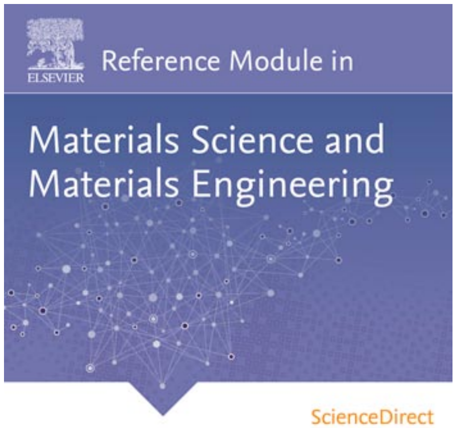

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Papermaking ☆

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1 Introduction

The operations involved in converting fibers and other materials 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. Production speed is 33 ms^{-1} for some grades. Papermaking has evolved from an art practiced by hand to a complex and technical manufacturing process with a high degree of automation. The principal steps of papermaking include stock preparation, forming to create a uniform wet web, pressing to remove liquid water, drying to evaporate most of the remaining water and consolidate the product, calendering to reduce the sheet thickness and improve the surface smoothness, and reeling to collect the dry product. All these operations are carried out on a single, large paper machine. Additional operations, such as winding to produce smaller rolls of paper suitable for printing or for further converting, the application of various additives onto the sheet, or super-calendering, may be carried out on- or off-machine to produce different grades of paper.

Many of the papermaking operations involve water removal. The development of sheet dryness as it proceeds along a typical paper machine is shown in **Figure 1**. 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 a web solids content somewhere between 38 and 50%. Drying is used only for the last stage of water removal, resulting in a final moisture content of the paper between 2 and 10%. In generally papermaking is regarded as an industry that consumes a great amount of energy and produces serious pollution (Li and Ma, 2015).

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

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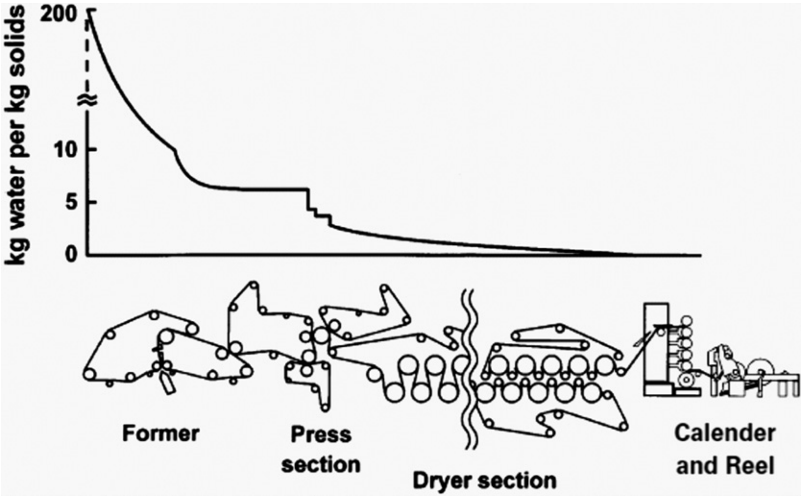

Figure 1 A large amount of dewatering occurs as the paper web proceeds down a typical paper machine, which includes forming, pressing, drying, calendering, and reeling sections.

2 Forming

Forming is the critical step of the papermaking process. The objective of forming is to drain water from a dilute fiber suspension deposited on a forming fabric, and to create a uniform fiber mat that has a sufficient consistency to be passed to the press section of the paper machine. Forming has a strong influence on a range of paper properties. A sheet with ideal formation would have a uniform mass distribution in the plane of the sheet with no flocs and no difference in fiber orientation at all points across the machine. Forming sets the fiber orientation in the sheet, which will influence the directionality of paper properties. As well, forming 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. It is thus useful to consider not only the process and equipment but also how the forming and drainage processes are coupled to quality.

Stock preparation is a series of operations in which the paper machine furnish is prepared for papermaking. The operations involved might include dispersion of dry pulp or paper in water, refining of pulp, blending of several pulps and the addition of fillers, dyes, or other additives. The prepared stock at a consistency of about 3% is stoved in a machine chest and is referred to as 'thick stock.'

According to Gamelas *et al.* (2014) the benefits of using mineral fillers in papermaking, particularly for the production of fine printing and writing papers, are widely recognized and thoroughly described in the literature (Antunes *et al.*, 2008; Ariffin *et al.*, 2012; Sang and Englezos, 2012; Shen *et al.*, 2010). But, for a fine paper grade with 60 g m^{-2} basis weight, values superior to 25% are uncommon and, at present, both fillers manufacturers and academia are focused in finding strategies for increasing the paper filler content.

2.1 Approach Flow System

The approach flow system includes all pumps, pipes, and apparatus through which the stock flows from the machine chest to the headbox. The function of the approach flow system is to provide a continuous, uniform flow of cleaned, screened, and deaerated fibrous suspension to the paper machine. Screens and centrifugal cleaners in the approach flow system remove large and heavy contaminants from the pulp. Some additives such as retention aids might be added to the pulp in the flow approach system. Dissolved and dispersed air may interfere with the formation, and is often removed from the pulp suspension. In the approach flow system, water drained during forming is used to dilute the thick stock from the machine chest from a mass concentration, or consistency, of about 3–1%. This low consistency is required to minimize fiber flocculation, which impairs the quality of formation.

2.2 Distributor and Headbox

The stock arrives through a pipe at the side of the paper machine. The function of the distributor and headbox is to convert the flow from the cross-direction to the machine direction and to spread the pipeline flow into a jet of full machine width, but only a few centimeters thick. The jet is then deposited onto the forming fabric. The uniformity of the jet has a considerable effect on the quality of paper formation. It is critical that the thickness and velocity of the jet is uniform across its full width, since this determines the uniformity of product basis weight.

Tapered headers are the most common type of flow distributor. The flow turns from the incoming pipeline into a bank of tubes, or holes in a drilled plate. 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 machine.

The stock flows through holes or tubes directly into the headbox, which may be either an air pad or hydraulic headbox. The air pad headbox was dominant until the early 1970s. In this design the flow from the tubes emerges into a chamber equipped with one or several rotating, perforated rolls. These rolls disperse flocs of fibers and provide a flow resistance that blends the jets emerging from individual tubes and minimizes side flows within the headbox, which could cause nonuniformity in the jet flow. This dampens out pressure disturbances in the incoming flow, which might otherwise produce basis weight variations. This headbox design is inappropriate for modern, wide, high-speed paper machines because its large chamber is not compatible with high stock pressures, and the long perforated rolls are easily deformed.

Hydraulic headboxes, commonly installed on modern paper machines, have no perforated rolls and usually no air pads. Instead, the flow from the distributor proceeds through deflocculating elements into a converging section, where it is accelerated to a speed close to that of the paper machine. Since the hydraulic headbox does not have a large-volume chamber, it can withstand the high stock pressures required to accelerate the jet to a high machine speed.

The jet of fiber suspension leaves the headbox through an adjustable slice consisting of two thin metal plates, referred to as the upper and lower lips. The basis weight, or amount of fiber mass deposited per unit area, is proportional to the flow of thick stock from the machine chest. The consistency of the suspension is controlled by the slice opening. Large adjustments to the slice lip opening are made when switching between different paper grades. Smaller adjustments are used to provide a uniform basis weight profile in the cross-machine direction. These adjustments are made at discrete locations, typically every 10–15 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 nonuniformities in the paper basis weight and fiber orientation. Very uniform basis weight profiles can be accomplished only with the assistance of sophisticated computer control.

The uniformity of basis weight profiles can also be adjusted by adding varying amounts of fresh water or white water entering the headbox, to modify the local consistency rather than the flow rate. 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 with respect to forming fabric. This angle affects formation, porosity, and other properties.

2.3 Formers

There are four main classes of former: cylinder-vatformers, fourdriniers, top formers, and gap formers.

(a) Cylinder-vatformers: Cylinder-vatformers were common in the past, but they are not suitable for high-speed operations. Today they are used mainly on multiply board machines.

(b) Fourdrinier formers: The fourdrinier was dominant from the early 1800s until the late 1960s. 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 machine direction alignment in the fibers. Consequently, the tensile strength will be much greater in the machine direction of the paper than in the cross-machine direction.

The forming fabric carries the suspension over foils, which generate pulses of suction and promote drainage of the water. The leading edge of successive foils skims water from the fabric surface. The pulses also cause lateral movement of the fiber suspension, which promotes even distribution of fiber and improved formation. In the past, table rolls were used to support the forming fabric. However, at high machine speeds table rolls generate excessive pressure pulses, which can disrupt the fibrous mat. Table rolls can still be found on some old, slow machines.

The resistance of the mat to drainage increases as water is drawn off. The mat is then drained over suction boxes with progressively higher levels of vacuum to a consistency of 8–10%, and over a suction couch to reach a solids content of 15–25%. The design of the forming fabric, 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 fiber, 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 might be depleted of fines, filler, and other small particles, which can lead to problems with print quality, curl, and other properties.

(c) 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 consists of a conventional fourdrinier table having a second fabric applied on top of the mat at the point where consistency of the web is about 2%. The fibrous mat sandwiched between the lower and upper forming fabrics proceeds 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.

Top formers were installed on many conventional fourdriniers in the early 1980s. However, they did not completely eliminate two-sidedness, since the initial drainage still occurs from only one side.

(d) Gap or twin wire formers: The gap former uses two fabrics for the full length of the forming section to minimize two-sidedness and maximize drainage. It is the dominant choice for new formers where surface quality and machine speed is critical.

A typical configuration has a hydraulic headbox with the jet impinging at the nip where two fabrics come together. The previous discussion of fabric selection, jet impingement, and jet to fabric speed differentials apply in a similar manner to the fourdrinier. However for a gap former, the fiber mat is contained between the two forming fabrics that wrap around a forming roll and a series of forming blades, mounted on a forming 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. Associated pressure gradients provide an opportunity to redistribute fibers and improve formation. The quality of the paper sheet is strongly dependent on the quality of pulp, the uniformity of the headbox jet, and the design of forming fabrics. While roll–blade formers are most common on new machines, some gap formers have only blades or only a pair of rolls.

3 Pressing

The key objective of pressing is water removal from the wet web, although two other results of pressing, namely improvements of 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 that occur in pressing cause a three- to fourfold increase in 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, is deficient in wet web has a low density, strength, and smoothness, and is poorly suited for use as a printing base or packaging product. Only 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.

3.1 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^{-1}. 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 that 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 20–40 mm wide, resulting in a nip residence time of only 1 ms at a machine speed of 30 ms^{-1}. 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 with a 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 with very short nip residence times such as those machines operating at high speeds 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 replacement of one of two press rolls with a hydraulically loaded shoe. 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 10 times greater than in nips formed by conventional roll presses.

3.2 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 1950s the first open draw occurred between the former and the first press, and frequent breaks at this point limited the machine speed to about 11 ms^{-1}. On modern paper machines the first open draw occurs in the press section, and therefore this is the point 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 multinip 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 a higher solids content and is stronger, which improves the paper machine runnability. Open draws have been eliminated from the wet end of some new paper machines of the future to permit higher operating speeds.

3.3 Press Fabrics

The role of press fabrics is to distribute evenly 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 fibers. During its life, which might range 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.

3.4 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 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 unknown. 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 nonlinear 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, which is a product of nip pressure and the duration of pressure pulse. 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 the sheet temperature. Increasing the temperature has a similar effect on the results of pressing as does increasing the press nip impulse, namely that the sheet solids content is higher 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. A heated press roll can also be used to heat the sheet, but this method is not commonly used. Considerable development of a technique commonly referred to as 'impulse drying' has been carried out. In this approach the sheet is pressed using a press roll heated to a temperature around 300 °C. Impulse drying, which is more closely related to pressing than it is to drying, has yet to be used on a commercial machine. It is likely that the potential for improving pressing by further increasing the sheet temperature will be exploited in the future.

3.5 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.

4 Drying

In drying, the web is heated and moisture is removed by evaporation. The principles of heat and mass transfer are integral aspects of the process. The high energy requirements of the dryer section make it the most expensive part of the paper machine to operate, and paper is dried only when a large portion of water is removed by drainage, suction, and pressing. Typically, the web leaves the press section and enters the dryer section of a paper machine at a moisture content around 60%. 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 additional binders. Capillary forces developed during drying draw the fibers into close contact, providing in the fibrous network numerous sites for bonding. The final product quality is greatly dependent on drying.

4.1 Multicylinder Dryers

The conventional multicylinder drying section used to dry most paper and paperboard is the longest part of the paper machine, sometimes having up to 90 cylinders. 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 thickness of 2.5–4 cm. The cylinders are pressure vessels typically rated for 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 siphon along with some of the uncondensed steam, known as blow-through steam. The dryer is usually covered by a canopy or hood that may be partly or fully closed. This serves to exhaust the humid drying air and facilitates the recovery of energy for reuse. Hot, dry make-up air is continually supplied to the hood.

A typical cylinder dryer consumes 1.5 kg of steam per kilogram of water evaporated. The overall drying rate depends on the grade and the basis weight of the paper, and varies between 3 and 8 $gs^{-1}\ m^{-2}$ for steam temperatures in the range 100–190 °C.

The cylinders are usually arranged in sections having upper and lower tiers, through which the paper travels in a serpentine fashion. The configuration, in which each tier has an endless felt or fabric to press the sheet against each dryer to maximize heat transfer, 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 that 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 rather than an upper and lower fabric is used. Some single-felted dryer sections are built with a single tier of heated cylinders. Since the cylinders coming into contact with the fabric rather than the paper in a single-felted system provide little heating of the sheet, they are often replaced by plain or vacuum rolls. Single-tier sections are sometimes 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. The sheet is heated from one side only. The single-tier arrangement improves machine runnability, which becomes critical as machine speeds approach 33 ms^{-1}. Drying rate on some new machines is enhanced by blowing of hot combustion gas onto paper from a hood that surrounds the drying cylinder. This drying technique is expected to be widely used in the future.

It is important to achieve a uniform moisture profile across the width of paper. The web has a tendency to become wetter in the center, where the hood air is more humid than at the edges. If a uniform moisture profile is critical, the sheet can be overdried to a very low moisture level at the expense of operating efficiency. However, nonuniformities 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. Nonuniform moisture profiles cause difficulties in the subsequent operations such as coating, calendering, and winding, and may result in overdried or grainy edges, baggy or slack areas, and poor reel building. Other drying-related defects may include the following: blisters caused by an overheated cylinder; brittleness and loss of strength from over-drying; machine direction dryer wrinkles from a variety of causes, including misalignment, improper tension, or excessive flutter in the draw; felt seam marks or holes in the sheet from dripping of condensed vapor in the hood; and poor surface finish because of dirt on the cylinder.

4.2 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 of around 7.5 cm. Apart from their size and the special design considerations that 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 decreasing 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 that greatly increase the drying rate by blowing jets of hot gas onto the paper surface. Jet velocities of around 200 ms^{-1} and jet temperatures up to 700 °C can be found on the most modern impingement hoods. Drying rates are around 560–1400 gs^{-1} 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 microridges 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 a 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 the creping doctor is not used and the surface of the cylinder is more highly polished. 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 that achieve the same finish and are simpler to operate.

4.3 Other Types of Dryer

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 noncontact drying use combined convective and infrared drying systems. 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 nonrestrained drying to induce product strength properties use air flotation drying. This technique uses high-velocity hot air streams from alternate air bars on both surfaces of the web for simultaneous floating and drying. Air flotation dryers are commonly used for drying thick sheets of market pulp. 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.

Much effort has been devoted to the development of press drying and impulse drying since the 1980s. In these concepts the distinction between pressing and drying is blurred since they are performed simultaneously to achieve high drying rates and special product properties. A few commercial 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.

4.4 Heat and Mass Transfer During Drying

Paper is dried at temperatures well below the boiling point of water. 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 multicylinder 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, shell thickness, contact resistance at the paper–cylinder interface, and the web itself.

Increases in the drying rate can be achieved by increasing the heat transfer to the paper, which is the rate-limiting step for the greater part of the drying. This can be done by increasing steam pressure, which increases 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 siphon arrangements, increasing the turbulence of the condensate layer through the use of longitudinal dryer bars inside the cylinder, keeping the inside and outside surfaces of the shell clean, and decreasing the contact resistance by increasing the fabric tension.

For 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 low basis weights used for these grades.

After a sufficient amount of heat has been transferred to the wet web, a given mass of water vapor is transferred 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.

4.5 Effects of Drying

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

During drying, shrinkage of individual fibers in the radial direction induces shrinkage and cockle unless paper is restrained. Shrinkage begins to occur at about 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. Restraint during drying reduces hygroexpansivity, and improves the dimensional stability of the sheet. Nonuniform drying stress in the thickness direction of the paper, as occurs in single-sided drying, causes the sheet to curl. Pressure in the thickness direction during drying increases the sheet density and lowers its porosity.

Multicylinder 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 nonuniform 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 multicylinder drying.

5 Calendering, Winding, and Reeling

5.1 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 accumulate, 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. Linear nip loads do not usually exceed 150 kN m^{-1}. 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 fibers 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 is decreased by increasing the 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 lose their opacity. This defect occurs more readily if the sheet moisture content is high. Printing papers made from mechanical pulp may lose as much as 30% of their tensile strength during calendering, since compression of the sheet in the dry state causes 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 about 400 kN m^{-1}. Supercalenders are usually self-standing machines, used on coated paper and board to obtain high-gloss products.

Hot–soft calenders installed at the end of a paper machine can also be used to obtain gloss and smoothness values approaching those produced by supercalenders. These calenders usually consist of two or four nips formed by a metal roll heated to 160–200 °C and a 'soft' roll with a synthetic cover.

5.2 Reeling and Winding

At the end of the paper machine, the dried and calendered sheet is reeled onto a large-diameter spool to produce large reels of paper called parent or jumbo rolls. The full machine width rolls obtained on the reel weigh several tonnes 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.

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. Roll density should be highest near its core and gradually decline toward 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 bursts 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. Therefore, reeling and winding are as important for the final product quality as any other papermaking operation.

6 Surface Treatment

The most common forms of surface treatment after drying involve 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.

Sizing agents such as starches and binders can be applied to dry paper or board 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 achieved off- or 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, blade, and metered film transfer coaters can be used to spread coating onto paper. 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.

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