PAPERMAKING

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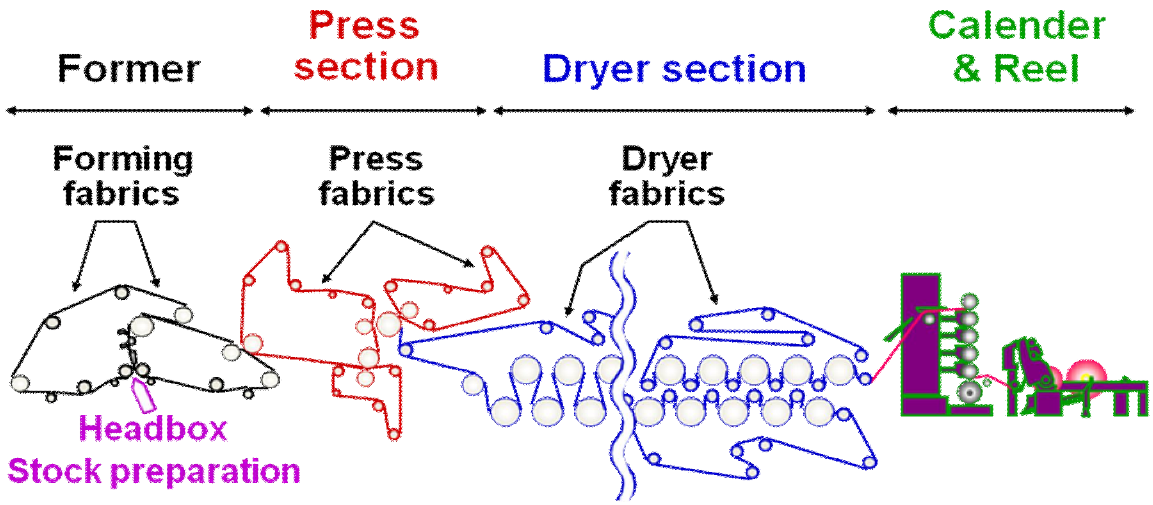
The operations involved in converting fibers (see Paper: Pulping and Bleaching, Pulp and Paper Sources: Non-wood) and other materials (see Paper: Non-fibrous Components) into a sheet of paper or paperboard are collectively known as papermaking. Paper having a width up to 10 m is manufactured on a continuous basis on paper machines as long as 150 m. Modern paper machines producing lightweight grades operate at speeds close to 2,000 m/min. Papermaking has evolved from an art practiced by hand to a complex and technical manufacturing process with a high degree of automation (see Paper: History of paper).

The principal unit operations of papermaking include: stock preparation to create aqueous slurry of fibers suitable for paper production, forming to create a wet and fragile web, pressing to remove excess water and consolidate the web, drying to evaporate most of the remaining water and bond the fibers together, and calendering to reduce the sheet thickness and smooth the surface. Additives such as starch and chemicals are spread onto the surface of some paper grades in a surface treatment operations called sizing. Reeling and winding is then required to produce rolls of paper suitable for printing presses or for converting to sheets (paper size). Additional operations, such as coating - the application of various additives to the sheet surface or soft calendering and supercalendering may be carried out on- or off-machine to produce different grades of paper.

Many of the papermaking operations are concerned with dewatering. The development of sheet dryness as it proceeds along a typical paper machine is shown in Figure below. In the forming section, about 95% of the water ejected from the headbox is removed as the web solids content is rapidly increased from less than 1% to a value ranging anywhere from 13% to 25%. This is followed by pressing, which typically achieves the web solids content somewhere between 38% and 50%. Drying is then be resorted to for the last stage of water removal, resulting in a final moisture content of the paper between 2% and 10% depending on the grade.

Scheme of paper machine



Paper is truly an engineered material, manufactured according to the requirements of its final use. A myriad number of properties such as surface texture, color, strength, stretch, absorbency, permeability, translucency, grease or moisture resistance, electrical conductivity, permanency, stiffness and many more can be imparted by carefully tailoring the manufacturing process.

1. *Forming*

Forming is the first step in the papermaking process. Its specific objective is to drain water from a dilute fiber suspension on a forming fabric, and to create a uniform fiber mat that is strong enough to be passed to the press section of the paper machine. Forming has a strong influence on a range of paper properties. It determines the uniformity of mass distribution in the x-y plane, alternatively known as formation for small-scale variations, or basis weight variation for larger-scale variations. Forming determines the fibre orientation in the sheet, which will influence the directionality of paper properties. Forming also determines the fines and filler distribution in the z-direction, which determines the two-sidedness and surface smoothness of the product. The characteristics of the web created in the forming process can be linked to many of the final paper properties. The process and equipment of forming and drainage processes are coupled to determine the quality of paper and paperboard.

1.1 Approach Flow System

The forming process is preceded by an approach flow system that receives the aqueous fiber suspension, or stock, and prepares it for the forming process. Fibres are produced using kraft process or other pulping/bleaching processes (see Bleaching of wood pulps) and the proportions of fibers from different sources are blended here. Drained water from the forming process, known as whitewater, contains useful fibrous material and is continuously recycled back into the stock.

Screens and centrifugal cleaners in the approach flow system remove oversize and heavy contaminants from the pulp. Additives such as minerals, pigments and dyes are introduced to make particular grades of paper and paper board. Air bubbles may be removed from the pulp suspension. The mass concentration, or consistency, of the suspension is kept low to prevent fibre flocculation prior to forming and is usually adjusted to a value in the range of 0.5 to 1.5%.

1.2 Manifold and Headbox

The stock is delivered from the approach flow system in a pipeline. The function of the manifold and headbox is to spread the pipeline flow into a jet which is up to 10 m wide, depending on the width of the paper being produced, but only a few millimeters thick. The jet is then presented to the forming section. The quality of the jet from the headbox has a considerable effect on fiber orientation and formation. However, the greatest challenge of the manifold and headbox is to ensure that the quality and velocity of the jet is uniform across its full width, since there are no opportunities to correct for non-uniform basis weight after the forming section.

Tapered manifolds are the most common type of flow distributor. The flow turns from the incoming pipeline into a bank of tubes. The taper provides a uniform pressure across the entries to the tube bank, so that the flow will spread equally across the paper machine. The recirculation flow at the narrow end of the manifold is adjusted to ensure a uniform pressure across the tube inlets.

The stock flows through the manifold tubes directly into the headbox, which may be either an air-pad type or hydraulic headbox. The air-pad headbox was dominant until the early 1970’s. In this design, the flow from the tubes emerges into a plenum and then passes through two or three rotating, perforated rolls. The first roll provides a flow resistance which blends the jets emerging from individual tubes, and helps avoid the creation of any secondary flows within the headbox which could cause non-uniformities in the jet flow. The following rolls continue this action and disperse any fiber flocs that have formed. The air-pad at the top of the headbox dampens out pressure disturbances in the incoming flow, which might otherwise produce basis weight variations in the machine direction. This design of headbox is not appropriate for modern, wide, high-speed paper machines however because of the engineering challenges associated with very high headbox pressures, and the structural limitations of the long cantilevered roll supports.

A hydraulic headbox is the design commonly installed on modern paper machines. This type of headbox has no air pad or perforated rolls. Instead, the flow from the manifold and tube bank discharges into a stilling chamber, which is substantially smaller than the plenum of the air-pad headbox and thus avoids the structural problems that limited the application of the air-pad headbox. From the stilling chamber, the flow goes to a converging section where it is accelerated to a speed close to the paper machine.

The jet of fibres leaves the headbox (for both air-pad and hydraulic headboxes) through an adjustable slice consisting of two thin metal plates referred to as the upper and lower lips. The grammage (basis weight), or amount of fibre mass deposited per unit area, is proportional to the slice opening. Large adjustments to the slice lip opening are made when switching between different paper grades. Smaller adjustments are required to provide a uniform basis weight profile in the cross-machine direction. These adjustments are made at discrete locations, typically every 10 to 15 cm across the paper machine width. However, a local correction at one slice position can lead to secondary effects in the flow of adjacent control zones, resulting in non-uniformities in the paper basis weight and fiber orientation. Very uniform basis weight profiles can be accomplished only with the assistance of sophisticated computer control.

Another approach to achieving uniform basis weight profiles is based on dilution control devices, which became popular in the 1990's. This approach effects a local change in basis weight in the cross-machine direction by adding varying amounts of dilution water just before the slice, to alter the local consistency rather than the flowrate. Dilution control thus provides basis weight uniformity without affecting the local flow patterns.

The positioning of the slice lips are also used to set the discharge angle of the jet from the headbox. This determines the angle and point of impact on the forming wire, which affects formation, porosity and other properties.

1.3 Fourdrinier Formers

There are three main classes of formers: fourdriniers, top formers and gap formers. The fourdrinier was dominant from the early 1800's until the late 1960's. In the classic fourdrinier design, the jet from the headbox impinges on the forming fabric at the forming board. Substantial dewatering occurs due to the momentum of the jet. Small differences in the speed of the jet and the fabric speed (termed "rush" or "drag") will induce a strong degree of alignment in the fibers. This will cause a directionality in paper properties so that the tensile strength, for example, will be much greater in the machine direction of the paper than in the cross-machine direction.

After impingement, the suspension is carried on so-called forming table by the fabric over foils which cause suction pressure pulses. The suction promotes drainage of the water. The leading edges of successive foils skim water from the fabric surface. The pulses also cause spouting of the fiber suspension which promotes even distribution of fiber and improved formation. Traditionally the forming fabric was supported on the forming table by table rolls, but today table rolls are only found on older, slower machines. The general principle of table rolls action is similar to that of foils, however rolls produce undesirable positive pressure pulses, which can disrupt the mat being formed.

The resistance of the mat to drainage increases as water is drawn off. The mat is then passed over suction boxes with progressively higher levels of vacuum to induce drainage. The wet sheet is exposed to the highest level of vacuum as it travels over the final element of forming fabric, namely perforated couch roll that contains inside a containing a vacuum box. The fibre mat laving the former has a consistency of 13% to 25% and it is strong enough to be transferred to the press felt and the pressing process.

The design of the forming fabric mesh itself must be considered along with the drainage forces through the forming process. The size of the individual filaments, their weave and the number of layers in the forming fabric will affect the drainage rates, retention of fines and fibre, the surface quality of the paper and other paper properties. Fabrics must be carefully selected for each application.

A significant problem with the fourdrinier is that drainage occurs through only one side of the fiber mat. This side suffers from a depletion of fines, filler and other small material that is washed out of the mat. The effect persists as a two-sidedness in the paper, which leads to problems in printability, curl and other properties.

1.4 Hybrid or Top Formers

The top-former or "hybrid" former reduces the two-sidedness of paper, and increases the dewatering capacity of a paper machine by draining water from both sides of the mat. This style of former begins with a conventional fourdrinier table having single-sided drainage with foils and suction boxes. However, a second fabric is applied on the top of the mat at the point where consistency of the web is about 2%. The combination of the mat and the lower and upper forming fabrics is then wrapped around a curved forming roll and/or series of forming blades to produce positive drainage pressures. The pressures can be applied to either side so that an appropriate program of pressures minimizes two-sidedness.

The top-former was widely adopted in the early 1980's. It could be retrofitted onto conventional fourdrinier, which reduced the cost of installation. It did not, however, completely eliminate two-sidedness since the initial drainage still only occurred from one side.

1.5 Twin Wire Formers

The top former uses two fabrics for the full length of the forming section to minimize two-sidedness and maximize drainage. Almost all new paper machines a build with some type of twin wire former. The most common types of twin-wire formers are gap formers in which the jet of fibrous suspension is injected into the gap formed by two converging forming fabrics.

A typical configuration has a hydraulic headbox with the jet impinging at the nip where two fabrics come together. All of the previous discussion of fabric selection, jet impingement, jet-fabric speed differentials apply here in a similar way to the fourdrinier.

However for a gap former, the fibre mat is contained between the two forming fabrics that wrap around a forming roll and a series of forming blades, known as a shoe, before going over suction boxes and the couch roll. The tension of the fabrics and the curvature of the forming roll and blade shoe create a positive dewatering pressure. The associated pressure gradients provide a limited opportunity to redistribute fibres and improve formation. The quality of the paper sheet is strongly dependent on the quality of the incoming fibre, the action of the headbox to provide a uniform jet, and the design of the fabrics to control the rate of drainage. While the roll-blade former design reflects current practice, some gap formers have only blades or only a pair of rolls.

2. *Pressing*

The best known objective of pressing is water removal from the wet web, although two other results of pressing, namely wet web strength and product quality, are of equal importance. On a modern paper machine, the web leaving the former is weak and readily damaged or broken as it proceeds at high velocity through the subsequent machine parts. In the press section, the solids content of the sheet is increased to about 43 % on machines using roll presses, and up to 50% on machines using at least one shoe press. The sheet compaction and water removal which occur in pressing result in a three to fourfold increase of wet sheet tensile strength.

Pressing also has an important influence on the finished product properties. The network of wet fibers leaving the former is bulky and contains a large volume of air. The product obtained by drying an unpressed, uncompressed wet web has low density, strength and smoothness and is poorly-suited for use as a printing base or packaging product, although some hygienic tissue papers are made from unpressed webs. Upon pressing the wet web, malleable wet fibers are forced into close proximity, air and most of the water separating the fibers are expelled, tubular fibers are flattened, and the fiber to fiber contact area is greatly increased. Paper obtained by drying a pressed web is much denser, stronger and smoother than that obtained from unpressed webs.

2.1 *Roll and Shoe Presses*

The press section of a paper machine generally consists of two to four press nips, each consisting of two counter-rotating hydraulically-loaded press rolls. The wet sheet is compressed in each press nip at linear loads ranging from 30 to 200 kN/m. The sheet is usually pressed along with a permeable press fabric to provide a means for removing the water expelled from the sheet. The press fabric is an endless loop which continuously passes through the press nip. In single-felted presses, one side of the sheet is in a direct contact with a press roll, while the other contacts the press fabric. The press roll backing the press fabric is usually vented, that is, equipped with holes or grooves to receive the water escaping from the press fabric. Some press rolls have a shell made permeable by drilled holes and a suction box located inside the roll. Elastic covers made of hard rubber or polyurethane often cover the vented rolls. The press roll contacting the wet web must be smooth since any roughness of the roll will be replicated on the paper surface.

The press nip formed by a roll press is about 20 to 40 mm wide, resulting in a nip residence time of only one millisecond at a machine speed of 1800 m/min. If the nip residence time is too short for adequate water removal, the moisture content of the sheet leaving the press may be too high. Excessive hydraulic pressure generated in a nip under these conditions may damage or break the sheet by so-called "sheet crushing". A sheet having higher solids content can withstand higher pressure and the press nip load is thus increased from the first to the last press.

Two strategies are used to improve water removal and to prevent sheet crushing, especially on machines operating at high speeds, which have a short nip residence times, or those producing heavy grades of paper and board, which require a lot of dewatering. Press nips of such machines may be double-felted, which means that the sheet is pressed between two permeable press fabrics, allowing water to leave the sheet through both sides.

The second strategy is the application of a shoe press rather than a two-roll press. This type of press is formed by a press roll and a hydraulically-loaded shoe rather than another roll. The shoe is shaped in such a way that it matches the contour of the press roll. The nip formed in this manner can be about 300 mm wide and the time available for sheet compression and water removal is about ten times greater than in nips formed by conventional roll presses. The original shoe presses developed by Beloit Co. had a trade name Extended-Nip Press abbreviated as ENP.

2.2 Press Section Configurations

Sheet breaks are a common problem that limits the speed and productivity of many machines. Most frequently, the sheet break occurs when the weak wet web is for the first time transferred unsupported between two machine parts in a so-called "open draw". Until the 1950's, the first open draw occurred between the former and the first press and frequent breaks at this point limited the machine speed to about 700 m/min. On many paper machines, the first open draw occurs in the press section and therefore this is the are where most sheet breaks occur.

Modern paper machines often employ a cluster of three or four rolls that form two or three press nips respectively. These multi-nip presses are more expensive to build and to operate, but they press the sheet in several nips before the first open draw. The repeatedly pressed sheet has higher solids and is stronger, which improves the paper machine runnability. Open draws were eliminated from the wet end of modern paper machines equipped with shoe presses, and this allowed for a drastic increase in the operating speeds.

2.3 Press Fabrics

The role of press fabrics is to evenly distribute the pressure applied by grooved or drilled press rolls and to receive water expelled from the web in the press nip. In spite of its much heavier weight, the press fabric normally has a greater permeability than the wet web. Press fabric structures are carefully engineered to remain permeable to water even under compression. Modern press fabrics consist of a woven base covered by a batt of loose fibres. During its life, which might be from 10 to 60 days, a press fabric passes through the press nip several million times. To prevent plugging of the fabric by various contaminants associated with the expelled water, continuous cleaning with showers, vacuum suction boxes, and occasionally chemical agents is required. When the fabric permeability can no longer be restored by chemical or other cleaning methods the fabric must be replaced.

2.4 Mechanism of Pressing

Water remaining in the fibrous web at the end of the forming section is located on the surface of the fibers, in the the fiber lumens, and inside the swollen fiber walls. As the wet web and the adjacent press fabric start entering the press nip, the air contained in the sheet-fabric sandwich is expelled and the nip becomes saturated with water. Further compression of the sheet and press fabric is possible only if some water escapes into cavities in the press roll. Water flow out of the sheet is driven by the hydraulic pressure in the press nip, but is limited by the low permeability of the sheet and its resistance to compression.

The compressed sheet and fabric, saturated with water in the midpoint of the press nip, begin to expand on the outgoing side of the nip. During this expansion, capillary forces transfer some of the water located within the press fabric back into the more compact wet paper in a process referred to as rewetting. Various authors have reported different estimates of the extent of rewetting in the outgoing side of the nip, but the real value is not known. If the sheet is not separated from the press fabric immediately upon its exit from the nip, rewetting continues and can decrease the solids content of the pressed sheet by as much as 3 %.

Numerous mathematical models with various degrees of complexity have been developed to describe water removal in the press section. Difficulties in modeling wet pressing include the short duration of the press pulse, the non-linear variation in the permeability of the compressed sheet and press fabric, rewetting, and other factors. Models can be used to calculate the effect of pressing only by employing some experimentally-derived factors, and the results are often not very accurate. Most models contain in some form the nip impulse “I”, which is a key pressing parameter. A practical form of the nip impulse is expressed by dividing the press nip load by the machine speed.

In addition to nip load and machine speed, the extent of pressing is strongly influenced by sheet temperature. The effect of increasing the temperature has a similar effect on the results of pressing as does increasing the press nip impulse, namely the sheet solids content is increased and its thickness is reduced. On many machines, the sheet is heated directly at the entrance of the press nip by a steam shower or by infrared radiation. It is likely that the potential for improving pressing by further increasing the sheet temperature will be further exploited in the future.

2.5 Problems associated with Pressing

Pressing difficulties can be related to the press section operation or to the product quality. One common operational problem is press vibration, often caused by variations in the properties of roll covers or press fabrics. Sheet breaks can be caused by excessive sheet adhesion to the press roll at the outgoing side of the nip. Press fabric life can be drastically limited by incorrect cleaning or operating procedures. Unscheduled machine shutdowns, for premature replacement felts or press rolls, are a common cause of low machine efficiency.

While pressing of the wet web improves the quality of finished paper and board, it can also generate several types of defects. In particular, excessive pressing in the first nip can cause sheet crushing and holes in the product. Uneven moisture distribution across the paper width can be caused by unequal nip load distribution or by a variation in the press fabric quality. Sheet two-sidedness can arise when the side contacting the press fabric in the last press nip becomes rougher than the side contacting the smooth press roll.

3. *Drying*

Drying transfers energy to the web to remove moisture through evaporation. The principles of heat and mass transfer are integral aspects of the process. The large energy requirements of the dryer section make it the most expensive part of the paper machine to operate, and drying is only resorted to when drainage, suction and pressing are no longer effective. Typically, the web leaves the press section and enters the dryer section of a paper machine at a moisture content around 60% by weight. The final moisture content after drying is 10% or less depending on the grade and the desired properties. During drying, bonding of the pressed and consolidated cellulosic fiber network occurs without the use of external binding agents. Capillary forces develop during drying which draw the fibers into close contact as the moisture is evaporated, providing numerous sites for bonding to occur. Final product quality is greatly dependent on drying.

3.1 Multicylinder Dryers

The conventional multi-cylinder drying section used to dry most paper and paperboard is the longest part of the paper machine, sometimes having 60 or more drying cylinders for heavy basis weight grades. Paper is dried in a conduction-based process by contacting the hot surface of steam-heated cast iron cylinders with diameters of 1.2-1.8 m and shell thicknesses of 2.5 cm. The cylinders are pressure vessels typically rated for operation at about 1.1 MPa. The pressure is gradually increased as the paper proceeds through the dryer. The steam is introduced into the cylinders through rotary joints, and condenses inside the cylinder. The condensate is evacuated from the cylinder through a rotary or stationary syphon along with some of the uncondensed steam known as blow-through steam. The dryer is usually covered by a canopy or hood which may be partly or fully closed. This serves to exhaust the humid drying air and facilitates the recovery of energy for reuse. Hot dry makeup air is continually supplied to the hood.

It is typical for cylinder dryers to consume 1.5 kg steam/kg of water evaporated. The overall drying rate depends on the grade and the basis weight of the paper. It is between 10-30 kg/hr m^2 for steam temperatures in the range of 100-190°C. The entire surface area of the drying cylinders, rather than only the part in contact with the paper, is traditionally used to compute the overall drying rate.

The cylinders are usually arranged in sections having upper and lower tiers, through which the paper travels in a serpentine fashion. Each tier usually has an endless felt or fabric to press the sheet against a large part of each dryer to maximize heat transfer; this configuration is known as a double-felted dryer section. The unsupported portion of the web is called a draw, and two neighboring draws together with the felt form a pocket. The sheet is not restrained in the draws, leaving it vulnerable to fluttering and breaks and allowing the sheet to shrink. The vapor released in the pocket induces localized high humidities which will retard further evaporation unless the pocket is ventilated with hot dry air.

Over the years, incremental improvements to multicylinder drying have been primarily driven by the desire to increase the machine speed. Dryer felts were replaced by more permeable drying fabrics, and double-felted sections are being progressively replaced by single-felted ones, where a single drying fabric is used, rather than an upper and lower fabric. Some single tier sections are usually arranged in such a way as to provide alternate heating for both sides of the sheet.

The dryers for the fastest machines are now being designed as one long single tier with no alternating sections; thus one side of the sheet is always in contact with a fabric and the other in periodic contact with the drying cylinders. Drying is done from one side of the sheet only. The single-tier arrangement is favored for achieving high runnability, which becomes critical as machine speeds approach 2,000 m/min.

It is important to achieve a uniform moisture profile across the width of paper. The web has a tendency of being wetter in the center than at the edges unless the pockets are properly ventilated to prevent this effect. In certain operations where a level moisture profile is critical, the sheet is over-dried to a very low moisture level at the expense of operating efficiency. However, non-uniformities in moisture profile are usually corrected through the appropriate use of steam showers in the press section, remoisturizing showers in the dryer section, or infrared profiling units. Non-uniform moisture profiles cause difficulties in the subsequent operations such as coating, calendering and winding, and may result in over-dried or grainy edges, baggy or slack areas, and poor reel building. Other drying-related defects may include the following: blisters caused by too hot a cylinder, over-drying leading to brittleness and loss of strength, machine direction dryer wrinkles due to a variety of causes including misalignment, improper tension or excessive flutter in the draw, felt seam marks, holes in the sheet due to the dripping of condensed vapor in the hood, and poor surface finish due to dirt on the cylinder.

3.2 Yankee Dryers

Drying of tissue and towel is carried out in contact with a single large polished cast iron cylinder called a Yankee dryer, which has a diameter of 3-6 m and a shell thickness around 7.5 cm. Apart from their size and special design considerations which this imposes, Yankee dryers are similar to the cylinders used in multicylinder drying and are heated with steam. Circumferential grooves inside the cylinder are used to provide more condensate heat-transfer area , as well as decrease the shell thickness through which heat must transfer before reaching the paper. Yankee dryers are almost always equipped with gas-fired impingement hoods or caps which greatly increase the drying rate by blowing jets of hot gas onto the paper surface. Jet velocities around 200 m/s and jet temperatures up to 700°C can be found on the most modern impingement hoods. Drying rates are around 200-500 kg/hr m^2, which is one order of magnitude greater than those for multicylinder drying.

The wet web is pressed onto the hot dryer with a rubber roll, and the dry paper is detached from the dryer by means of a creping doctor. The micro-ridges induced in the paper by the creping doctor create bulk and softness. Most Yankee dryers use a spray system to apply adhesion and release agents to the surface of the cylinder prior to the press roll. The proper adhesion and release of the sheet is critical to the drying and creping processes. Tissue and towel typically have much lower basis weight than other paper grades, and are manufactured and dried at speeds beyond those of other paper products.

Machine glaze (MG) cylinders are similar in all respects to Yankee dryers except that no creping doctor is used and the surface of the cylinder is more highly finished. The impingement hood is optional since the principal function of this type of dryer is to impart a smooth and glossy finish to one side of the paper or paperboard, rather than achieve a high drying rate. MG cylinders may be used in conjunction with conventional cylinder dryers, although more and more they are being replaced by special calendering processes which achieve the same finish and are less problematic to operate.

3.3 Other Types of Dryers

Alternative drying methods using convective or radiation heat transfer, or a combination of pressing and drying have found niche applications for certain paper grades. Coated papers requiring non-contact drying use systems combining convective and infrared drying. The quality of the coated surfaces is sensitive to the drying method, and the absorption of radiant energy in the infrared region is confined to a very thin layer especially suitable for coating drying. Sack grades requiring non-restrained drying to induce product strength properties use air floatation drying. This technique uses high-velocity hot-air streams from alternate air bars on both surfaces of the web for simultaneous floating and drying. Although these approaches are not used for bulk drying of printing and writing grades, microwave or dielectric drying is especially effective in correcting moisture profile for all grades.

Some tissue manufacturers use through-drying of an unpressed web to enhance softness and bulk. Hot air is drawn through the web, which is supported on a perforated cylinder under a vacuum. The drying rate is similar to that obtained on a Yankee dryer.

Over the last two decades much effort has been devoted to the development of methods that combine pressing and drying, such as conde-belt, press-drying Papridry™, and impulse drying. In these concepts, the distinction between pressing and drying is blurred since both are performed simultaneously to achieve high drying rates and special product properties. A few commercially implemented designs have been applied in the manufacture of board grades.

There are now several applications using gas rather than steam-heated cylinders in multicylinder dryers. This approach permits much higher surface temperatures than can be obtained with steam heating and increases the drying rate.

3.4 Heat and Mass Transfer during Drying

When wet paper is dried, simultaneous heat and mass transfer take place. For optimal drying, heat and mass transfer must be maximized while at the same time respecting the various operational and energy efficiency constraints. For the case of multi-cylinder drying, the rate of heat transferred from the hot steam inside the cylinder to the cooler paper on the outside depends on the overall temperature gradient and the different resistances to heat transfer. These include the condensate inside the dryer, the shell thickness, the contact resistance at the paper-cylinder interface, and the web itself.

Increases in drying rate can be achieved by increasing the heat transfer to the paper, which for the greater part of the drying is the rate-limiting step. This can be done by increasing the steam pressure which will increase the overall temperature gradient, or by decreasing the resistances to heat transfer. The latter approach may include minimizing the thickness of the condensate layer rimming the inside of the cylinder through appropriate syphon arrangements, increasing the turbulence of the condensate layer through the use of longitudinal spoiler bars inside the cylinder, keeping the inside and outside surfaces of the shell clean, and decreasing the contact resistance by increasing the fabric tension. Little can be done about the heat transfer resistance of the web itself, which increases with web thickness, void fraction, and dry content.

For the case of Yankee dryers, heat transfer occurs not only from the steam-heated cylinder but also by convective heat transfer from the impinging jets. The contact resistance is low because the paper is pressed on the surface rather than being held with a fabric, and the heat transfer resistance of the web itself is low because of the light basis weights used for these grades.

Mass transfer for any type of dryer occurs after a sufficient amount of heat has been transferred to the web, resulting in a transfer of a given mass of water vapor from the paper through a boundary layer to the air in the dryer section. This can occur by molecular diffusion, convective diffusion, and bulk movement or ventilation. The driving force for mass transfer is a vapor concentration (or partial pressure) difference between the web and the surrounding dryer air. The evaporation rate can be maximized by reducing the thickness of the boundary layer through proper pocket ventilation, keeping the vapor pressure of water in the sheet at a high level by keeping the sheet temperature elevated, and maintaining a low vapor pressure in the ambient dryer air by keeping it hot and dry.

3.5 Effects of Drying

For most applications, the rate of drying does not affect the properties of paper significantly and the most important aspect is to achieve a uniform moisture profile so that subsequent operations such as calendering, surface treatment and printing will produce uniform results.

During drying, the shrinkage of individual fibers in the radial direction induces shrinkage and cockle in the bonded paper structure unless it is restrained. Shrinkage begins to occurs around 65% solids content. The action of restraining the sheet during drying leads to the development of drying stress or tension, the extent of which depends on the degree of imposed restraints. Tension in the machine or cross-machine direction increases the tensile strength and reduces the toughness and stretch-to-failure in that direction. The action of restraining the sheet during drying reduces the hygroexpansivity of the sheet and improves the dimensional stability. Non-uniform drying stress in the thickness direction of the paper, as would occur in single-sided drying, is one of the causes of curl, a problem of dimensional stability. Pressure in the thickness direction during drying raises the sheet density and lowers its porosity.

Multi-cylinder drying results in high machine direction tension although the sheet is relatively free to shrink intermittently in the cross direction in the open draws. This cross direction shrinkage is not uniform and is greater at the edges, resulting in non-uniform strength profiles. Air floatation drying used for sack grades allows shrinkage to occur in all directions with essentially no stress or strain on the sheet, resulting in high stretch and toughness but lower strength than is obtained in multi-cylinder drying.

4. Calendering, Reeling and Winding

4.1 Calendering

Improving paper smoothness is the primary objective of calendering for printing and writing papers, and also for some packaging grades of paper and board. The dry web leaving the dryer section is bulky and has a rough surface. For most printing processes, print quality is proportional to paper smoothness. Even paper that is not used for printing or which is used as a base for coating is often calendered to improve roll building, since small differences in sheet thickness add up causing variations in reel diameter and wrinkles in the sheet.

A calender consists of a vertical stack of two to ten polished steel or chilled cast iron rolls. The paper passes in a serpentine fashion through the nips between each roll starting at the top of the stack. The pressure in each calender nip is generated by the weight of the rolls above the nip, or the calender might be hydraulically-loaded or relieved. The paper is repeatedly compressed as it passes through each nip. After each compression, the paper expands but does not recover its original bulk. The surface of the calender roll is replicated onto the paper surface, and calender rolls must be periodically reground to maintain their smoothness as well as to correct any variations in their diameter caused by unequal wear.

Calendering is enhanced by all factors that render fibres less rigid and more malleable. Therefore paper made from chemical pulp requires less calendering than paper made from mechanical pulps, and calendering can be improved by increasing the sheet moisture content and temperature. The effect of calendering is increased by increasing the number of nips or the nip load, and decreased by increasing machine speed or roll diameter.

The high nip loads in the calender can result in product damage. Calender blackening occurs at very high nip loads when fiber flocs are compressed to the extent that they loose their opacity. This defect occurs more readily if sheet moisture content is high. Printing papers made from mechanical pulp may loose as much as 30 % of their tensile strength during calendering, since compression of the sheet in the dry state results in the destruction of fiber to fiber bonds. Creases in the paper entering the calender usually results in calender cuts. Any damage or scratch on the roll surface can be replicated on calendered paper.

In a supercalender, highly polished steel rolls alternate with rolls covered with a soft cover made from a plastic material or from heavily compressed cotton. The softness of this cover helps to prevent calender blackening and therefore supercalenders can be loaded up to several hundred kN/m. Supercalendering is commonly used on coated paper and board to obtain high-gloss products.

4.2 Reeling and Winding

At the end of the paper machine, the dried and calendered sheet is reeled on a large-diameter spool to produce large reels of paper called parent rolls or jumbo rolls. The full machine width rolls obtained on the reel weigh several tons and are not suitable for final use. Therefore a winder is used to unwind the jumbo rolls, slit the sheet and convert the jumbo roll into smaller rolls suitable for shipment to press rooms or for further conversion to a final product. The basic principles of reeling and winding are similar and both topics can be discussed jointly.

During reeling, the spool of paper is pressed against a drum to obtain the desired roll density. The correct roll density profile is important for good final product quality. The roll density should be highest near its core and gradually decline towards the periphery of the roll. The density profile is controlled by the pressure between the spool and the drum and by the tension of the incoming paper. The top paper layers of the roll are under tension and this belt of strained paper compresses the paper wound closer to the core. A well-wound roll is rigid and resists deformation by external forces.

Incorrect density profiles can result in various defects of the press roll, including burst rolls and excessive stretching of the outside plies of the roll. Rolls with too low a density near the core and a large paper tension at the perimeter can collapse in a star pattern when subjected to even modest external pressure. Reeling and winding are thus as important for the final product quality as any other papermaking operation.

5. *Surface Treatment*

The most common forms of surface treatment after drying involve the application of sizing agents to increase the water repellency of the sheet and improve printability, barrier agents for packaging grades, and coating formulations required for various grades to improve surface optical and physical properties.

Surface sizing is carried out prior to the last section of dryers. Sizing agents such as starches and binders can be applied using flooded nip, gate roll or film transfer size presses. The degree of sheet rewet is minimized in film transfer size presses, requiring less sheet strength to prevent breaks and less after-drying. Precautions must be taken to prevent picking and sticking of the sheet on the first dryers following the size press.

Coating of the sheet with formulations containing pigments, minerals, binders, and other additives can be carried out off or on-machine. When carried out on-machine, both sides of the sheet may be coated sequentially (with drying of the first side prior to coating of the second) or simultaneously after the calendering operation. Roll coaters, blade coaters and metered film transfer coaters have all been used, although high-speed modern operations use film coaters. Coatings are very delicate when wet and initial drying must set the coating without disrupting it. For this reason convective and radiation type dryers are used immediately after coating, although conventional dryers may be used after the initial drying.

Index terms:
papermaking, paper, paperboard, paper machine, headbox, formation, forming, former, gap former, roll former, hybrid former, twin wire former, fourdrinier former, top former, drainage, basis weight, pressing, roll press, cluster press, shoe press, consolidation, drying, evaporation, cylinder dryer, Yankee dryer, moisture, tissue, towel, MG cylinders, heat transfer, mass transfer, calendering, sizing, coating, fibres, paper properties, reeling, winding

Bibliography

Papermaking Science and Technology, a series of 19 books Published in 2000 by Fapet Oy, Helsinki, in cooperation with Finish Pulp and Paper Engineers' Association and TAPPI,

Polat O 1995 In: Mujumdar A S (ed.) *Handbook of Industrial Drying.* Marcel Dekker Inc., New York

Smook G A 1987 *Handbook for Pulp and Paper Technologists.* Joint Textbook Committee of the Paper Industry, Tappi, Atlanta, GA USA

Thorp B A, Kocurek M J (eds.) 1991 *Pulp and Paper Manufacture V.7 Paper Machine Operations*, Joint Textbook Committee of the Paper Industry, Tappi, Atlanta, GA USA

Casey J P (ed.) 1980 *Pulp and Paper Chemistry and Chemical Technology V.2,* Wiley & Sons, New York NY