# Paper Drying: Theory and Practice

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## Abstract

*In this manuscript the drying of paper is examined first from the standpoint of the chemical and physical changes that occur during drying. The examination focuses both on the individual fibers and on the paper web as a whole. This is followed by a discussion of the methods used to dry paper in industrial applications. The traditional steam cylinder methods as well as several other methods are discussed.*

## Introduction

Paper is a composite material made primarily from wood fibers. It generally includes one or more polymer additives used to assist the production process or modify the characteristics of the final product. The specific application for which the paper is made determines the fiber type used and whether or not any additional components are included. Depending on the application the paper may also include various types of inorganic particles, calcium carbonate, kaolin clay, calcium sulphate, titanium dioxide that are added to modify final sheet properties or as fiber replacements.

Paper is a unique material in that a large amount of water must be used in the production process yet the production process must also remove the vast majority of this water if recognizable flat sheet of paper is to be produced. A further complicating factor is that the fibers which make up paper readily absorb water from the atmosphere; any increase in relative humidity will increase the equilibrium moisture content of the paper. Relatively small changes in the equilibrium moisture content of the finished sheet can have a significant effect on its mechanical properties.

## Summary of Papermaking Process

During the paper making process water is held in the sheet in three distinct locations (1) between the fibers, (2) in large pore within the fiber (3) chemically adhered to the fiber in small pores. The water in the first two locations is referred to as "unbound" or "free" water because it is not chemically bound to the fiber and, at least theoretically can be removed by mechanical means. In practice some of this water is removed by drying. The water in the third category is referred to as "bound" or "non-freezing" water and can only be removed by drying [1, 2]. The relative amounts of water in these locations are shown in Figure 1.

The production of a paper sheet process begins with a dilute fiber-water mixture which contains approximately 1 part fiber and 1000 parts water. This mixture is feed onto a moving screen and water is removed by passive and vacuum assisted drainage. This is referred to as the forming process; it is the key process in determining how the individual fibers will be arranged in the paper web matrix. The fibers are the main structural element in the paper web and the arrangement of the fibers plays a significant role in determining the mechanical characteristics of the final sheet [3]. The objective of the process is to produce a uniform distribution of fibers while at the same time ensuring that there is maximum retention of small fibers and inorganic additives. At the end of the forming process a recognizable sheet or web exists consisting of 1 part fiber and 4 parts water.

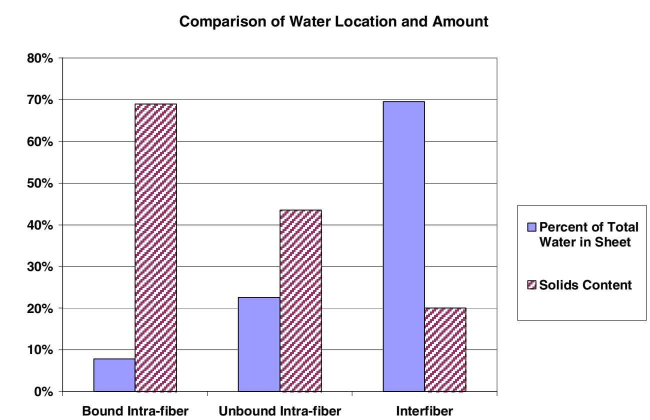


***Figure 1.*** *Comparison of amounts of water in a paper web [1, 2]*

The web is then subjected to a second mechanical dewatering process, pressing. During pressing the paper web is compressed reducing the available volume for the water to occupy and thus forcing the water from the web. Web compression is controlled by the amount of water in the web and compressibility of the individual fibers. Fiber compressibility is a function of fiber type and the prior processing of the fibers [4, 5]. In addition to water removal, the process is also used to control the level of web consolidation. High compression leads to significant consolidation and increased tensile strength. Lower levels compression result in increased bulk. Some products require the strength be optimized while others require the bulk be optimized. Typically, several roll presses are used in series, resulting in the web attaining a fiber-water state of 1 part fiber and 1 part water. The web is transported through the press nips on a "felt" which is designed to hold the water expressed from the sheet. After each pressing, the web is transferred to a relatively dry felt and the felt with the water in it is subjected to a vacuum to remove the water and ready it for the next pass through the press.

The final production process is thermal drying, during this process most of the water remaining in the sheet is evaporated. Traditionally, this process employs passing the paper web over steam heated cylinders. The sheet is transported on a synthetic fabric which is used to hold it against the cylinder surfaces. It is heated via conduction and the water is removed from the sheet surface via a convection heat and mass transfer process. Since the drying process involves a phase transition, liquid water to water vapor, it is the most energy intensive of all the processes used to remove water form the paper web. Drying also results in a number of physical changes to both the fibers which make up the paper web and to the paper web itself [1, 6, 7]. The objective of the process is to remove the water in as efficient a manner as possible while not causing any deterioration in paper web properties that were developed in the previous processes. The drying process results in a sheet which is 1 part fiber and 0.05 parts water. Once dried, the paper then may be coated or printed on. Both processes involve the reintroduction of water into the web fiber matrix which then must be removed by drying. The methods used and the effects on web properties are similar to those for the original production process. Alternative drying methods are also used in printing and coating; these include air impingement and infrared heating.

## Fibers and Fiber Matrix Formation

The fibers used to make paper are obtained from plants. In the 1800's the fiber source was rags made from cotton. Today in the North America, South America and Europe the primary source for the fibers are trees. In other parts of the world non-wood fibers such as bamboo, grass, and bagass are used, however, the vast majority of paper made today is made using wood fibers. Figure 2 shows a cross section of a typical softwood tree which has been cut perpendicular to the long axis of the tree. The individual fibers which make up the tree are the closely packed, roughly square shaped objects. These fibers have an open center and can have many "holes" or pits along the longitudinal axis. A typical softwood fiber is 2-3 mm in length with a diameter about 1/50$^{th}$ of the length. Hardwood trees have a similar structure although the fibers tend to be shorter (~1 mm) and with diameters also about 1/50$^{th}$ of the length [8]. Prior to the production of a paper sheet, the fibers that make up the sheet are subjected to a number of process designed to alter both the chemical composition of the fibers and the physical properties of the fibers.

Each fiber has a number of layers and each layer is comprised of "fibrils" which are a composite of long cellulose chains, hemi-cellulose and lignin. The cellulose is in both amorphous and crystalline forms, while the other two components are amorphous. The amorphous components of the cellulose and hemi-cellulose have hydroxyl (OH) groups on the surface which will readily form hydrogen bonds in the presence of water molecules [9].

A schematic of the structure of the individual fiber is given in Figure 3. The outer or primary layer is usually removed by the processing steps that occur before paper is made. In the remaining layers, S1, S2, S3 (or secondary layer) the fibrils are arranged in a helical manner as denoted by the diagonal lines in the figure [10]. The S2 layer has the greatest wall thickness and comprises the majority of the material in the fiber. It therefore is the portion of the fiber that determines the physical characteristics of the overall fiber. The angle of the fibrils relative to the longitudinal axis (fibril angle) determines the stiffness or elastic modulus of the fiber. The greater the angle the less stiff the fiber and the greater elongation the fiber can undergo when stretched [11]. This is some what analogous to an extended spring (small fibril angle) versus an un-extended spring (large fibril angle). The fiber is a visco-elastic element whose characteristics are in part determined by the moisture content of the fiber. The greater the moisture content the more viscous and less elastic is the fiber. Given the amorphous nature of its components the fiber will have an equilibrium moisture content which is determined by the ambient air humidity. The equilibrium moisture content is path dependent, i.e., there is a hysterisis associated with the adsorption and desorption of moisture. This hysterisis also exists in the finished sheet.

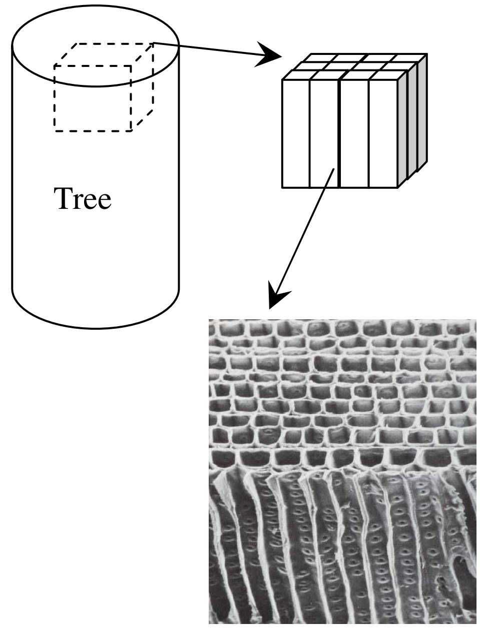


***Figure 2.*** *Intersection of radial and cross sectional planes of Jack Pine – SEM 200X (IPST)*

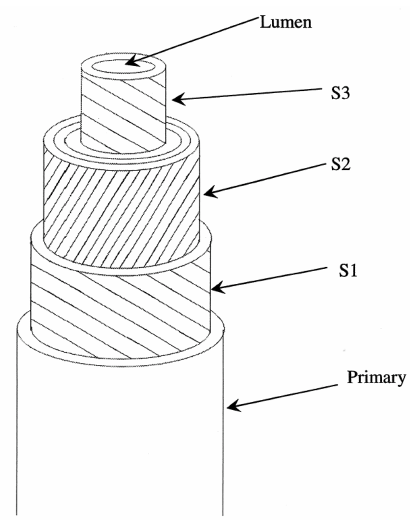


***Figure 3.*** *Schematic of softwood fiber [10]*

The structure of the fiber and the interaction of the fiber elements with water are manipulated during the processing of the fibers to enhance the ability to form a uniform, strong sheet of paper. During the processing which occurs prior to being formed into a sheet some of the fibrils comprising the S1 and S2 layers are delaminated from the main fiber surface. Many of these fibrils will stay attached to the fiber at one end. These fibrils add a significant amount of surface area to the fiber. The fibrils which do not stay attached are referred to as fines and are typically extremely small in size compared to the fibers. However, the fines also have significant surface area and can also contribute to increased sheet strength and water holding ability. Since the fiber processing occurs in an aqueous solution which ranges from 0.1% to 3% fiber content, water molecules form bonds with any available hydroxyl groups on the exposed surfaces of the fibrils, fines or fibers. This water is often referred to as bound water or non-freezing water because due to the hydrogen bonding it will not freeze at 0 $^{o}$C or boil at 100 $^{o}$C.

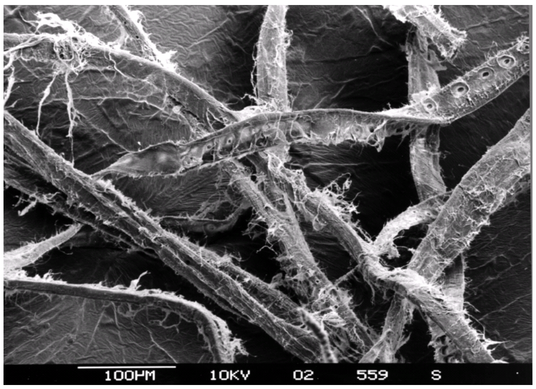


***Figure 4.*** *Softwood fiber with delaminated fibrils visible (IPST)*

An additional physical effect of the processing is that the interfaces between the S1 and S2 and between the S2 and S3 layers are disrupted, creating open spaces internal to the fiber [12]. Bulk water enters into the internal structure of the fiber, fills the open spaces and causes the fiber to swell and become more flexible. This is desirable, as flexible fibers will form a more compact paper web matrix then will be possible with rigid fibers. A useful analogy is to compare the matrix formed by uncooked spaghetti to that formed by cooked spaghetti. The internal delamination also decreases the ability of the fiber to resist compression loads and thus the cylindrical shape is more likely to collapse when pressed. A collapsed or flattened fiber will have a greater area of surface contact with adjacent fibers which in turn increases the strength of the final sheet.

Forming the fiber matrix which eventually becomes a sheet of paper requires forcing the fibers into close proximity to one another. This occurs during the formation and pressing phases of paper making; it is greatly assisted by the surface tension of water. As menisci begin to form when water drains away from the web, surface tension tends to pull the fibers and fibrils closer together. When two fiber surfaces are sufficiently close together and water is present, hydrogen bonds can form which securely hold the two surfaces together [13].

Hydrogen bonds are the primary bond structure holding the fiber web matrix together and from wherever two fiber surfaces come into close proximity and water is present. The area of the contact is increased by higher press loads. In forming the sheet, hydrogen bonds will begin to form when as the web begins to exceed 30% solids content (1 part fiber – 2.25 parts water). These bonds continue to increase in number as the solids content increases. Surface tension effects remain a factor holding the web together until the web reaches about 45% solids content (1 part fiber – 1.5 parts water) [13]. Beyond this point the bulk or unbound water on the exterior surfaces of the fiber decreases rapidly. Water not bound to the fiber, but held inside the fiber, exists until the solids content reaches ~70% (1 part fiber – 0.4 parts water), beyond that point all water in the fibers and fiber matrix is bound (non-freezing water).

## Fibers and Drying

In general the water that is initially removed from the fiber web is removed from between the fibers. This occurs during the forming and pressing portions of papermaking. Once the web attains a solids content of 40% water begins to be removed from the interior of the fibers. During pressing unbound water can be removed from the interior of the fiber. As unbound water is removed via pressing and the bound water is removed via drying the fibers undergo physical changes. Nanko [14] has described the five stages of fiber drying as shown in Figure 5. The two most important aspects are that the fiber surface changes, becomes wrinkled, and that the fiber shrinks in the transverse direction. The surface becomes wrinkled due to a reduction in cross-sectional area and due to fibrils bonding to the fiber surface. The transverse shrinkage of an individual fiber is considerably more than the shrinkage in the longitudinal direction.

A comparison of transverse and longitudinal shrinkage is given in Figure 6. The transverse shrinkage has what at first may seem the non-intuitive affect of shrinking fibers in the longitudinal direction. This is explained as follows, each fiber may have 20 – 50 fibers crossing it. The fibers at each crossing shrink in the transverse direction; however each of these fibers is bonded to the fiber being crossed. Thus, the transverse shrinkage of each individual crossing fiber causes a longitudinal shrinkage in the crossed fiber in the area of the bond. This causes an overall longitudinal shrinkage, but also induces residual stresses in the bonded area.

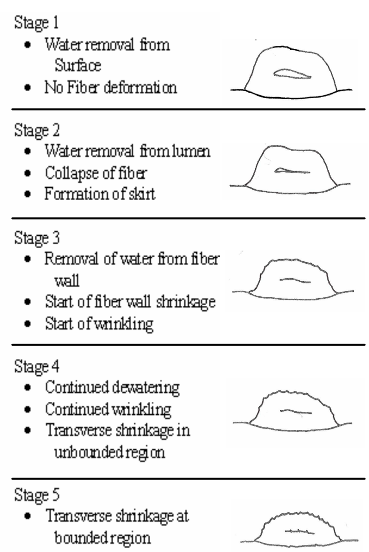


***Figure 5*** *Five stages of drying [14]*

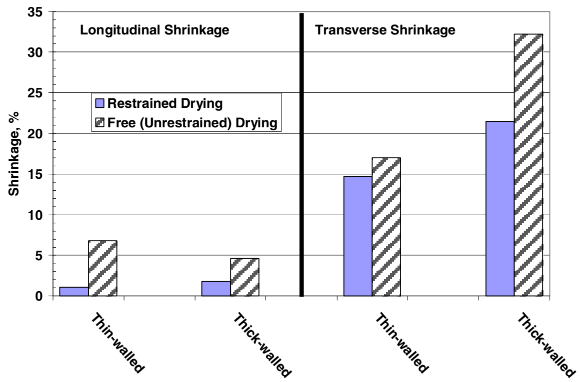


***Figure 6*** *Effects of restraint on fiber shrinkage [15]*

Another cause of residual stresses being induced in the fibers is restraining the fibers during drying, inhibiting shrinkage. This is also shown in Figure 6. A fiber that is dried under restraint has a more ordered arrangement of fibrils and tends to have a smaller fibril angle relative to the longitudinal axis of the fiber [15]. This is shown in Figure 7. As a result, a restraint dried fiber is stiffer (higher elastic modulus) and deforms less under tension than a free dried fiber. The level of residual stress that exists in a fiber is determined by the level of restraint during drying and to some extent the rate at which it is dried [16]. Since fibers are visco-elastic the residual stress relaxes over time. The rate of relaxation is proportional to logarithmic time [17, 18]. If the fiber is exposed to moisture either liquid water from printing or coating or from an increased level of humidity the relaxation rate will increase.

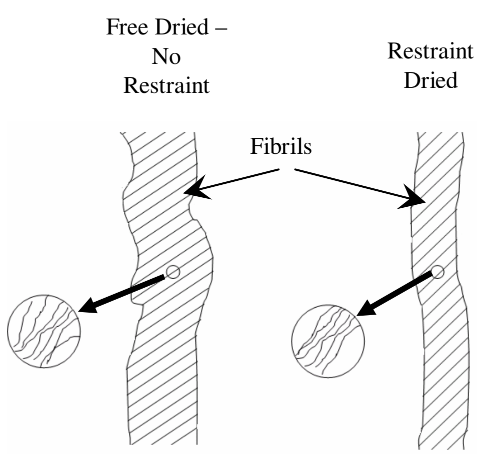


***Figure 7.*** *Comparison of free and restraint drying of individual fiber*

## Paper Web Structure and Drying

Paper has an orthotropic structure which is the result of the formation process. Paper machines run at high speeds, in some cases in excess of 2000 m/min. Due to the fluid dynamic forces that exist during the initial part of the formation process more fibers are aligned with the direction of web motion than perpendicular to web motion. The fibers tend to lie in the plane of the paper, there are few if any fibers oriented in the out of plane direction. The direction of web motion is referred to as *machine direction*, MD and the perpendicular direction is referred to as the *cross direction*, CD. The out of plane direction is referred to as the ZD. This is shown in Figure 8. The in plane arrangement of the fibers is depicted in Figure 9.

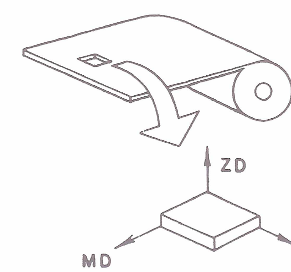


***Figure 8*** *Sheet orthotropic axes*

The strength and elastic properties of a paper sheet are determined by two factors, the strength and elastic properties of the individual fibers and the strength of the bonds between the fibers. The fiber properties are a function of fiber type, prior processing, drying conditions and moisture content. The bond strength is a function of total bonded area and the strength of the individual bonds. Bond area and bond strength can be increased by employing higher pressing loads, bond strength can also be altered by the addition of chemical additives [19, 20]. Since in most paper, there are more fibers oriented in the MD direction than in the CD direction, the MD direction has higher strength than the CD direction. The strength in the ZD direction is controlled primarily by fiber-fiber bonding and therefore is lower than in either the MD or CD directions.

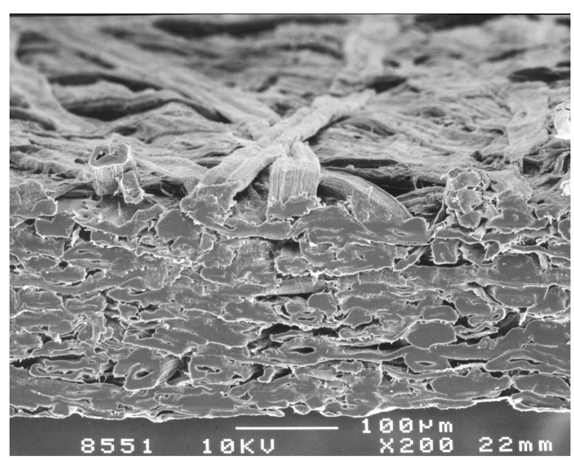


***Figure 9*** *Cross section of sheet show in plane arrangement of fibers (IPST)*

As the paper web travels through the paper machine there is tension applied in the MD direction, this in effect restrains the fibers in the MD direction as the water is removed from the web. This restraint is relatively constant across the width of the machine. The web is only partially restrained in the CD direction. When the web passes over a dryer cylinder it is held against the cylinder by a dryer fabric, this retrains the CD shrinkage of the web while it is on the dryer cylinder. The web, however, must move from cylinder to cylinder, during this time the edges of the web are effectively unrestrained, while the center of the web experiences restraint due to the surrounding web material. The MD and CD restraint during drying leads to residual stresses being created in the web. As with the individual fibers, the residual stress will relax over time, but because the relaxation is proportional to logarithmic time, considerable time is required for removal of the majority of the residual stresses. Changes in sheet equilibrium moisture content, due to changes in humidity or addition of water through printing and coating, cause the residual stresses to change. In the case of printing and coating the moisture content changes can be localized which creates discontinuities in the residual stress. If the discontinuities are of sufficient magnitude laddering or waviness will develop in the printed surface of the paper [21].

Another cause for localized residual stress distributions is non uniform drying. Non uniform drying occurs as a result of dryer cylinder surfaces with non uniform conduction characteristics or as a result of non-uniform sheet basis weight (areal density). This can result in “cockle” which is localized out of plane deformations of the finished sheet. The effect can sometimes be duplicated by wetting a finished sheet and letting it dry without restraint. The lack of restraint allows localized non uniform drying due to sheet non uniformities with the result being a non uniform stress distribution which are in part relived by the out of plane deformations [22].

## Overview of Drying on a Paper Machine

In discussing the specific methods employed to dry paper on a modern paper machine it is useful to review the scale of the operation. A modern machine used to make a printing and writing grade produces a web that is 10 m across and dries that web while it is traveling at a linear sheet speed of 2000 m/min. The paper production rate is ~2100 tons/day on a dry fiber basis. This will typically require the removal of in excess of 8300 tons of water per day with about ~4400 tons being evaporated. The evaporation constitutes 50% of the energy used during the papermaking process.

Thus, a critical factor in the economics of paper production is the amount of water that must be removed via drying and the efficiency with which the drying is done. The amount of water that must be removed via pressing and drying increases linearly with the machine speed. The relationship is shown in Figure 10. As can be seen in Figure 11 an almost linear relationship exists between the amount of water that must be removed via drying and the solids content of the sheet when it enters the dryer section. Given that energy costs are directly related to the solids content of the sheet when it enters the drying phase, papermakers run the machine at the highest press loads possible. Therefore, in many case the press loading is determined by the minimum bulk requirement for the grade being produced.

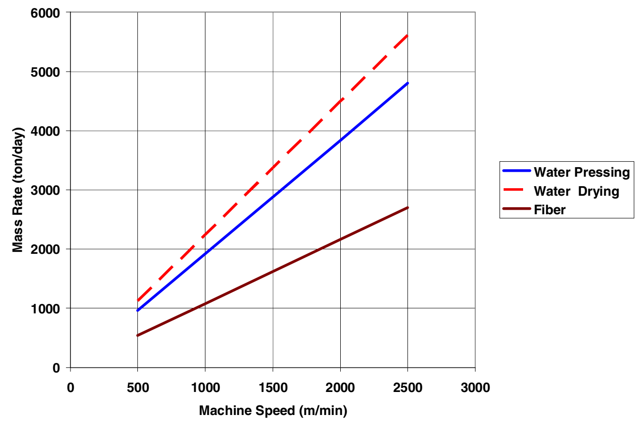


***Figure 10.*** *Water removal rate for a 75g/m² that enters the press section at 25% solids and enters the dryer section at 45% solids. “Fiber” is the dry mass of paper produced.*

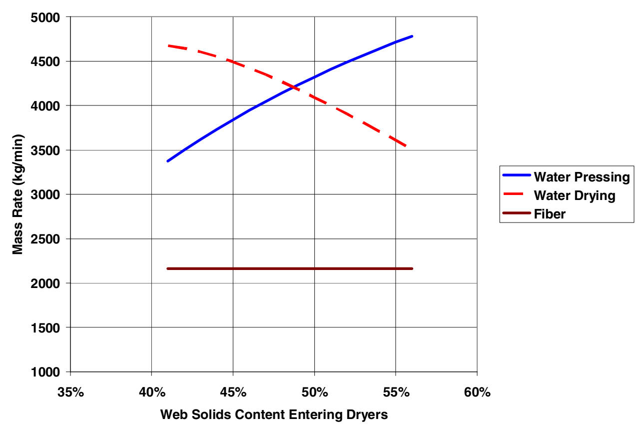


***Figure 11.*** *Variation in water removed via pressing or drying as the solids content of the sheet entering the dryer section is varied.*

## Steam Heated Cylinder Drying

All major types of paper are dried using some form of steam heated cylinder drying. In steam heated cylinder drying, the cylinder is used to heat, conductively, the wet paper web. The moisture is then removed from the web via convection drying. Most paper grades (packaging grades, printing and writing grades, newsprint, etc.) are dried using multiple cylinders, therefore there are a number of repeated conduction heating-convection drying cycles applied to the sheet. The cylinder drying process has been in use for well over 100 years. The primary disadvantage of the process is the drying rate is relatively low, necessitating the use of a large number of dryer cylinders. The primary advantage of the process is that it can be highly efficient, with 1.3 – 1.5 kg of steam being used to evaporate 1.0 kg of water. [23].

The body of the dryer cylinder is cast iron, generally about 2 m in diameter. The end caps are bolted in place and are proved with a bolted hatch to allow internal inspection of the cylinder. The cylinder extends the entire width of the paper machine. Steam is supplied to one end of the cylinder at slightly above saturated conditions at temperatures ranging from just over 100 $^{o}$C to in excess of 165 $^{o}$C, depending on the machine and where in the dryer section the steam is being supplied [24]. After entering the cylinder the steam condenses and transfers its heat energy to the metal wall of the cylinder, heating the cylinder. At the end opposite of where the steam entered the cylinder a siphon removes the condensate. A layer of condensate can build up on the interior of the cylinder, this layer provides an additional resistance to heat transfer. Bars are often attached to the interior surface of the cylinder. The bars run the length of the cylinder, are equally spaced about the circumference and are used to create turbulence in the condensate layer. This results in a decreased resistance to heat transfer. Proper control of condensate is essential to uniform temperature along the entire length of the cylinder and for optimum drying efficiency.

The drying rates attainable using steam cylinder are in the range of 20 – 40 kg water/hr/m$^2$ [25]. As a result, a typical paper machine may have 50 – 90 steam cylinders. The cylinders are usually arranged in either double or single tier as shown in Figure 12 and Figure 13 respectively. The double tier arrangement dries alternate side of the sheet as the sheet moves from cylinder to cylinder. This insures that moisture is removed from both sides of the sheet and that each side is subjected to the same drying. As a result the shrinkage and residual stresses developed during drying are equally divided between the two sides. In the case of the single tier arrangement, the sheet is dried from only one side and there is an unequal development of shrinkage and residual stresses. This can result in the sheet having a noticeable curl across the CD dimension of the sheet. Water sprays are sometimes used toward the end of the dryer section to momentarily raise the moisture content and allow relaxation of the residual stresses. The single tier arrangement provides some runnability advantages [26].

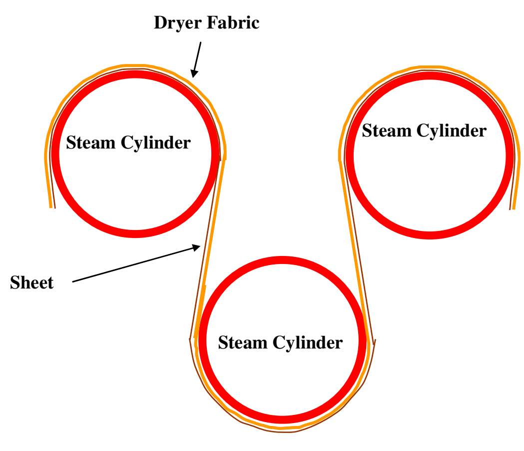


***Figure 12**. Double tier dryer cylinder arrangement*

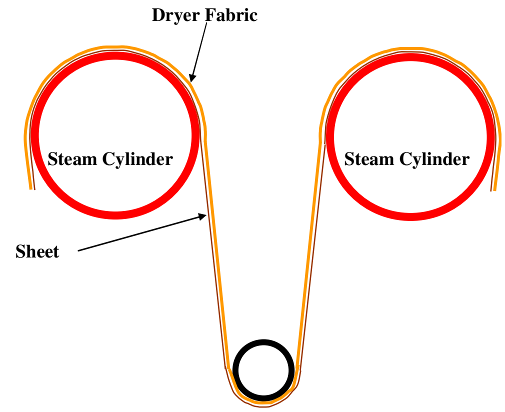


***Figure 13.** Single tier dryer cylinder arrangement*

The sheet is heated only while it is in contact with the cylinder. The side of the sheet against the cylinder is at the highest temperature. The sheet side opposite the cylinder is cooler, however there is limited evaporation while on the cylinder. What can occur is a vaporization-condensation cycle between the cylinder side and the fabric side of the sheet. At the cylinder side water evaporates and moves toward the cooler fabric side. Upon approaching the fabric side the vapor can cool and condense giving up heat. There can be some liquid movement back to the cylinder side of the sheet, one theorized cause being capillary action [27, 28]. The process tends to transfer heat within the sheet. The majority of the evaporation occurs in the open stretches between the cylinders. The hot surface of the sheet is exposed to the ambient air, which is circulated to control the humidity next to the sheet and promote evaporation.

During the drying process there are three distinct phases (1) Heating, (2) Constant Drying Rate and (3) Falling Drying Rate [29]. As the sheet leaves the pressing operation its average temperature is ~40-50 $^{o}$C and both the fiber and the water in the web must be heated for evaporation to occur, this is the heating phase. It is shown in Figure 14 adjacent to the right of the graph, in the region where the temperature is rising and there is little change in moisture content. In Figure 15 the heating phase is adjacent to the left axis where there is a rapid increase in drying rate. Ideally the heating phase is done as quickly as possible. However, there is a practical limitation. When a sheet at ~45-50% solids contacts a dryer cylinder at an elevated temperature, the sheet tends to stick to the cylinder. When peeled from the cylinder fibers can be pulled from the sheet. These fibers can then build up on the dryer cylinders causing an increased resistance to heat transfer. If the build up is non-uniform, non-uniform drying occurs causing quality problems. The sheet surface quality can also be adversely impacted. If the sheet contains a significant amount of recycle content the problem is exacerbated. Recycled fiber goes through a cleaning process prior to use which is intended to remove dirt as well as polymer based contaminants. The polymers are particularly difficult to remove and any that remains with the fibers is easily transferred to the cylinder surface. To partially alleviate the problem the steam pressure supplied to the cylinders, and the resultant cylinder temperatures are graduated, with first cylinders having surface temperatures less than 100 °C. This allows the surface fibers to gradually form bonds with one another while minimizing the adhesion forces between the sheet and the dryer cylinder.

When the sheet reached the dryer cylinder there still exists unbound water in the sheet and continuous water paths through the sheet. Once the sheet is heated to 100 °C, this water insures that the sheet temperature does not increase. The result is that the drying rate remains constant. This is shown in Figure 14 where the temperature remains constant and in Figure 15 where the drying rate remains constant. This is the constant drying rate phase.

A critical moisture content is eventually reached, this occurs when there is no longer continuous water paths through the sheet. At that time the temperature of the sheet rises rapidly and the drying rate decreases as shown adjacent to the left axis in Figure 14 and adjacent to the right axis in Figure 15. Typically there is a target final moisture content for the sheet which ranges for 4 – 8%. If the paper were to be dried to 0% moisture the fibers would be permanently damaged.

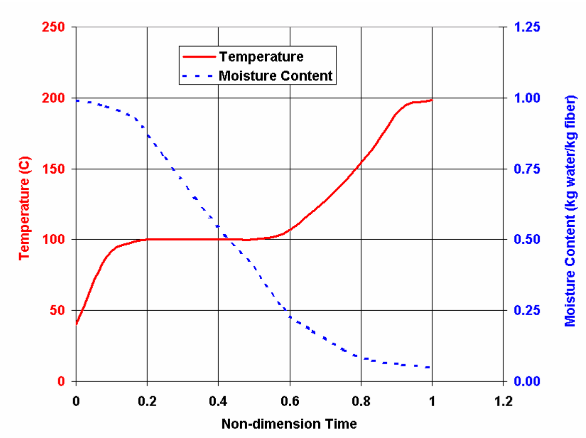


***Figure 14.*** *Sheet temperature and moisture content changes during drying*

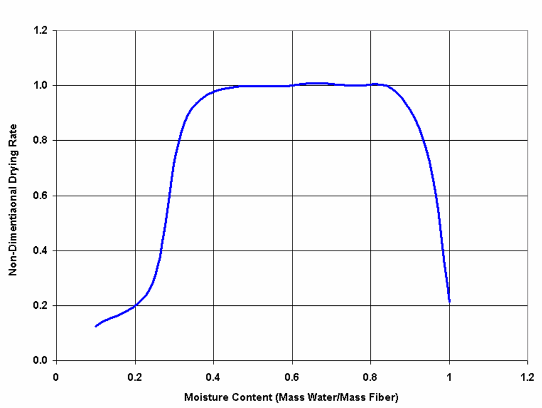


***Figure 15.*** *Changes in drying rate with sheet moisture content during drying*

## Impingement Drying

Hot air impingement drying is used extensively in the production of tissue and towel products. In this application, the sheet is passed over a single large diameter (4-5 m) steam heated cylinder, known as a Yankee Dryer. The sheet remains on the cylinder for approximately 270° of rotation. Over most of that range of rotation the sheet is also exposed to an array of high velocity, hot air impingement jets. The reason for employing impingement is to increase the overall drying rate and thus increase production. Impingement drying for multi-cylinder machines was proposed in the 1990's. In the proposed applications impingement drying is used in a manner to a Yankee Dryer and is implemented only on the dryer cylinders at the beginning of the dryer section. Again the motivation for employing the technology is to increase the drying rate. In both cases mentioned above the sheet is restrained during drying and as a result the final sheet is flat.

In contrast to steam cylinders alone, which produce drying rates of ~ 20 kg $H_2O/m^2/hr$, impingement drying can produce drying rates of at least 100 kg $H_2O/m^2/hr$ with impingement air temperatures of 300 °C. The increased drying rate has one significant drawback; the energy costs are higher. In the case of steam cylinders the energy cost to evaporate water is in ~3300 kj/kg $H_2O$. For impingement drying the cost is on the order of 4500 kJ/kg $H_2O$. The reason for the difference lies in the factors which control the heat transfer coefficient for impingement drying and the factors which control energy use in creating an impingement jet. The heat transfer coefficient increases with Reynolds Number, thus for a given nozzle configuration and jet temperature the heat transfer increases as jet velocity increases. The relationship is not linear, but is rather approximately a logarithmic relationship [30]. In addition, the power required to produce the jet is proportional to the product of the volume flow rate and the pressure drop across the nozzle. The pressure drop is in turn proportional to the jet velocity squared. Therefore, the power required to produce the jet is proportional to jet velocity cubed [28]. As a result of these non-linear relationships there is currently a maximum practical jet velocity of ~100 m/s in impingement systems used to dry paper. Evaporation rates are linearly dependent on jet temperature, however there is also a practical limitation on jet temperature. This limitation is due to the requirement for any hood system, enclosing the orifice plates, to span the width of the machine. As temperatures approach 500 °C it becomes more difficult and expensive to construct hood systems which can withstand the temperatures and not deflect significantly at the center of the machine.

In practice an impingement drying system uses a gas fired burner to produce the hot air. The hot air is blown through an orifice plate. The orifice plate has a regular pattern of holes in it. Typically these holes are ~ 1 cm in diameter and the open area or the plate is ~2% of the total plate area. The plate is positioned 2-3 cm above the sheet surface. The high drying rates also require that a means be provided to remove the saturated air that has absorbed the evaporated water. This air it dehumidified and the heat recovered.

If impingement drying is used to fully dry the sheet, it produces a constant rate and a falling rate drying phase similar to that produced by cylinder drying. The reasons for the two phases are also similar to that for cylinder drying.

## Through Air Drying

In conventional tissue and towel manufacture the sheet is first pressed to remove water, it is then transferred to the Yankee dryer for final removal of water by evaporation. The pressing operation uses relatively low press loads in comparison to other paper grades; however it still compresses the sheet. Various operations can be performed to create a bulky sheet after drying; these include creping and embossing, however the final product is not as bulky or absorbent as it would be if it had never been pressed. The Through Air Drying (TAD) process was introduced to tissue and towel manufacturing about 25 years ago. It is used in the production of tissue and towel products and removes water without compression; thus preserving bulk. It also allows a sheet with a three-dimensional surface topography to be produced using less fiber than would be required with conventional techniques. In addition, it is possible to manipulate the production process to produce a predefined topology. When two TAD produced sheets are formed into a two ply sheet, the gap between he sheets provides a large volume in which to carry absorbed liquids.

The TAD process is a two stage process. Stage 1 is a vacuum forming process. The sheet at ~20% solids is transferred to a synthetic porous fabric which has a surface topology equivalent to that desired in the final paper product. The sheet is then passed over a high vacuum source which pulls the wet sheet against the 'hills' and 'valleys' of the fabric. In this stage the sheet attains a solids content of ~28% solids. In stage 2 which immediately follows the vacuum forming, the sheet is then transported on the same fabric to and passed over one or more large porous rolls. While on the rolls, hot air is either pulled or pushed through the sheet. This dries the sheet and the sheet retains the topography of the carrying fabric. This stage is similar to standard impingement drying, with drying rate showing a constant rate zone, a falling rate zone and the drying rate being dependent on the moisture content of the sheet [31]. The drying in stage 2 must raise the solids content of the sheet from the entering solids of ~28% to the final sheet solids of ~95% solids. Final drying, above solids levels of 65 to 80%, is sometimes done on a Yankee dryer. As result a larger amount of water must be evaporated than in the conventional tissue/towel production method. This is off set by two factors. The first is that a bulkier sheet is created using less fiber. The second is that virtually all TAD produced products are consumer products and can be sold for a premium price.

In addition to the 70 to 100% greater water evaporation load (per unit mass of fiber) for the TAD process, its associated vacuum dewatering step consumes an enormous amount of electrical power, the amount escalating exponentially in the same manner as for impingement drying. There is a limit to the amount of water that can effectively be removed by the vacuum dewatering stage as demonstrated by the diminishing returns produced by increased vacuum levels in Figure 16 and Figure 17. The data in these figure was obtained from a laboratory apparatus which duplicates both stage of the TAD process. This sets a minimum possible level of evaporation that must be performed in Stage 2, and thus defines the cost of the TAD process.

## Infrared Heating and Drying

Infrared radiation (IR) has been used for paper sheet heating over the last 50 years, though its application has been limited to specific purposes, such as drying of coatings and moisture profiling. The effectiveness of infrared heating in these implementations is controlled by the heater energy output, the heater spectral emittance characteristics and the sheet transmittance and absorption properties. One of the advantages of IR heating is the ability to rapidly change the output of the heaters and to segment an IR system so that specific CD locations of a sheet can be targeted for greater or lesser energy input. Thus, IR heating is generally used at the end of the dryer section to eliminate wet streaks or on coated grades after coating.

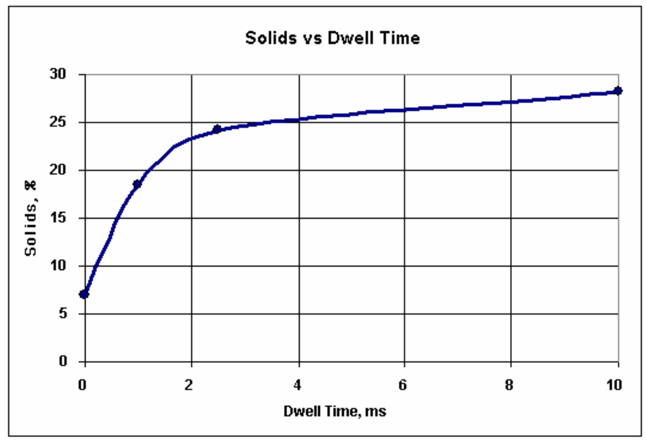


*__Figure 16.__ Vacuum dewatering final solids content versus dwell time for a 30 g/m$^2$ sheet and $\Delta p$ = 15 in Hg).(IPST)*


*__Figure 17__. Vacuum dewatering final moisture ratio (mass water/mass fiber) versus dwell time for a 30 g/m$^2$ sheet and $\Delta p$ = 15 in Hg).(IPST)*

The commercially available IR heaters are of two types, electric and gas fired. In electric heaters a heating element is resistively heated. The distribution of the spectral output of the spectral output can theoretically be influenced by the material of the element. In the case of gas fired heaters, propane or methane is burned on a rigid grid work. This heats the grid work which then acts as the spectral emitter. As with the electric heaters, it is theoretically possible to manipulate the distribution of the spectral output by properly selecting the material from which the grid is made. Despite the possibility of intentionally manipulating the output spectrum, both types of commercial heaters use conventional material as emitter elements and have gray body emittance spectrums. The majority of a gray body emittance spectrum spans the wavelength range from 800 nm to 5000 nm. Water has almost 100% absorption of IR energy in the range of 2800 – 3400 nm. As the temperature of the emitter increases, the energy peak shifts to the shorter wavelengths (peak @ 500°C – 3000 nm, peak at 1000 °C – 2100 nm). Given that electric heaters generally operate at higher temperatures than gas heaters, the peak of the emittance spectrum is shifted to shorter wavelengths when compared to the emittance of gas heaters. It is often stated that paper is highly transmissive at shorter wavelengths and therefore a larger portion of the electrically generated infrared energy will pass through the sheet. Since the peak of the spectrum produced by the gas emitters is shifted towards longer wavelengths, the infrared radiation is stated to be more readily absorbed [32-37]. Whether or not this type of behavior actually occurs is the subject of some debate.

There has been relative little work done on the transmittance or absorption spectrums of wet paper. An example of a transmittance spectrum for a wet paper at varying solids levels is shown in Figure 18. As can be seen from the figure a sheet at a low solids level has almost no transmittance and presumably absorbs most of the IR energy. Conversely, a sheet at a high solids level has a higher transmittance and potentially does not absorb the as much energy per unit thickness. The effect of the energy absorption on increasing the temperature of the sheet depends on the proportion of water and fiber in the sheet. The heat capacitance of water is approximately three times the heat capacity of the fiber, thus a drier sheet can be heated to a higher temperature using less energy.

One of the drawbacks to IR heating is the maximum heat flux possible. Because the total energy that can be delivered to the sheet per unit time is less than other methods of drying, a large expanse of IR heaters would be required to dry completely a sheet of paper.

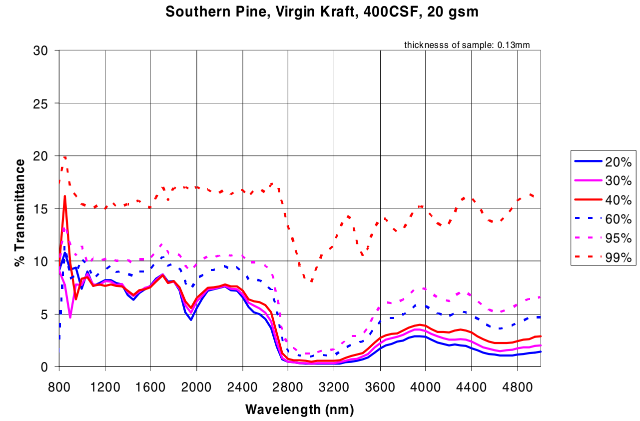


***Figure 18.*** *Infrared tranmitance for a southern pine sheet exposed to black body IR radiation (IPST)*

## Concluding Remarks

Drying of paper produces changes in the individual fibers as well as provides the means for bonding those fibers to one another. The bonding of fibers is one of two primary factors which determine the final strength of the sheet. The process of drying should be control to insure that the fiber matrix physical properties are not adversely affected; if not properly controlled the paper quality can be impacted. The current technology for drying paper, steam heated cylinders, is highly efficient but yields slow drying rates. Due to the nature of paper making, high volumes produced at high production rates alternative drying methods such as, air impingement, through air drying and infrared drying are employed only in specific case where product quality or cost justifies the higher energy costs characteristic of those methods.

## References

[1] T. C. Maloney, “On the pore structure and dewatering properties of the pulp fiber cell wall” Acta Polytechnica Scandinavica, Chemical Technology Series, n 275, 2-45, (2000).

[2] B. Alince, “Porosity of Swollen Pulp Fibers revisited”, Nordic Pulp and Paer Research Journal, 17, 1 (2002.).

[3] D. Page, P. Tydeman, M. Hunt, “The Behavior of Fibre-to-Fibre Bonds In Sheets under Dynamic Conditions”, Transactions of the 2nd Fundamental Research Symposium. FRC, Oxford, pp. 249-276 (1961).

[4] L. H. Busker, D. C. Cronin, “The Relative Importance of Press Variables in Water Removal”, Pulp & Paper Canada, 85, 6 (1984).

[5] D. F. Caufield, T. L. Young, T. H. Wegner, “The Role of Web Properties in Water Removal by Wet Pressing”, Tappi Journal, 65, 2 (1982).

[6] J. E. Stone, A. M. Scallan, “The Effect of Component Removal Upon the Porous Structure of the Cell Wall of Wood II. Swelling in Water and the Fiber Saturation Point”, Tappi Journal, 50, 10 (1967).

[7] H. Nanko, J. Ohsawa, “Scanning Laser Microscopy of the Drying Process of Wet Webs”, J. of Pulp and Paper Science, 16, 1, (1999)

[8] G. Smook, Handbook for Pulp & Paper Technologists, 3rd Ed. (Angus Wilde Publications, Vancouver, Canada) pg. 16. (2002).

[9] G. Smook, Handbook for Pulp & Paper Technologists, 3rd Ed. (Angus Wilde Publications, Vancouver, Canada) pg. 5-6. (2002).

[10] G. Smook, Handbook for Pulp & Paper Technologists, 3rd Ed. (Angus Wilde Publications, Vancouver, Canada) pg. 12-13. (2002).
[11] D. H. Page, F. El-Hosseiny, K. Winkler, A. P. S. Lancaster "Elastic Modulus of Single Wood Pulp Fibers", TAPPI Journal, v 60, n 4, (1977).
[12] A. M. Scallan, "Accommodation of Water Within Pulp Fibers", Trans. BPBIF Symp. Fiber-Water Interactions in Papermaking, pg 9. (1977).
[13] T. Patterson, T. Smith, *"Investigation of Wet Paper Cohesive Properties"*. 2006 Progress in Paper Physics, Miami University, Oxford, OH. October 1-5, (2006).
[14] H. Nanko, S. I. Asano, J. Ohsawa, "Shrinking Behavior of Pulp Fibers During Drying", TAPPI Int. Paper Physics Conf. (Kona, HI) Proc. (Book 2): 365-374 (1991).
[15] K. Niskanen, Papermaking Science and Technology - Paper Physics, Book 16 (Fapet Oy, Helsinki, Finland) pg 69, (1988).
[16] M. Htun, A. deRuvo, "Correlation Between the Drying Stress and the Internal Stress in Paper", TAPPI Journal, 61, 6, (1978).
[17] A. DeMaio, T., Patterson, "Influence of Bonding on the Tensile Creep Behavior of Paper in a Cyclic Humidity Environment", Mechanics of Time-Dependent Materials.
[18] R. Hill, "The Creep Behavior of Individual Pulp Fibers Under Tensile Stress". Tappi J. 50, 8, (1967).
[19] R. Seth, D. Page, "The Stress Strain Curve of Paper", Transactions of the 7th Fundamental Research Symposium. FRC, Cambridge, pp. 421-452. (1981).
[20] A. DeMaio, T., Patterson, "Influence of Fiber-Fiber Bonding on the Tensile Creep Compliance of Paper", Transactions of the 13th Fundamental Research Symposium. FRC, Cambridge, pp. 749-775, (2005).
[21] d. Coffin, "A buckling analysis corresponding to the fluting of lightweight coated webs", International Paper Physics Conference, Proceedings, p 31-36, (2003).
[22] F. Ahrens, T., Patterson, S., Mueller, B., Hojjaitie, B., "*Investigation of Paper Dryer Picking, Web Transfer and Quality Issues Using a New Web Adhesion and Drying Simulator*". Brazilian Journal of Chemical Engineering, 22, 2, (2005).
[23] Technical Information Paper 0404-33, Dryer Section Performance Monitoring, TAPPI Press, (2005).
[24] Technical Information Paper 0404-07, Papermachine Drying Rate, TAPPI Press, (2005).
[25] Technical Information Paper 0404-07, Papermachine Drying Rate, TAPPI Press, (2005).
[26] R. Deshanpande, G. Wedel, J. Breiten, "Application of Impingement Drying to Future Dryer Sections", Annual Meeting - Technical Section, Canadian Pulp and Paper Association, Preprints, v Pt B, B67-B73, (1999)
[27] J. Lehtinen, "The Heat Pipe Process in Intraweb Heat Transfer in Hot Surface Paper Drying", Paperi Ja Puu, 74, 7, (1992).
[28] S. Tan, "Drying of Paper", Tappi J, 53, 6, (1970).
[29] P. Lee, J. Hinds, "Analysis of Heat and Mass transfer within a Sheet of Papermaking Fibers during Drying", Drying '82 (Mujumdar, A. S., ed.): pg 74, (1982).
[30] G. Chen, G. Gomes. W. Douglas, "Impingement Drying of Paper", Drying technology, 13, 5-7, (1995).
[31] S. Hashemi, G. Gomes, R. Crotogino, W. Douglas, "Through Air Drying Characteristics of Machine Formed Semi-Permeable Paper", Drying Technology, 15, 2, (1997).
[32] Sharma, R. "Using Infrared Selectively for Improving Paper Quality and Production". TAPPI 1986 Practical Aspects of Pressing and Drying. pp171-178. (1986).
[33] K. Ratnani, "The Application of Gas-Fired Infrared Technology to the Pulp and Paper Industries". CPPA Annual Mtg. (Montreal) Preprints 73A: 227-229 (Jan. 27-28, 1987).
[34] S. Bouchard, "Electric Technologies for Paper Drying" CPPA Annual Mtg. (Montreal) Preprints 73B: 221-215 (Jan. 27-28, 1987).
[35] T. Bjornberg, "Electric Infrared Drying – New Drying Method and Practical Experience". 1988 TAPPI Coating Conference. New Orleans, LA. pp 239-246. (1988).
[36] J. Goovarts, D., Lavigne, "High Efficiency Gas-Fired IR Drying a Major Breakthrough in the Paper Industry". Helsinki Symposium on Alternate Methods of Pulp and Paper Drying, Helsinki, Finland. (June 1991).
[37] M. Sain, L., Marchildon, C., Deneault, C., Pendault, S., Robard, "Infrared Energy Transfer Mechanism in Constant Rate Periods of Paper Drying and Its Correlation to Drying Efficiency". Appita Journal, 48, 5, (1995).

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