying of the uncoated side isn't desirable (e.g. producing sticker laminate), single-sided impingement dryers are still in demand (Figure 16). The web is supported from the uncoated side by rolls, which can be arranged to form a linear or a curved path for the web as it runs under the dryer. This type of dryer is useful in case of relatively low web speeds or high web strengths. Another version of impingement drying is an air cap dryer (Figure 17) where the web is supported by a large, often steam-heated cylinder that is equipped with an air impingement hood. /1, p.548-549/

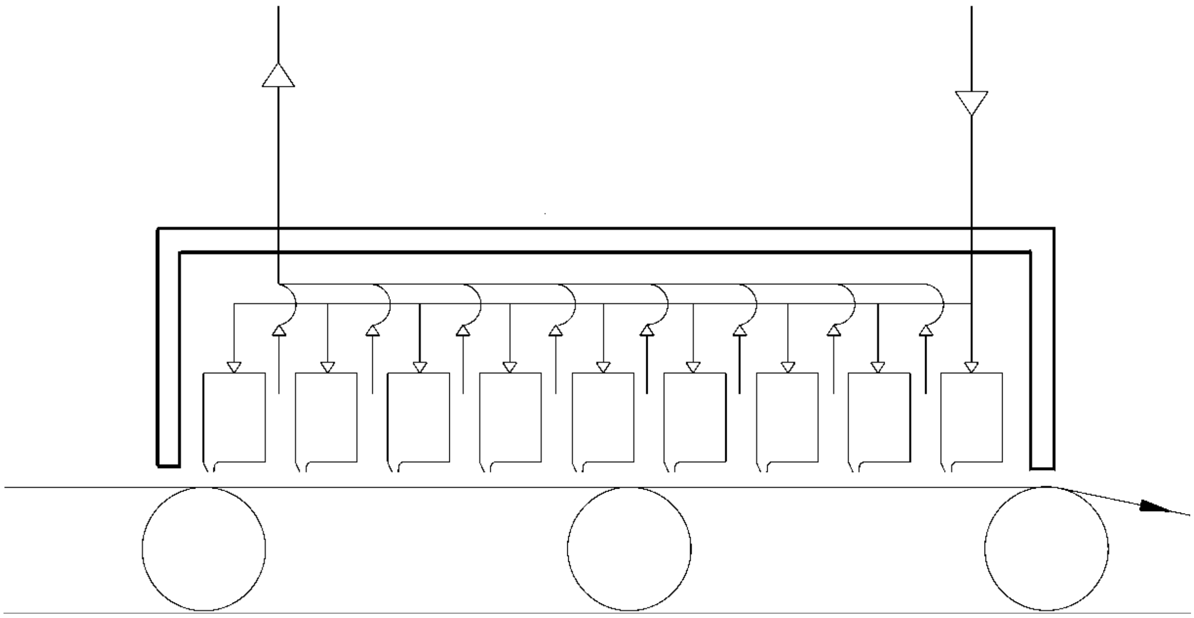

Figure 16. Single-sided impingement dryer with web-supporting rolls /1/

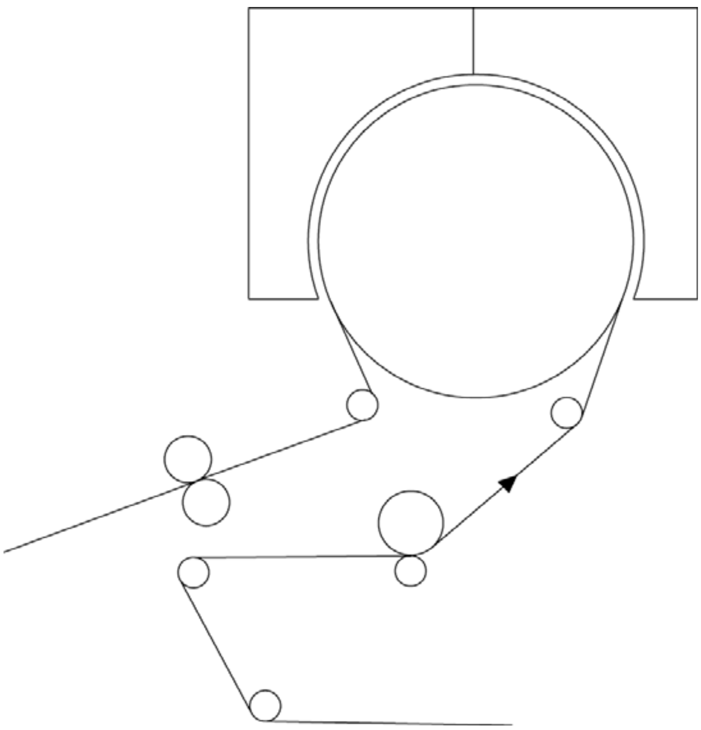

Figure 17. Air cap-dryer /1/

3.3 Combination dryers

A large part of the evaporated steam and the hot leakage air from a separate IR dryer goes to the machine hall, where it is of no use. To improve the energy economy of IR dryers, a combination of IR dryers and air dryers has been made. The IR emitter can be powered either by gas or by electric, and it is located inside an air flotation dryer. The advantage of this system is that the vapor and hot air from the IR section is run through the same air circulation channels as the air dryer's.

An air dryer can use the cooling air from the electrical IR dryer in front of it, thus not having the need for a separate heat source, although in that case the air temperature is limited to 100-150°C. /2; 3, p.196; 11/

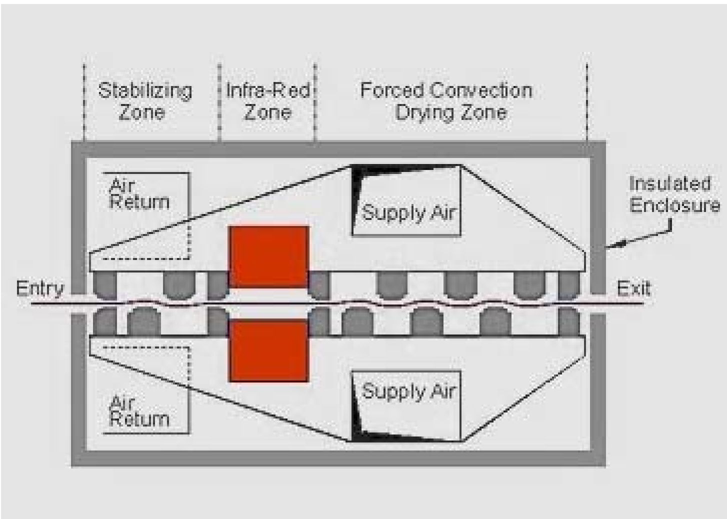

Figure 18. Combination dryer /14/

3.4 Cylinder drying

Cylinder dryers use conduction to transfer heat to the paper web. They can be heated by using oil or electricity, but most commonly by saturated steam since it's available in all paper mills. The operation principle is the same as the cylinders' in a paper machine drying section; the steam condenses into water in the cylinder, delivering its heat for the cylinder shell. The condensate (condensed steam) is collected from inside the cylinder by siphons into the condensate system by using a condensate switch. /2; 6, p.154; 13, p.110/

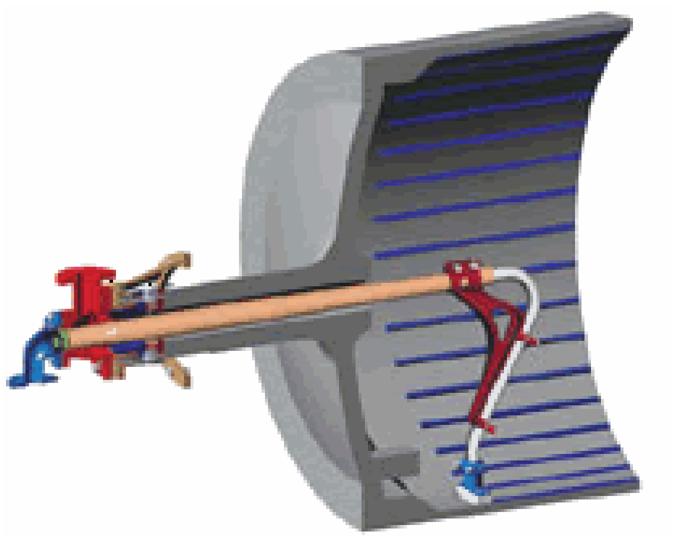

Figure 19. Siphon inside a drying cylinder /15/

3.5 Comparison between drying systems

There are several factors that affect the evaporation efficiency:

- moisture level in the coating and base paper
- distance of drying equipment from the web
- web structure and coating color composition
- web temperature
- machine speed

Evaporation rates for different dryer types can be seen in table 1. In the table it is assumed that the initial drying is performed by IR dryers. With airborne web dryers (i.e. flotation dryers) it is, however, possible to achieve drying rates as high as 150 $kg/h/m^2$ if the temperature of the impingement air is 400°C and the velocity 60 m/s. /2; 16/

Table 1. Dryer comparison with drying rates /2/

Dryer	Specific evaporation range [kg/h/m²]	Efficiency range [%]
Electric IR dryer	60-120	25-40
Gas IR dryer	50-100	30-45
Airborne web dryer	10-30	55-70
Drying cylinder	2-8	75-85

IR dryers have the advantage of being small in dimensions in terms of delivering quickly a lot of energy to the web. When choosing between a gas- and an electric infrared dryer, there are significant differences to be considered. Gas infrared dryers have the benefit of being the more economical solution, if gas is readily available. The operating, investment and maintenance costs are lower. Electric infrared dryer's main advantage is its excellent moisture profiling capability, since the width of the profiling section can be as narrow as 70 mm (for gas IR: 140 mm) and the power can be adjusted automatically according to the information coming from on-line moisture measurements. Also, electrical infrared dryers require less space and they have a higher drying rate. /1, p.546; 2; 11; 16/

Table 2. Dryer comparison table with drying power /16/

Dryer type	Efficiency	Power consumption (kW/m²)	Max. power to the web (LWC) (kW/m²)
Gas IR	30-40%	210	70
Electrical IR	25-35%	310	90
Combined IR+air	30-45%	200	80
Air Dryer	60-75%	110	80
Cylinder	50-70%	15 (coat) 45 (size)	10 (coat) 30 (size)

In the course of time, air dryers have become more and more efficient and they are much more economical to use than IR dryers. The high drying temperatures that result from drying coated paper with IR dryers cause certain problems, such as fiber rising (with mechanical pulp containing grades) and poor dimension stability (WF grades). Effective initial drying with an impingement dryer gives better coated paper quality than if using IR. /7; 16/

Air dryers promote good and stable web runnability. The web temperature is not forced above the evaporation temperature, making it easier to control dimension stability, fiber rising and dusting. /16/

4 DRY COATING STRUCTURE

Drying theories and the effect of drying on quality is discussed in this chapter. The drying of coating doesn't have a major effect on most of the properties of the final product compared to e.g. calendering, altering base paper composition or coating recipe. However, gloss, roughness and most of all, backtrap mottling can be greatly influenced by choosing an optimal drying strategy. /1, p. 560-561/

4.1 Formation of coating layer during drying

The drying process can be divided into three phases to make it easier to study the progression.

The phases are:

1. Initial drying phase
2. Critical drying phase
3. Final drying phase

Figure 20 illustrates the structure of a coating layer and dewatering mechanisms as the solids content increases during drying. /1, p.559-560; 17; 18/

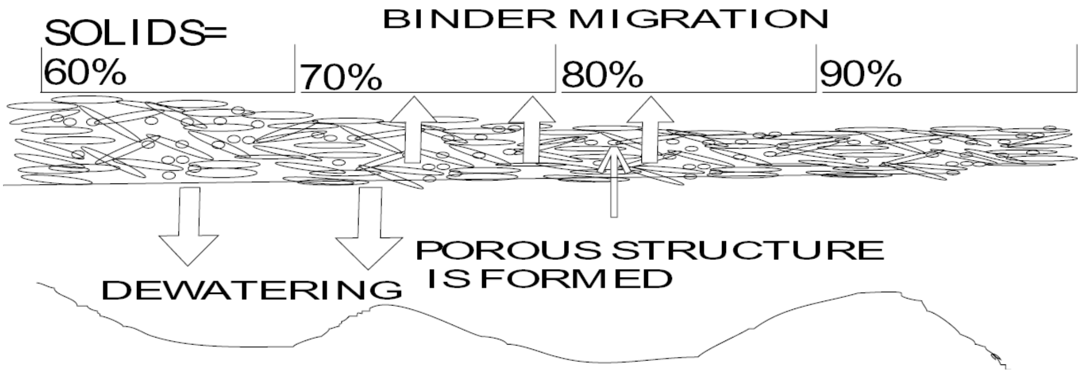

Figure 20. Structure of coating layer. /1/

Initial drying phase

At the beginning of the initial drying phase, energy is transferred to the web to increase the temperature of the paper. The vapor partial pressure inside the web increases above the vapor pressure in the drying medium (i.e. a dryer); evaporation tends to compensate the pressure difference. During this phase, diffusion of vapor initiates a remarkable dewatering process. Capillary flow to the base paper, which starts immediately after the application of color, continues during this phase. Figure 21 illustrates how a $CaCO_3$ suspension gives less flow resistance, thus a higher dewatering rate than a kaolin suspension because of the shape of the pigment particles. As the temperature rises, viscosity of the coating decreases and promotes drainage. However, as the thickness of the coating layer grows, its water retention increases and the importance of capillary flow decreases.

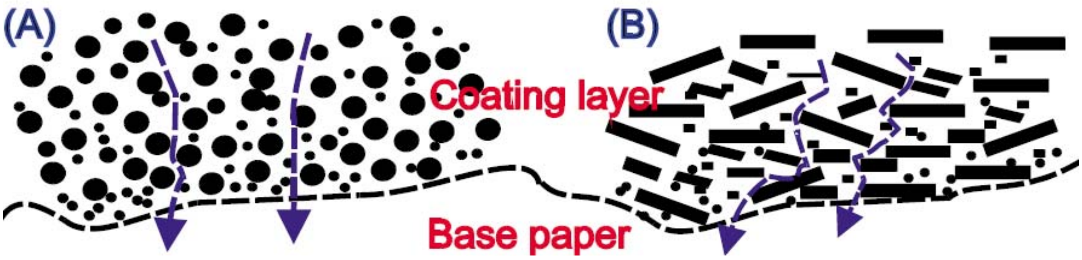

Figure 21. Dewatering process of a) $CaCO_3$ and b) kaolin particle suspension on a paper substrate /1/

There have been conflicting theories on the effect of initial drying on paper quality. Now it's generally accepted that effective initial drying has mainly a positive influence on the quality of coated paper. Strong heating in the initial phase accelerates consolidation of coating, which is considered to improve the quality. After the heating period, the constant rate drying phase begins. /1, p.712; 17/

Critical drying phase

At the consolidation phase of the coating color, the volume fraction of the solid phase becomes so high that pigment and latex particles start to touch each other and pigments stop their movement. Capillary forces will begin to shrink the coating. As the pores empty, the coating structure is formed as the latex particles have lost their form. The consolidation phase takes place when the solid content of the coating is between 73% and 85%. During this phase the coating is very sensitive to drying conditions and that's why it is considered to be a "critical phase". /1, p.563; 7; 17/

Final drying phase

At the final drying phase, the coating layer is stable and the final moisture level will be achieved. Since the effect of this phase on the final quality of the paper is, according to several studies, minimal, the drying can be effective. /17/

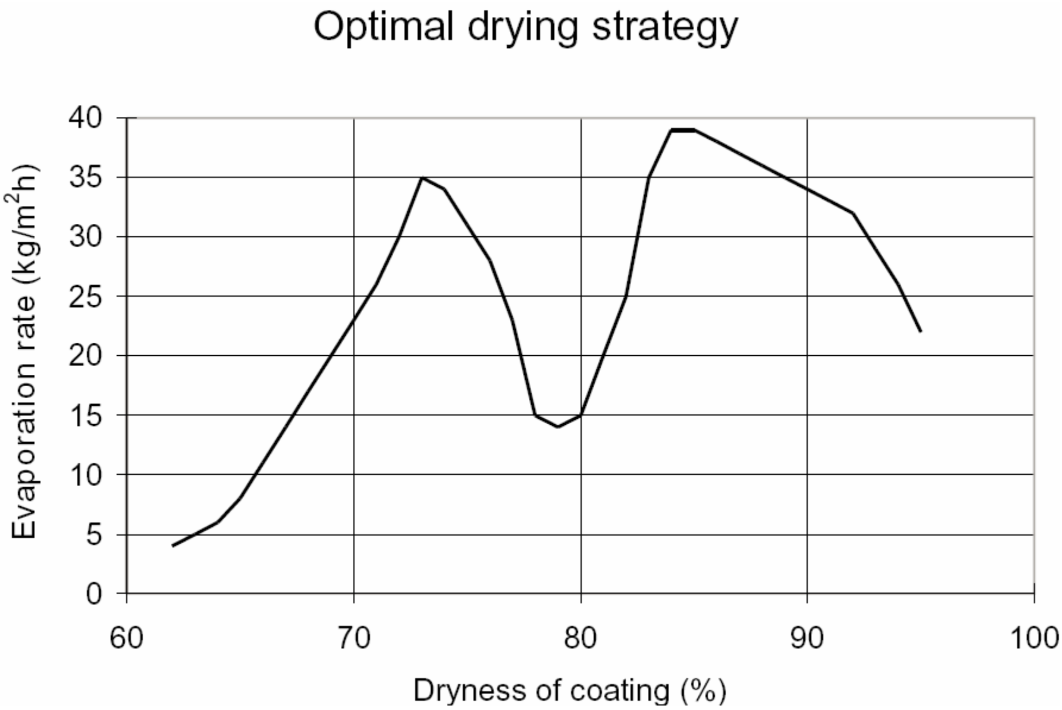

Figure 22. The three phases of drying /1/

Figure 22 shows the optimal drying strategy according to the high-low-high-strategy, where the drying rate at the so-called critical phase is kept low to decrease mottling. /1, p.563/

4.2 Mottling

Mottling is low contrast and low frequency (0.5-10 mm) printing unevenness and is caused by uneven ink absorption in offset printing. It can be seen as differences in the shades of colors. Backtrap mottle is the usual cause of mottle in coated papers. During printing, film splitting and setting of the ink are dependent on the state of the former ink layer. If the previously printed ink layer has settled incompletely, the splitting of a new layer is also incomplete and ink will be transferred unevenly to the cylinder, leaving the ink layer on the paper mottled.

The reasons behind mottling are unclear, but coat weight or base paper variations in the surface direction are the basic reasons for it. If different areas of coating color consolidate at different parts of the drying section under different drying rates, it makes the structure of the coating varied, which makes the printed image mottled.

In the majority of studies, it has been suggested that mottled offset print is caused by binder migration, which causes uneven binder distribution on the paper surface. The studies haven’t been conclusive, though, and even though the amount of binder on the surface correlates with the coat weight and base paper drainage capacity, it’s not necessarily the cause of mottle. One study (18) states that the pigment type and the uneven shrinkage of the coating in plane direction might be the key factor affecting mottle when using latex as a major or the sole binder. /1, p.560-561; 17; 18; 19/

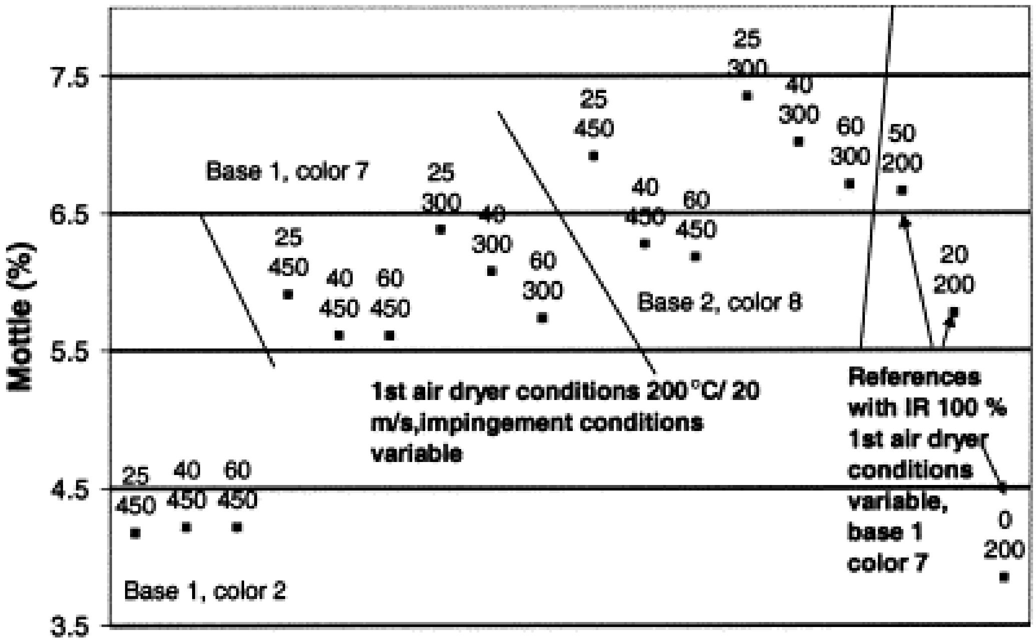

Figure 23. Mottle at different trial points, 70 g/m^2 LWC. In the legends impingement dryer conditions, or in the reference points first air dryer conditions, speed 1000 m/min /7/

In figure 23, the reference (on the right) has an infrared (IR) dryer and the consolidation occurs in the first air dryer. Decreasing the drying rate in the air dryer decreased mottle, proving the high-low-high strategy to be valid in this case. The other results present how effective impingement drying decreases mottle (the impingement dryer was installed 2 m after the coater in the trial). /7/

4.3 Roughness and gloss

Figures 24 and 25 show how gloss improves when drying power is increased in an impingement dryer as the first dryer. Surface roughness decreases with a higher drying rate. Assuming that "valleys" in the coating are denser in the mottled points than "hills" with less coating, there are two explanations that could be valid:

a) The hills become smoother and less porous when effective initial drying is applied and the surface characteristics are evened out, or

b) The valleys become rougher and more porous when effective initial drying is applied.

In a study, a) was valid. Alternative b) is typically valid when IR drying is used as the initial method, giving higher web temperatures but lower evaporation rates because of lower mass transfer. /7/

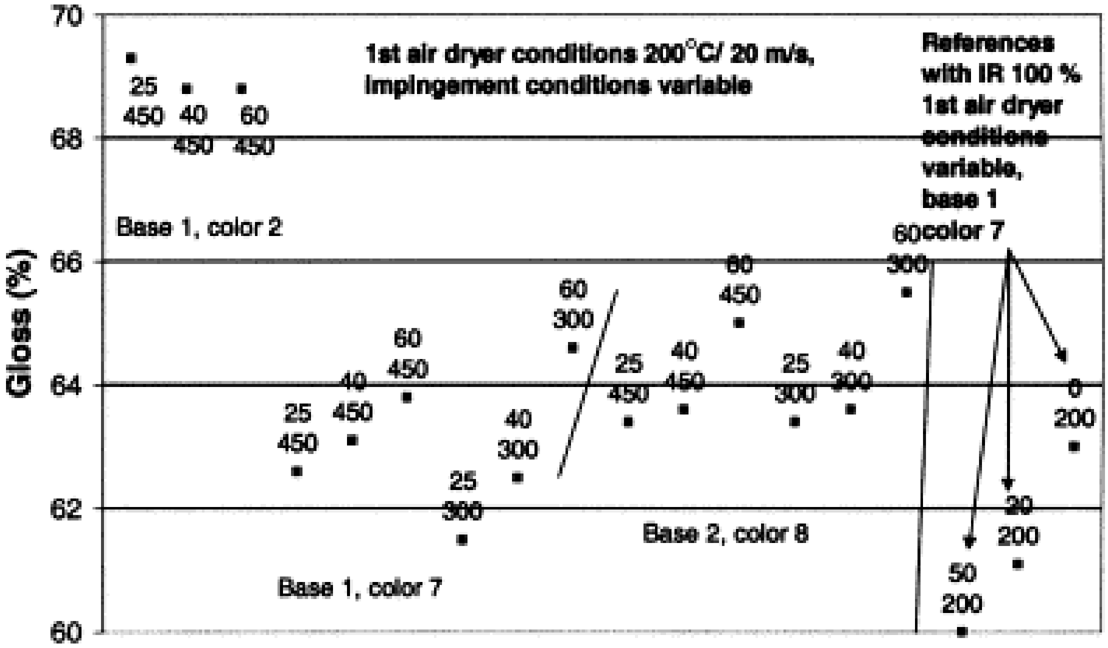

Figure 24. 70 g/m^2 LWC, increasing the air velocity gives better gloss /7/

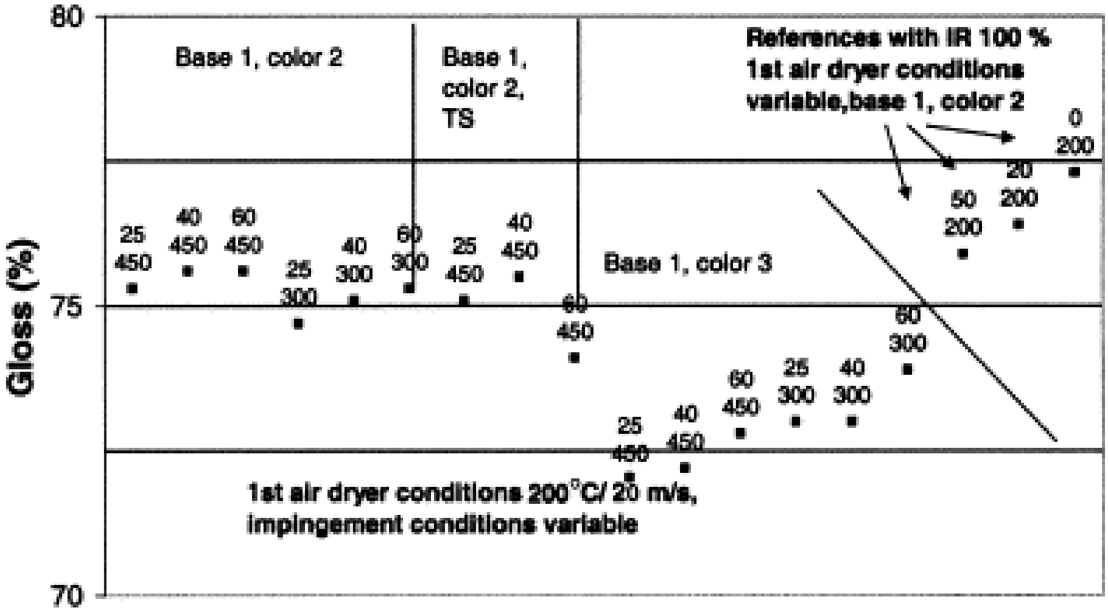

Figure 25. 110 g/m^2 WF, increasing the air velocity gives better gloss /7/

4.4 New drying strategy

Correct drying strategy depends on the layout of the coating section, coating color composition and the base paper properties. There are general guidelines for drying, however:

- Initial drying has to be effective
- The existence of a certain critical phase is generally accepted
- Final drying has only a minor effect on the quality of a coating, so the drying rate can be maximized

The problem with the high-low-high-studies has been the layouts of the pilot coaters – IR, free draw and air drying. If the coating has consolidated partly in the IR dryer or during free draw, the rest of the coating has to be consolidated in similar conditions to reach the same coating structure. According to some studies, it has been clear that if the coating color contains starch, the evaporation rate at that consolidation phase is important. With latex colors, it is characteristic that a high drying rate in initial drying decreases mottling. /1, p.564; 7; 16/

With a single, highly effective air dryer installed immediately after a blade coating unit, with maximum air temperature of 400°C and maximum air velocity of 60 m/s, it was possible to achieve better mottle results with higher evaporation rates (Figures 26 and 27). This was true to coating colors including starch (5%) and without starch. Also, gloss and smoothness are better with all-high-strategy. For WF grades, both single- and double-coated, and board grades, the all-high theory is also valid. /7; 19; 16/

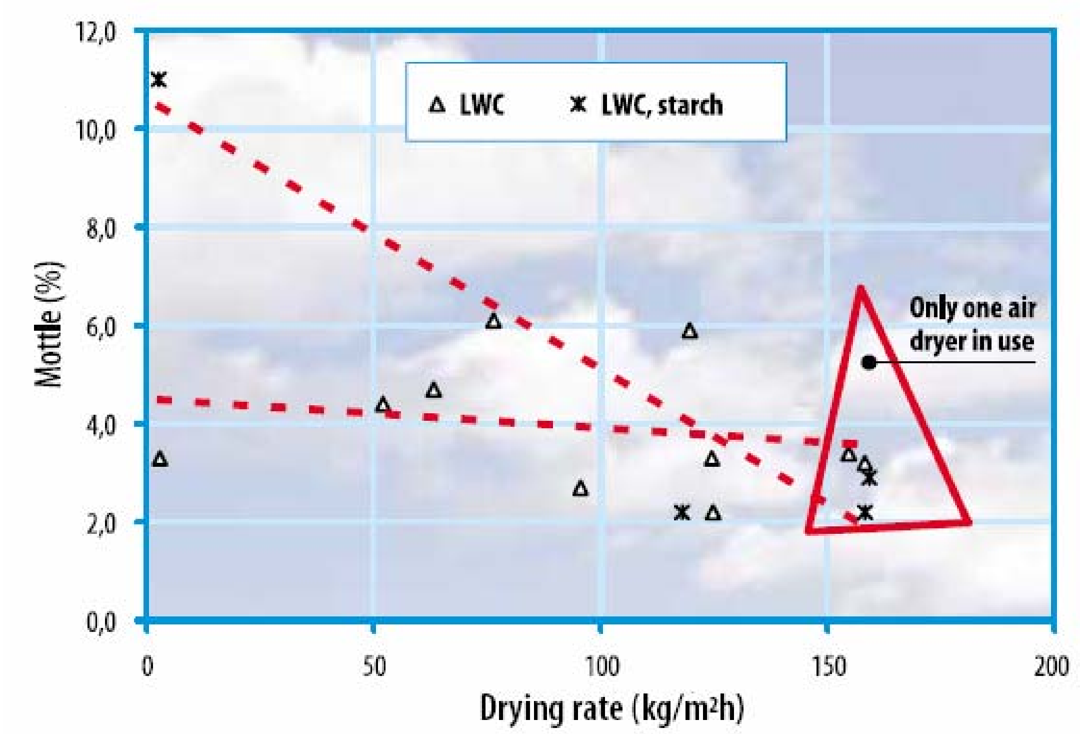

Figure 26. Mottle as a function of drying rate when using a single air dryer /16/

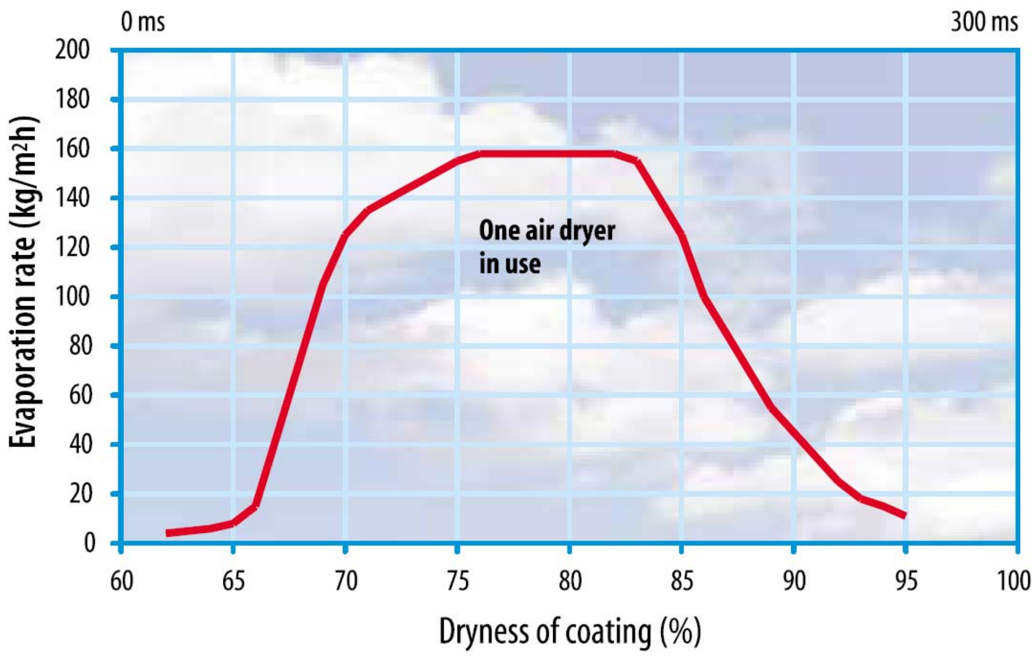

Figure 27. Optimal drying strategy according to the new all-high theory /16/

5 DRYING LAYOUTS

When planning a drying layout, the following factors need to be taken into consideration:

- How much space is available
- Drying capacity
- Drying costs (energy, maintenance)
- Investment costs
- Quality of the end-product
- Availability of energy source (gas for IR or air dryers)

Also, the coat weight difference in z-direction defines the importance of drying on quality. If the paper is film-coated, the variation is smaller than with blade coating. /20/

5.1 Estimating drying requirements

Before building a drying section for a coating, an estimate of required evaporation capacity has to be determined. Since the calculations are always only approximations and there can be surprises which reduce the effectiveness of a drying system, it is best to overplay and build a line which has plenty of drying power, instead of risking a possibility of having a line with not enough power. /6, p.170-173/

Water load required for each section:

$$EV = CW \cdot S \cdot (R_1 - R_2) \qquad (1)$$

EV = Water evaporated per meter of width [kg/h/m]
CW = Coat weight [g/m^2]
S = Machine speed [m/min]
R_1 = Ratio of water to solids entering the dryer

R_2 = Ratio of water to solids exiting the dryer

Heat load required for a section:

$$Q = WT \cdot S \cdot SH \cdot \Delta T \qquad (2)$$

Q = Energy per meter of width [J/h/m]
WT = Basis weight dry [kg]
SH = Specific heat of substance [J/kg/K]
ΔT = Temperature rise [K]

To introduce a method for estimating the drying loads, an example has to be defined:

Basis weight:	100 g/m^2, moisture 5%
Coat weight:	10 g/m^2
Coating solids:	62%
Machine speed:	1000 m/min

Two configurations for the drying section have been made:

1. The conventional arrangement of dryers: Gas IR, air dryer and cylinder drying
2. Air dryer and cylinder drying

In the first calculations, a gas IR dryer dries the coating from 62% to 72%, an air dryer from 72% to 90%, and cylinder dryers from 90% to the final 95% dryness. The IR unit will operate with a sheet input energy of 80 kW/m^2 and the air dryer unit's evaporation rate is 25 kg/h/m^2 (assumptions). A cylinder's diameter is 1830 mm and evaporation rate 4 kg/h/m^2. The final sheet moisture will be 4%. All of the rising of temperature will occur in the IR dryer, the rise being from 25°C to the evaporation temperature of 75°C (also an assumption).

In the second calculations, an air dryer with a high evaporation rate of 100 kg/h/m^2 dries the coating from 62% to 90% and cylinder dryers from 90% to the final 95%. Other factors remain the same as in the first set of calculations.

The calculations are located in the appendices. The results are as follows:

Configuration 1.	IR drying:	3.5 m
	Air drying:	8 m
	Cylinder drying:	5 cylinders
Configuration 2.	Air drying:	6 m
	Cylinder drying:	5 cylinders

Also, calculations have been made to get an idea of how paperboard's higher basis weight affects the drying requirements. Paperboard of 300 g/m^2 requires three times more energy to heat the base paper and the moisture in it to the desired evaporation temperature. All the other factors are kept the same as in the previous calculations. In this case, using the configuration 2, air drying should be almost twice as long as with a base paper of 100 g/m^2.

The equations presented only help in estimating drying requirements. For the optimum drying setup, only coating and drying tests can determine the best temperatures and evaporation rates that should be used. /6, p. 170-173; 16/

5.2 Layouts for different paper grades

In the figures below, examples of common drying layouts for different paper and paperboard grades are illustrated. Normally after each coating station the newly-applied coating is dried with a combination of drying devices. The high-low-high-strategy for drying of coatings is in use for the majority of coating machines, both on- and off-machine. IR dryers are widely used after coating color application, after that comes air drying and in the end, cylinder drying. /1, p. 543; 3, p.193; 11/

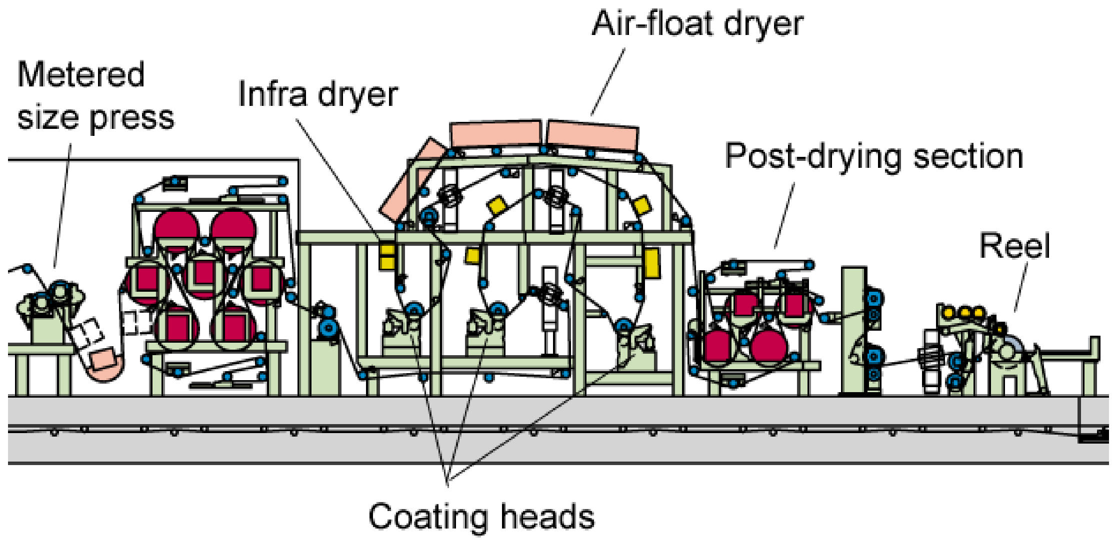

Figure 28. Coating section of a folding boxboard machine /2/

Figure 29 shows how IR-dryers have been dropped out of the layout. Rauma PM1 applies the new all-high drying strategy, producing LWC paper using jet blade-coating and gas-heated air flotation drying. The difference to the picture below is that in Rauma, electrical IR-dryers are located after the air drying units to provide moisture profiling. /21/

Also, with board grades it has been proven that drying of coating can be performed without IR-drying and quality won't suffer from this. /20/

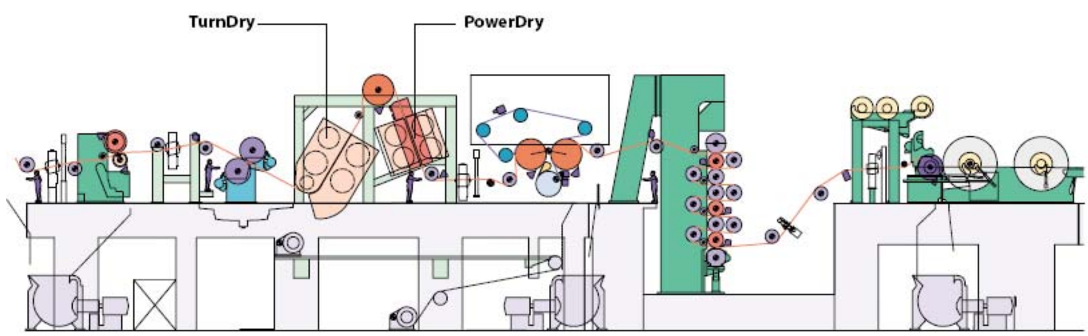

Figure 29. Air turn flotation and a conventional flotation dryer /12/

On-machine coating's benefits are lower investment and utilization costs, as the energy and personnel expenses are smaller. Off-machine coaters have certain advantages compared to on-machine coating. It can use different base papers and the defects in the base paper can be corrected before already inadequate paper is coated in vain. Also, problems in the paper machine won't affect the coating procedure. /2/

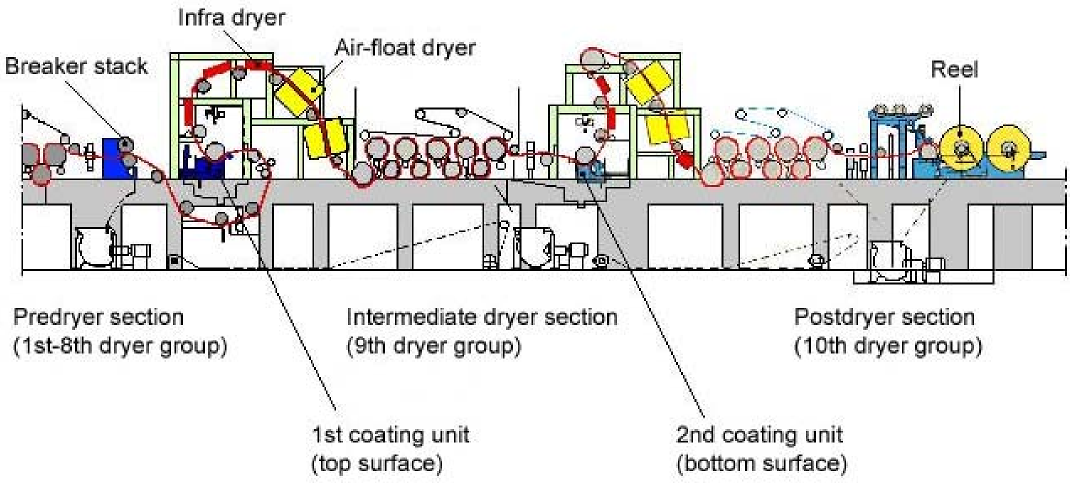

Figure 30. On-machine coating of LWC /2/

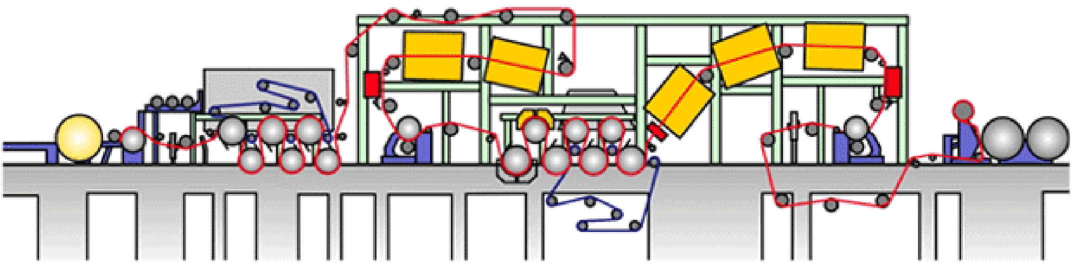

Figure 31. Off-machine coater for LWC, IR and air drying /2/

In off-machine coating the paper has cooled down on its way from the paper machine. More energy has to be transferred to the web, and IR dryers are a good choice to quickly heat the coated web to the evaporation temperature. In that case, the IR doesn't actually have a drying effect. /20/

6 CONCLUSIONS

After film coating, air dryers and cold pull-roll groups have been an industrial standard and continue to be so. Since film transfer coaters apply an even layer of coating, mottling isn't such a problem, but after blade coaters, the drying sections are still traditional with IR dryers taking care of the initial drying. As the power of air dryers has increased, the fact that IR drying should be performed in the beginning of the drying has been questioned.

The newest trials suggest that also after blade coating stations, the use of IR drying isn't necessary, which will lead to simplified drying sections and reduced energy costs in the future. The first LWC and board machine constructions without IR drying are out and running already and they seem promising. Most likely there will be more of the same kind of configurations.

Off-line coating machines will continue to benefit from the IR dryers' effective heat transport capability and electric IR dryers will be used after air dryers to control moisture profiling. If air dryers' profiling capability can be increased, the need for IR dryers will decrease even more.

REFERENCES

1. Lehtinen, Esa. *Pigment coating and surface sizing of paper*. Helsinki: Fapet Oy, 2000.
ISBN 952-5216-11-X

2. VTT Industrial Systems. Knowpap 8.0. Vantaa: Prowledge Oy, 2006.

3. Häggblom-Ahnger, Ulla; Komulainen, Pekka. *Paperin ja kartongin valmistus*. Helsinki: Opetushallitus, 2000.
ISBN 952-13-0605-X

4. Savolainen, Antti. *Paper and paperboard converting*. Helsinki: Fapet Oy, 1998.
ISBN 952-5216-12-8

5. Alderfer, George; Aarni, Esko; Rajala, Pasi; Anderson, John. *An investigation of the evaporation energy demands of coatings formulated with narrow particle size distribution PCC compared to coatings formulated with other pigments*. Tappi Coating and Graphic Arts Conference and Trade Fair Proceedings. Atlanta: Tappi, 2002.

6. Walter, Jan C. (ed.). *Coating Processes, the*. Atlanta: Tappi, 1993.
ISBN 0-89852-058-4

7. Rajala, Pasi; Milosavljevic, Nenad; Kiiskinen, Harri; Hendrickson, Melissa. *The effect of the impingement air drying on print mottle and other coated paper properties* (online). Available in the World Wide Web: http://www.sciencedirect.com/, also published in Applied Thermal Engineering, December 2004, Volume 24, Issues 17-18.

8. Glittenberg, Detlev; Voigt, Andreas; Becker, Andreas. *Optimisation of the precoating share and binder compositions of double-coated woodfree papers to improve quality and reduce costs*. Published in Paper Technology Vol. 47 nr. 1. Bury, Lancashire: Pita, 2006.
ISSN 0-306-252X

9. Kouris, Michael; Kocurek, Michael J. (eds.). *Pulp and paper manufacture Vol. 8, Coating, converting and specialty processes*. Atlanta: Tappi, 1990.
ISBN 0-919893-91-0

10. Wikipedia, [Internet encyclopedia], by Wikimedia foundation (cited 13.4.2007). Available in the World Wide Web: http://en.wikipedia.org

11. Rintamäki, Jaakko. Päällystystekniikan luentomateriaali. Tampereen Teknillinen oppilaitos, 1997

12. Tampella, Paper Tech, T&K; by Rintamäki, Jaakko. *Päällystys ja sen kuivausmitoitus, SELOSTE 2/91*.

13. Metso Paper Inc. *Valmet Air Dryers. Higher quality, lower costs* (online). Metso Corporation, 2002 (cited 22.3.2007). Available in the World Wide Web: http://www.metsopaper.com/, also published in Fiber & Paper 2001 / 4 (Metso's customer magazine).

14. Global Technology LLC. Picture modified by the author. Original available in the World Wide Web: www.globaltechllc.com (cited 22.3.2007).

15. Kadant Johnson Inc. Picture modified by the author. Original available in the World Wide Web: www.kadantjohnson.com (cited 14.4.2007).

16. Metso Paper Inc; by Rajala, Pasi. *New drying strategy for coated papers* (online). Metso Corporation, 2001 (cited 22.3.2007). Available in the World Wide Web: http://www.metsopaper.com/, also published in Fiber & Paper 2001 / 4 (Metso's customer magazine).

17. Mäkinen, Jukka; Rajala, Pasi; Nuyan, Seyhan. *Optimization of drying of coated paper by means of automation*. Tappi Coating/Papermakers Conference Proceedings, Book 1. New Orleans: Tappi 1998.

18. Rajala, Pasi; Koskinen, Timo M. *Experimental and statistical investigation of drying effects on coated offset paper quality* (online). Tappi, 2004 (cited 26.3.2007). Available for the members of Tappi in the World Wide Web: http://www.tappi.org/, also published in Tappi Journal, July 2004, Vol 3.

19. Rajala, Pasi; Häkkänen, Heikki; Berg, Carl-Gustav; Solin, Richard. *The effect of intense air drying on material distribution and quality in coated papers*. Published in Drying technology, Vol. 21, Issue 10. London: Taylor & Francis, 2003.
ISSN: 1532-2300 (electronic) 0737-3937 (paper)

20. Robert Havukainen, DI. Metso Paper Inc.

21. Antti Vaajakoski, Production Manager. UPM-Kymmene Rauma.

APPENDICES

CALCULATIONS FOR THE APPROXIMATION OF DRYING CAPACITY

Configuration 1.

IR dryer:

Water to be evaporated with the IR dryer:

$$EV = CW \cdot S \cdot \left(R_1 - R_2\right) \qquad (1)$$

$$= 10\,\frac{\mathrm{g}}{\mathrm{m}^2} \cdot 1000\,\frac{\mathrm{m}}{\min} \cdot \left(\frac{38}{62} - \frac{28}{72}\right)$$

$\approx$ 134.4 kg/m/h

Heat load Q for the temperature rise of the components:

$$Q = WT \cdot S \cdot SH \cdot \Delta T \qquad (2)$$

SH for water at 25 °C is 4.19 J/kgK, other SH's evaluations, depending on the composition of material

Paper:

$$= \left[100 - \left(100 \cdot \frac{5}{95}\right)\right] \frac{\mathrm{g}}{\mathrm{m}^2} \cdot 1000\,\frac{\mathrm{m}}{\min} \cdot 1.465\,\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}} \cdot 50\,\mathrm{K}$$

$\approx$ 416,368 kJ/m/h

Moisture:

$$= \left(100 \cdot \frac{5}{95}\right) \frac{\mathrm{g}}{\mathrm{m}^2} \cdot 1000\,\frac{\mathrm{m}}{\min} \cdot 4.19\,\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}} \cdot 50\,\mathrm{K}$$

$\approx$ 66,158 kJ/m/h

Coating:

$$= 10\,\frac{\mathrm{g}}{\mathrm{m}^2} \cdot 1000\,\frac{\mathrm{m}}{\min} \cdot 2.095\,\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}} \cdot 50\,\mathrm{K}$$

$\approx$ 62,850 kJ/m/h

Water in the coating:

$$= \left(\frac{10}{0.62} - 10 \right) \frac{\text{g}}{\text{m}^2} \cdot 1000 \frac{\text{m}}{\text{min}} \cdot 4.19 \frac{\text{J}}{\text{kg} \cdot \text{K}} \cdot 50\,\text{K}$$

$\approx$ 77,042 kJ/m/h

EV load:

EV · 2330 kJ/kg (latent heat value of water)

134.4 kg/m/h · 2,330,000 J/kg

$\approx$ 313,152 kJ/m/h

$Q_{total} = Q_{paper} + Q_{moisture} + Q_{coating} + Q_{water} + Q_{EV}$

$\approx$ 935,570 kJ/m/h

Length of IR needed:

$$\frac{935{,}570\,\text{kJ/m/h}}{80\,\text{kW/m}^2} = \frac{935{,}570\,\text{kJ/m/h}}{288{,}000\,\text{kJ/m}^2\text{/h}} \approx 3.25\,\text{m}$$

<u>At least 3.5 m of IR drying needed</u>

Air dryer:

Water to be evaporated with the air dryer:

$$EV = CW \cdot S \cdot \left(R_1 - R_2\right) \tag{1}$$

$$= 10 \frac{\text{g}}{\text{m}^2} \cdot 1000 \frac{\text{m}}{\text{min}} \cdot \left(\frac{28}{72} - \frac{8}{92} \right)$$

$\approx$ 181.2 kg/m/h

Length of air dryer needed:

$$\frac{181.2\,\text{kg/m/h}}{25\,\text{kg/h/m}^2} \approx 7.25\text{ m}$$

<u>At least 8 m of air dryer</u>

Cylinder dryer:

$$EV_{COATING} = 10\frac{\text{g}}{\text{m}^2}\cdot 1000\frac{\text{m}}{\text{min}}\cdot\left(\frac{8}{92}-\frac{4}{96}\right) \qquad (1)$$

≈ 27.2 kg/m/h

$$EV_{PAPER} = 100\frac{\text{g}}{\text{m}^2}\cdot 1000\frac{\text{m}}{\text{min}}\cdot\left(\frac{5}{95}-\frac{4}{96}\right) \qquad (1)$$

≈ 65.8 kg/m/h

$EV_{\text{COATING+PAPER}} = 93$ kg/m/h

The number of cylinders required:

Length of a cylinder: $\Pi \cdot 1830$ mm ≈ 5.75 m

Number of cylinders: $\frac{93\ \text{kg/m/h}}{5.75\ \text{m}\cdot 4\ \text{kg/h/m}^2} \approx 4.04$

At least 5 cylinders needed

Configuration 2.

Air dryer:

Water to be evaporated with the air dryer:

$$EV = CW \cdot S \cdot (R_1 - R_2) \qquad (1)$$

$$= 10\frac{\text{g}}{\text{m}^2}\cdot 1000\frac{\text{m}}{\text{min}}\cdot\left(\frac{38}{62}-\frac{8}{92}\right)$$

≈ 315.6 kg/m/h

Heat loads Q for the temperature rise of the components are the same as in conf.1 except for the EV load:

EV load:

315.6 kg/m/h · 2,330,000 J/kg

$\approx$ 735,348 kJ/m/h

$Q_{total} = Q_{paper} + Q_{moisture} + Q_{coating} + Q_{water} + Q_{EV}$

$\approx$ 1 358 000 kJ/m/h

$$\frac{1358000\ \text{kJ/m/h}}{2330000\ \text{J/kg}} \approx 582.8\ \text{kg/m/h}$$

Length of air dryer needed:

$$\frac{582.8\ \text{kg/m/h}}{100\ \text{kg/m}^2\text{h}} \approx 5.8\ \text{m}$$

At least 6 meters

Cylinder dryer:

The same as in configuration 1.

Paperboard of 300 g/m², drying with air dryer:

Water to be evaporated with air drying:

$$EV = CW \cdot S \cdot (R_1 - R_2) \qquad (1)$$

$$= 10\,\frac{\text{g}}{\text{m}^2} \cdot 1000\,\frac{\text{m}}{\text{min}} \cdot \left(\frac{38}{62} - \frac{8}{92}\right)$$

$\approx$ 315.6 kg/m/h

Heat load required for the temperature rise:

Paper:

$$= \left[300 - \left(300 \cdot \frac{5}{95}\right)\right] \frac{\text{g}}{\text{m}^2} \cdot 1000\,\frac{\text{m}}{\text{min}} \cdot 1.465\,\frac{\text{J}}{\text{kg} \cdot \text{K}} \cdot 50\ \text{K} \qquad (2)$$

$\approx$ 1249,105 kJ/m/h

Moisture:

$$= \left(300 \cdot \frac{5}{95}\right) \frac{\text{g}}{\text{m}^2} \cdot 1000\,\frac{\text{m}}{\text{min}} \cdot 4.19\,\frac{\text{J}}{\text{kg} \cdot \text{K}} \cdot 50\ \text{K} \qquad (2)$$

$\approx$ 198,473 kJ/m/h

The heat loads for the coating remain the same as before

EV load:

315.6 kg/m/h · 2,330,000 J/kg

$\approx$ 735,348 kJ/m/h

$Q_{total} = Q_{paper} + Q_{moisture} + Q_{coating} + Q_{water} + Q_{EV}$

$\approx$ 2 323 000 kJ/m/h

$$\frac{2323000\ \text{kJ/m/h}}{2330000\ \text{J/kg}} \approx 997\ \text{kg/m/h}$$

Length of air dryer needed:

$$\frac{997\ \text{kg/m/h}}{100\ \text{kg/m}^2\text{h}} \approx 10{,}0\ \text{m}$$

At least 11 meters