Rate-limiting Mechanisms of Water Removal during the Formation, Vacuum Dewatering, and Wet-pressing of Paper Webs: A Review

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Because some of the critical events during the removal of water before the dryer section on a paper machine happen very rapidly within enclosed spaces – such as wet-press nips – there have been persistent challenges in understanding the governing mechanisms. In principle, a fuller understanding of the controlling mechanisms, based on evidence, should permit progress in achieving both higher rates of production of paper and more reliable control of paper attributes. In addition, energy can be saved, reducing environmental impacts. The goal of this article is to review published work dealing both with the concepts involved in water removal and evidence upon which existing and new theories can be based. The scope of this review includes all of the papermaking unit operations between the jet coming from the headbox and the final wet-press nip of an industrial-scale paper machine. Published findings support a hypothesis that dewatering rates can be decreased by densification of surface layers, plugging of drainage channels by fines, sealing effects, flocculation, and rewetting. Ways to overcome such effects are also reviewed.

Keywords: Drainage rate; Hydrofoil; Vacuum flatbox; Couch roll; Press felt; Extended-nip press

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Contents

INTRODUCTION

Given the capital-intensive nature of papermaking operations, there is a strong motivation to achieve high rates of production on the paper machine itself. Many paper machines are drier-limited, meaning that the maximum rate of production is essentially limited by the ability of the system to evaporate water from the sheet (Paulapuro 2000). In such situations, by achieving higher solids content in the wet-web of paper by the time it leaves the final nip of the press section may lead to a higher speed of production. In addition, a high-solids web entering the press section typically yields higher runnability in the press section; not only is the web stronger, but less water needs to be removed. Higher nip loading may then be possible, leading to higher outgoing solids and ultimately higher overall production (Räisänen 2000a).

The production of pulp and paper requires large amounts of energy, but much of that energy comes from the incineration of biorenewable resources. In particular, the combustion of lignin in the black liquor from alkaline pulping processes can provide a major proportion of the steam and electrical energy needed to run paper mill equipment and evaporate moisture as the paper is being dried (Empie 2009; Bajpai 2017). However, most pulp and paper facilities share power with the electrical grid, and others use any excess steam for heating of nearby facilities. As a consequence, savings in energy usage during papermaking can provide large benefits for both profitability and the environment. In addition, steam that can be saved by improved efficiency of dewatering can be used for other purposes in the mill, such as the drying of market pulp.

As a general rule, the removal of water from paper during its production tends to become increasingly expensive, on a mass basis, as the process proceeds (Kullander *et al.* 2012). Gravity drainage through a screen can require large amounts of capital expense, but in other respects it is very cost-effective. Removing water from a paper web by means of vacuum boxes requires the running of vacuum pumps (Räisänen 2000a), and increased electrical power is needed to overcome the friction between the forming fabric and the cover of each vacuum box (Eames and Moore 1976; Hansen 1985). It has been estimated that vacuum boxes can consume one-fifth of the electricity used on a typical paper machine (Håkansson 2010; Nilsson 2014b). Since evaporation requires the highest amount of energy, based on the mass of water, there is an inherent advantage when the web solids are as high as practical once it leaves the final nip of the wet-press section (Afshar *et al.* 2012).

The manner of water removal during paper manufacturing also has a large impact on product quality. Examples of paper attributes that can be profoundly affected by water removal procedures include wiremark, pinholes, densification of surface layers, as well as the overall density, smoothness, and porosity of the resulting paper. Published literature dealing with the dewatering of paper tends to be disproportionately represented by some of the most traditional designs of equipment, such as the Fourdrinier forming section, in which filtrate (or “white water”) is mainly removed through the bottom side of the wet web. Readers will need to bear in mind that a corresponding emphasis in the present review article is partly a consequence of what topics have been most studied. It seems likely that many of the principles that can be derived from study of Fourdrinier dewatering and conventional wet-press nips, *etc.* can provide insights into other kinds of forming devices and presses, *etc.*

In addition to the practical issues mentioned above, a further motivation for the present review article is scientific curiosity. Much progress has been made in predicting the effects of various factors on different water-removing unit operations in paper machine systems (Ingmanson 1964; Wahlström 1969; Kerekes and McDonald 1991; Ramarao and Kumar 1996; McDonald *et al.* 2000; Nilsson 2014a; Koponen *et al.* 2016; Sjöstrand *et al.* 2017, 2020). But there are remaining questions concerning the implications and underlying assumptions used in the related models. Some key issues to be considered in this article include non-uniform distributions of solids within the paper web during water removal, mechanisms by which water removal rates can deviate from the predictions of some established models of dewatering, and mechanisms of rewetting of the paper web after vacuum dewatering and after wet-pressing. By better understanding the underlying causes, there may be opportunities to improve the design and adjustment of papermaking equipment, and optimize papermaking chemical programs to achieve better overall results.

Earlier Review Articles

As shown in Table 1, there have been many previous review articles and chapters dealing with water removal during papermaking processes. Regarding the historical development of studies of wet-pressing, MacGregor (1989) has provided a detailed overview. The present article attempts to build upon the existing progress, as documented in the works shown in Table 1, but with an emphasis on some phenomena that are not easily included in mathematical models.

Table 1. Notable Review Articles Dealing with Water Removal before the Dryer Section of Paper Machines

Focus	**Key Points**	**Citation**
Filtration	Fundamental principles of industrial filtration	Carman 1938
Surface area	Permeability tests to determine surface area	Sullivan & Hertel 1942
Filtration	Approximate theories of filtration and retention	Nelson 1964
Wet pressing	Compressibility and permeability of fiber mats	Han 1969
Economic aspects	Energy-saving technologies	Manfield 1986
Wet pressing	Historical perspective, analysis, commentary	MacGregor 1989
Forming of paper	Overview of the physics of forming	Norman 1989
Chemical effects	Retention & drainage aids promote dewatering	Allen & Y. 1991
Wet pressing	History and future trends	Paulapuro & N. 1991
Vacuum box	High-vacuum dewatering, dwell time, fines	Räisänen 1996
Hydrofoil effects	Table activity *vs.* paper uniformity & dewatering	Kiviranta 1992
Vacuum box	Factors affecting performance of suction boxes	Gagnon & Neun 1996
Vacuum box	Geometry of the box, cover material, and vacuum level control and progression	Baldwin 1997
Wet pressing	Accounting for the total compressive force	Paulapuro 2000, 2001
Wet pressing	Role of water within cell walls and fiber lumens	Paulapuro 2001
Vacuum box	Theory & empirical work, including air-flow	Ramaswamy 2003
Chemical effects	Chemical effects related to mat permeability, sealing, and plugging of drainage channels	Hubbe & Heitmann 2007
Vacuum box	Web compression, displacement of water by air, and rewetting	Åslund & Vomhoff 2008a,b
Plugging	Permeability reduction in packed beds and fiber mats due to plugging of drainage channels	Hubbe *et al.* 2009

Organization of the Article

The remainder of this article will be organized into four main sections, of which the next will be very short – introducing some working hypotheses. Next, to provide background, the operations of key dewatering equipment present in typical paper machine systems will be described. Then the next section will consider various mechanisms to account for dewatering effects, along with reported evidence relative to such mechanisms. Finally, before the concluding statements, a section will be devoted to strategies for achieving more effective dewatering in various unit operations of papermaking.

WORKING HYPOTHESES

Purpose of Proposing Hypotheses

A set of hypotheses will be considered in this article as a means to focus the discussion. Some of these hypotheses may pertain to more than one unit operation of papermaking. The overall goal is to provide background for more realistic prediction and estimates of dewatering effects in the future. There is a well-known saying that every mathematical model is incorrect, but some of them are useful (Box 1976). Early concepts that have been used to fit dewatering data from papermaking operations tended to be overly simple, not accounting for the compressibility of the materials (Sullivan and Hertel 1942). But even with advances in mathematical approaches, some aspects, such as the plugging and sealing to be described in this work, are inherently difficult to capture in a mathematical sense. Thus there is a need for creative work to incorporate additional mechanistic features into quantitative estimates of dewatering rates.

The Hypotheses

The hypotheses to set the stage for discussions in this article are listed in Table 2.

Table 2. Some Working Hypothesis Concerning Factors Affecting Rates of Release from the Wet-web of Paper During its Manufacturing

#	Brief Name	Hypothesis
1	General	It is proposed that changes in the relative positions of solids in the wet web of paper, in response to hydrodynamic and other forces, including changes in density *vs.* position, can play a major role with respect to dewatering rates in various unit operations of papermaking.
2	Densification	It is proposed that densification of the surface layers of the wet-web of paper, as generally observed adjacent to a surface from which water is leaving the web during dewatering, can have a dominant effect on dewatering rates, depending on the conformability of the fibers.
3	Plugging	It is proposed that relative movement of cellulosic fine material within paper, especially during its formation, can have a major effect in decreasing the rate of dewatering, especially when both the basis weight and the content of fines are relatively high.
4	Sealing	It is proposed that hydrodynamic forces pressing against conformable cellulosic fibers, as in the case of well-refined kraft fibers, can create a sealing effect, and that such effects can contribute to a significant decrease in the apparent permeability of forming fabrics. Two types of sealing can be distinguished. First is when a fiber, due to its conformability and position, is able to partly or fully block an opening in a forming fabric, *i.e.* fabric sealing. Second is when, in a layer of fibers, their mutual conformability, applied stresses, and the flow of water result in a sealing off of passages to water to flow between them.

5	Flocculation	It is proposed that the clustering of fibers, which can be a consequence of their crowded nature, *i.e.* their relatively high aspect ratio and the prevailing headbox consistency, can create a situation unfavorable to dewatering by vacuum or in the wet press. It is further proposed that such effects can be made worse by addition of chemical flocculants, *e.g.* retention aids.
6	Healing	It is proposed that at sufficiently low consistency and relative absence of flocculating agents, the paper forming process will allow fiber solids to follow streamlines of flow and thereby "fill in" relatively thin or low-density areas of the paper web, with significant effects happening within dimensions of about 2 mm or less.
7	Rewetting	It is proposed that significant rewetting takes place by a combination of three factors, *i.e.* film splitting during separation of the paper web from a forming fabric or felt, interfacial tension forces due to the meniscus at the surface or within the wet web, and additional capillary forces associated with the viscous flow of water within tight channels within the wet web as it expands after leaving a point of vacuum application or after a press nip.

PAPER MACHINE DEWATERING OPERATIONS

Paper Machine Overview

The scope of the discussion will begin more-or-less as the suspension of cellulosic fibers and fine matter (*i.e.* the "thin stock") emerges as a wide jet from the headbox of a typical paper machine and heads toward a forming fabric or fabrics. The fabric or fabrics will likely then pass over such dewatering elements as hydrofoils, forming blades, and vacuum boxes, and a vacuum couch roll. Then the paper will pass through a series of wet-press nips, which are often three in number, after which any additional water to be removed will require evaporation, which is the slowest and most expensive process, based on the mass of water to be removed.

Before discussing each of the main unit operations associated with dewatering, an overview is provided in Table 3, giving some approximate ranges for the consistency (percent filterable solids), as well as the main types of forces affecting dewatering in each operation.

Table 3. Overview of Unit Operations Contributing to Dewatering in a Paper Machine System

Unit Operation	Consistency Range (%)	Main Forces Affecting Dewatering
Impingement of jet on forming fabric	0.15 to 1.2	Inertia; shear due to jet-wire speed difference
Forming board	0.15 to 1.2	Delay of filtration
Hydrofoils	0.4 to 4	Initial pressure pulse; main suction pulse
Vacuum boxes	2 to 18	Doctoring; suction compression and filtration; rewetting
Vacuum couch roll	14 to 20	Suction compression and filtration
Wet-press	16 to 55	Pressure filtration, then expansion, rewetting

In view of issues raised in the hypothesis statements (Table 2), one can consider how the dominant mechanisms affecting dewatering are likely to be different in different parts of the paper machine system. Early in the process, especially between the forming board and the dry line of a Fourdrinier paper machine, it is reasonable to expect a filtration mechanism to be dominant. After the dry line (meaning that the surface of the wet web no longer looks smooth and water-like), some additional terms may be used to describe aspects of the process. The term displacement dewatering will be used here to indicate sub-processes in which the water held within a wet-web of paper is being displaced by air. The term compression dewatering will mean that water is expelled when the net volume of air-free paper is decreased due to an applied pressure, resulting in outward flow of water. For example, it is reasonable to expect air to begin to displace water within the wet web once a sufficient level of vacuum is applied, using a suction box (or vacuum flatbox). The ingoing part of a wet press nip is clearly dominated by a compression mechanism. Rewetting phenomena can be important following certain vacuum dewatering and wet-pressing operations. All of these issues will be considered more deeply in the sections that follow.

Impingement of the Jet on the Wire

At the headbox of a conventional paper machine, the fiber suspension already has been prepared by mechanical refining and addition of selected chemicals. Because the stock at that point has been already diluted by process water (white water), it has the lowest value of consistency that it will achieve anywhere in the process. Part of the reason for the relatively low consistency at the headbox is to avoid excessive crowding of the fibers, which would lead to a flocky appearance of the paper (Kerekes and Schell 1992; Kerekes 2006; Hubbe 2007). The low consistency also facilitates the action of hydrocyclones, which remove dense particles such as sand from the stock before it reaches the forming section. However, the high proportion of water, for instance about 99.5% of the mass present in the jet coming from the headbox, presents a tremendous challenge. Not only must the water be separated from the solids, but also this must be done in a way that results in a relatively uniform distribution of fibers. In addition, those fibers individually need to be relatively straight, generally oriented within the X-Y plane of the paper. If there is a preferred orientation, the mean value of orientation needs to be aligned with the direction of manufacture, not at an angle.

Some basics related to the flow from the slice of a headbox have been explained concisely by Zhao and Kerekes (2017). A detail that is particularly worth noting, when attempting to predict what will happen to the jet of furnish coming from the headbox, is the fact that the thickness of the jet typically contracts after it emerges from the slice opening. The contraction factor can be as low as 0.62 when comparing the height of the slice opening with the thickness at the *vena contracta*, *i.e.* the point of highest velocity and minimum jet thickness.

An interesting conceptual model of dewatering, starting at the point of jet impingement on the forming fabric, was presented by Herzig and Johnson (1999). Figure 1 is a new drawing inspired by an original in the cited work, but with some clarifications and updated terminology. As depicted in the diagram, this model is consistent with a process of simple filtration, analogous to the formation of a paper handsheet from a highly dilute aqueous suspension (see TAPPI Method T205). The model envisions basically two phases present within the wet web. Near to the forming fabric, which is the point at which water is being removed due to pressure resulting from the inertia of the jet, there is a “mat” or “boundary layer” phase, where the consistency is distinctly higher than the headbox consistency (Herzig and Johnson 1999; Helmer *et al.* 2006). But above that zone, the rest of the wet web is modeled as still having essentially the same proportion of water as it did within the headbox. A key argument in favor of the essential validity of the relatively simple model presented in Fig. 1 is the fact that most fibers in a typical sheet of paper are oriented in a layered structure, as if they belong to a series of two-dimensional sheets (Kufereth 1982a). Though many additional concepts will be discussed in this review article, it will be important to keep in mind that a filtration mechanism tends to be dominant in typical papermaking operations.

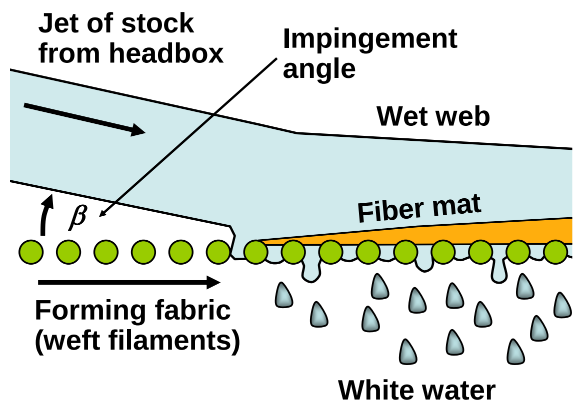

Fig. 1. Concept of paper mat buildup on the forming fabric of a Fourdrinier paper machine starting at the point of jet impingement (based on Herzig and Johnson 1999)

According to Herzig and Johnson (1999), resistance to the flow of water through a forming fabric will increase in direct proportion to the amount of fiber mass deposited onto it, at least up to an amount between 15 and 25 g/m^2. In fact, the flow-resistance attributable to the mat of fibers quickly becomes a more dominant factor than the flow-resistance of the forming fabric, especially if the pulp is well refined. The cited authors also pointed out something unique about the point of jet impingement on the forming fabric; that is the only location throughout the rest of the dewatering process where the momentum and inertia of the stock suspension itself provides a major component of force contributing to rapid release of water. Ingmanson and Andrews (1959) estimated that the velocity of water downward through the forming fabric near the beginning of the dewatering process can be as fast as 150 cm/s. Whether or not such rapid dewatering at the point of jet impingement is good papermaking practice will be questioned in later sections of this article, however, when some mechanistic issues are considered in more detail.

Three prominent aspects of the flow patterns associated with the jet impingement area can be called oriented shear, turbulence, and drainage (Parker 1972; Kufereth 1982a; Norman 1989, 2001; Kiviranta 1992). Oriented shear in the impingement zone comes from two sources. First, the fibers within the jet of furnish coming from the headbox tend to be preferentially oriented in the machine direction. Though the reasons for this orientation are not strictly within the scope of this article, they are related to elongational shear within the contracting zone of the headbox slice (Aidun 1998; Hubbe 2007). The other source of oriented shear is the fact that, in a great many cases, papermakers adjust the speeds of the jet and the forming fabric to be slightly unequal. The resulting “rush” or “drag” of the stock gives rise to oriented vorticity. This imparts an oriented rotational motion of elements of fluid, which further contributes to an average preferential alignment of fibers in the direction of flow or manufacture (Jeffery 1922; Stover *et al.* 1992; Orts *et al.* 1995; Gunes *et al.* 2008; Mortensen *et al.* 2008; Perumal *et al.* 2019). As part of this effect, an individual fiber can be drawn into machine-direction alignment when one end of the fiber is influenced by the fabric surface and the other end is influenced by fluid having a difference in velocity relative to the fabric. The word "turbulence" merely means that the flow is chaotic and contains multi-scale vortex flow (Aidun 1998). The word "drainage" means, in the case of a Fourdrinier paper machine, that there is a net movement of water downwards.

As will be discussed in more detail later in this article, there is some evidence that interactions between individual fibers at the forming fabric sometimes can result in resistance to dewatering that would not be predicted from either the fibers or the fabric alone. Such effects, even when imprecisely defined, have become known as "sheet sealing" or perhaps more accurately as "fabric sealing" (Kufereth 1983). In particular, it has become accepted wisdom among some papermakers that fabric sealing tends to be more of a problem if initial drainage is too rapid, for instance when the angle of impingement of the jet onto the forming fabric is too steep.

Forming Board Issues

The function of a forming board, though consistent with the issue of fabric sealing, may at first seem out of step with an overall goal of removing as much water as practical from paper in a relatively short period of time. The forming board is a relatively flat platform just below the forming fabric of a Fourdrinier forming section that temporarily blocks or slows down the progress of water through the forming fabric. One can consider the forming board as a way to achieve a stable layer of suspension on top of a fast-moving fabric. Papermakers call this "setting the sheet". Typically about a quarter of the fluid is drawn from the impinging jet before the forming board so that no air can be drawn in between the forming fabric and the wet web when it is resting on the flat part of the forming board. Otherwise, the jet may bounce, creating an unstable situation and operational problems.

Hydrofoils (Fourdrinier paper machines)

Though terms such as "gravity drainage" are widely used within the paper industry (Britt 1981; Ahonen *et al.* 1992; Rezk *et al.* 2013; Nilsson 2014b; Singh and Green 2015), there are essentially no modern paper machines that rely on gravity alone during the formation of the sheet. During the early years of Fourdrinier-type papermaking, the forming fabric was held horizontal by "table rolls," which were found to provide some benefits in terms of dewatering within favorable speed ranges (Victory 1969; Cadieux 1983; Zhao and Kerekes 2017). Wrist (1954) and Taylor (1956, 1958) provided a way to estimate the suction that can occur just behind the mid-point position of a table roll. Such suction helps to remove water from the wet web. The subsequent release of suction creates instabilities that, in moderate amounts, can improve the uniformity of formation. However, as further developments of technology allowed paper machine speeds to climb well beyond 300 m/min, surface instabilities caused by the sudden release of suction produced by table rolls became strong enough to disrupt the wet webs.

The problems with table rolls, as mentioned above, were overcome by the development of hydrofoils (often called "foils"), which are illustrated schematically in Fig. 2. The original development is attributed to Burkhard and Wrist (1956) of the Quebec North Shore Paper Co. The design of the most basic type of hydrofoil can be described as having a land area parallel to the forming fabric, followed by a surface having a diverging angle, often about 3 degrees (Miller 1998). Typical widths of blades were estimated to be about 50 to 89 mm. Hydrofoils became widely used after the introduction of plastic-type forming fabrics, which are many times more durable than the bronze "wires" that had been used on paper machines up to that point (Zhao and Kerekes 2017). Though hydrofoils have been found to be effective for removal of water during the initial part of a Fourdrinier forming section, they do not have the ability to achieve high levels of solids, as indicated in Table 3.

Two types of pressure effects are believed to act upon the wet web of paper as it passes over a typical hydrofoil. First, at the leading edge of the hydrofoil it is expected that some water will tend to be pushed up into the wet web, *i.e.* a brief pressure pulse (Eames 1993). Then, especially as the web passes over the area where the hydrofoil surface diverges from the linear path of the forming fabric, a vacuum event is expected (Taylor 1958). Cadieux (1983) reported that the maximum vacuum is generated relatively early as the sheet passes over a hydrofoil. These pressure and vacuum effects are indicated schematically in Fig. 2, which indicates a suction effect occurring where the surface of the foil is diverging from the linear path of the fabric. In addition to tending to dewater the wet web, the action of the hydrofoil tends to promote microturbulence within the wet web. The intensity of microturbulence (which is often called "action") can be judged from the appearance of images obtained with stroboscopic illumination (Miller 1998). The intensity of microturbulence can be optimized by adjusting the design, alignment, and spacing between subsequent hydrofoils (Kawka *et al.* 1981; Ahonen *et al.* 1992; Miller 1998). Also, various details of the shape of a hydrofoil can be changed (Sodergren and Neun 2000).

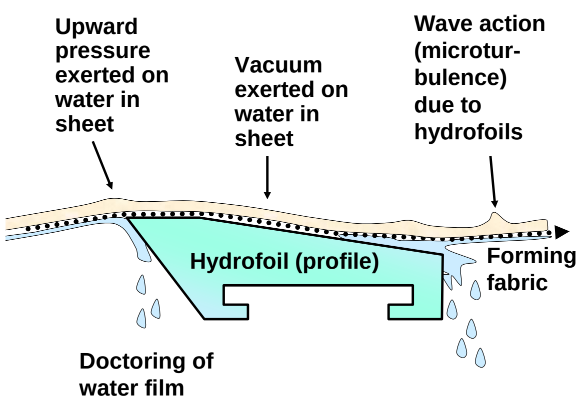

Fig. 2. Schematic diagram of a hydrofoil below a forming fabric with a wet-web of paper on it. Deflections are greatly exaggerated in the depiction as a means to suggest the mechanisms of action.

Another consequence of hydrofoil action is a partial refluidization of the wet web structure; this results in a washing out of cellulosic fines and other small particles, especially those near to the "wire-side" of the paper web (Eames and Moore 1976; Sodergren and Neun 2000). Neun and Fielding (1994) suggest that washing effects become much less important above a solids content of about 6% due to increasing strength and integrity of the wet-web structure. Such washing and refluidization effects happening in real paper machine forming sections appear to explain the poor correlations often observed between ordinary freeness and drainage tests, using simple equipment, in comparison to results of commercial trials on paper machines (Persson and Österberg 1969; Britt 1981; Hubbe *et al.* 2006).

Forming Blades (some gap-former paper machines)

Though published information about dewatering events on Fourdrinier (single forming fabric) paper machines is more abundant, some excellent studies have been reported having to do with dual-fabric paper machine designs (gap formers, which are also called twin-wire formers), which have become dominant in recent paper machine installations. In situations where a wet web of paper is sandwiched between a pair of forming fabrics, the function of a hydrofoil is generally replaced by a forming blade, which touches the outside surface of one of the forming fabrics over a very brief distance (Norman 1987, 1989; Räisänen 2000b; Wildfong *et al.* 2003; Zhao and Kerekes 2017). As shown by Brauns (1986) of the Beloit Corporation, as the sandwich of two forming fabrics passes a blade, with a wet web of fibers between them, there is a quick rise in pressure, followed by an abrupt fall. The mathematics to account for the effects were presented by Zhao and Kerekes (1995, 1996) and by Zahrai and Bark (1995). It has been shown that these sharp changes in pressure cause displacement of material in the middle of the wet web opposite to the direction of manufacture by as much as 3 to 9 mm (Zhao and Kerekes 1996). Two main consequences of such displacement of material are an improvement in the uniformity of formation and an increased tendency for machine-direction alignment of fibers. As shown by Akesson and Norman (2006), fiber flocs in the sheet can become elongated and ruptured by such movement.

Vacuum Boxes

The idea behind vacuum dewatering is simple: apply vacuum and remove water from the paper. However, as discussed in review articles on the topic, there are many questions and details about vacuum dewatering that are not yet fully resolved (Räisänen 1996; Baldwin 1997; Räisänen 2000a; Roux and Rueff 2012). One clear consequence of vacuum box application is a compression of the wet web (Campbell 1947; Nordman 1954; Ingmanson 1964; Jönsson and Jönsson 1992a,b; Åslund and Vomhoff 2008b,c; Åslund *et al.* 2008). This water removal process is called *compression dewatering*. Another, equally important consequence (after the dryline) is air flowing into the fiber network and forcing water out of the fiber network. This process is called *displacement dewatering* (Åslund and Vomhoff 2008b).

On a traditional Fourdrinier paper machine, the first vacuum boxes to interact with the paper web are the low-vacuum ("lo-vac") boxes. Figure 3 presents a schematic diagram of such equipment. A distinguishing attribute of the type of equipment shown is the use of water itself to generate the needed vacuum as it flows down tubes by gravity to a seal chest located in the basement of the paper mill. The cover is typically composed of ceramic or a hard plastic, and there are slots or holes in the cover.

For reasons that will be discussed later in this article, it is conventional practice to steadily increase the levels of vacuum applied in successive groups or individual flat boxes along the machine direction of a paper machine forming section (Eames and Moore 1976; Baldwin 1997; Jones 1998). Evans (1997) has provided a useful overview of control technology for vacuum levels on the paper machine. When the needed vacuum levels become too high to be practically generated by the siphoning action of water moving down in tubes, it is then necessary to use a vacuum pump. The use of a vacuum pump can be regarded as the practical demarcation between low-vacuum and high-vacuum boxes.

Typically, the slots on a modern vacuum flatbox are in the range of 13 to 25 mm in width (Räisänen 2000a). Thus, at typical speeds of paper machines, the vacuum pulse is often in the range of half of one ms to several ms. When similar devices are employed in twin-wire forming systems, the term "suction shoes" has been used (Roshanzamir *et al.* 2000).

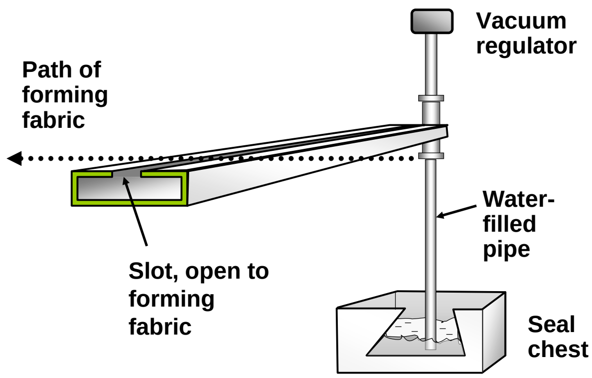

Fig. 3. Schematic diagram of a low-vacuum flatbox

Many studies have shown that when vacuum is applied at the same level continuously to a wet web, the moisture content will tend toward an asymptotic value (Norman 1989; Clos *et al.* 1994; Neun 1994, 1995, 1996; Räisänen 1995b; Jones 1998; Räisänen 2000a; Pujara *et al.* 2008a,b). According to Jones (1998) the relationship between ultimate achievable dryness and the dwell time is a hyperbolic tangent. Koponen *et al.* (2012) studied vacuum dewatering with a filtration device, enabling pressure differences up to 70 kPa. For LWC paper the solids content rose to 11% already at a vacuum of 25 kPa, whereas for SC fibers the solids content rose to 14% at 40 kPa. This suggests that the repeating compression – expansion cycles due to the sheet traveling on the forming board from a vacuum box to a vacuum box are beneficial for water removal.

At the leading edge of a vacuum box, depending on details of geometry, there is often a doctoring effect, by which water is skimmed off from the underside of a Fourdrinier forming fabric (Attwood 1960, 1962; Miller 1998). According to Miller (1998), such a doctoring effect has been incorporated into the design of vacuum boxes preceding the dry line, *i.e.* the position on a Fourdrinier table in which the sheet no longer appears glossy due to increasing consistency.

Though vacuum boxes can be very effective for the removal of water from paper, they have some characteristic problems. As already mentioned at the opening of this article, a consequence of vacuum forces holding the forming fabric against the covers of flat boxes is friction, which needs to be overcome by the electrical motor driving the forming fabric (Eames and Moore 1976; Hansen 1985; Skalicky *et al.* 1991a,b; Räisänen 2000a). The back surface of the forming fabric tends to get abraded over time, especially if sand particles become embedded in microscopic cracks in the covers of vacuum flatboxes (Eames and Moore 1976; Skalicky *et al.* 1991a). Another inherent problem is the development of pinholes in the paper (Campbell 1947; Eames and Moore 1976), which often can be attributed to entrained air bubbles that get pulled through the wet web by the force of vacuum. Finally, the strong forces pulling the wet web toward the wire can leave a lasting imprint on the paper, called wire marking (Eames and Moore 1976). Brundrett and Baines (1966) estimated that high vacuum may be able to exceed the threshold of capillary pressure, giving rise to pinholes of about 51 µm or larger.

At some point, the level of vacuum will be sufficient to pull air through the wet web (Brundrett and Baines 1966; Åslund and Vomhoff 2008b). As was shown by Britt and Unbehend (1985), a non-uniform formation of the wet web can render vacuum dewatering much less effective. The presumed reason is that air is able to essentially leak through thin areas of the paper, using up vacuum pumping energy without effectively removing the water from the denser, floc areas of the paper.

The air flow can be decreased by adding microfibrillated cellulose to the pulp. In (Koponen *et al.* 2015) the addition of microfibrillated cellulose (MFC) slowed down the drainage of handsheets but increased the final consistency. The same effect was observed at the pilot scale; the consistency was increased after the forming section when MFC was added. A possible reason for this behavior is MFC's film-making tendency. In this situation, the MFC possibly seals the sheet surfaces so that the applied vacuum becomes more effective because less air is flowing through the sheet after the dry line. As the airflow through the sheet decreases, the vacuum compresses the sheet more, which leads to higher solids content after the forming section.

Vacuum Couch Roll

Before the wet web passes forward to the wet-press section, there is one more chance to remove water as it passes over a vacuum couch roll (Brundrett and Bains 1996; Hansen 1987), if one is present on the machine. Because the couch roll is rotating, with its outer surface matching that of the forming fabric, the problem of high frictional drag, which is characteristic of high-vacuum flatboxes, is avoided. Also, due to the increased structural integrity of the wet web, compared to earlier in the process, a higher vacuum can be applied. Hence, under favorable circumstances, solids levels in the range of 15 to 23% can be achieved (Räisänen 2000a).

Two key limitations on the feasibility of applying high vacuum at a couch roll are sheet marking and centrifugal acceleration. Couch marking occurs when the vacuum-induced forces are strong enough, relative to the structure of the wet web at that point, to shift material within the sheet, resulting in denser areas facing each suction hole in the couch. Such patterns can be highly undesirable, depending on the intended use of the paper product. In practice, sheet marking at the couch is avoided by maintaining a high enough solids after the vacuum flatboxes (Hansen 1987). In addition, centrifugal acceleration at the periphery of a rotating couch roll can make it increasingly difficult to remove water from the paper, even by high vacuum levels. The problem tends to become compounded in the case of fast, wide paper machines, where the couch roll must have a sufficiently large diameter to withstand the imposed bending stresses.

Wet-press (single-felted)

After leaving the couch roll of a conventional Fourdrinier paper machine, the next set of unit operations that has significant dewatering effect is the wet press. Reviews of wet-press operations include the following (MacGregor 1989; Paulapuro and Nordman 1991; Räisänen 1996; Paulapuro 2000, 2001; McDonald and Kerekes 2017b). It is important, before wet pressing, to reach a solids content of the web as high as possible. Wet pressing can be used only to a limited extent for fixing problems in sheet structure resulting from vacuum dewatering. Koponen *et al.* (2012) used a dynamic wet pressing simulator to show that differences in solids content after vacuum dewatering remained after wet pressing regardless of the press levels employed. Similar results were obtained in Koponen *et al.* (2015) at the pilot scale.

One of the most intriguing aspects of dewatering paper within a wet-press nip has become known as stratification (Campbell 1947; Schiel 1972, 1973; Chang 1978; MacGregor 1983a,b, 1989; Szikla 1986; Paulapuro 2000, 2001; McDonald 2020). The phenomenon is most evident when the paper web is dewatered in a single-felted nip. In such a nip, the water pressed from the sheet is constrained to move mainly in only one direction, from the paper into the felt. A dense layer develops adjacent to the boundary from which water is leaving the web. The dense layer persists when the paper is dried by evaporation (Szikla and Paulapuro 1989).

Further evidence that might be used to understand what is happening during wet-pressing can come from a little-known phenomenon that can be called “membrane formation”. As reported and discussed by MacGregor (2002), high-resolution micrographs of cross-sections of the surface of paper obtained after a wet-pressing operation sometimes show a very thin (1 to 2 µm) membrane that appears to be composed mainly of colloidal-sized cellulosic matter. This is present at, though often not fully attached to, the side of the paper from which the water had been removed during pressing. Though the evidence showing the existence of such a membrane seems quite strong, the phenomenon has not otherwise been reported, presumably due to experimental challenges in obtaining the needed micrographs. Also, there is no direct evidence that this membrane restricts water removal from the wet web of paper.

Early insights on what happens within a wet-press nip were explained by Bergström (1959). In his view, dewatering takes place mainly in the entering side of a wet press nip, where water is forced into the void spaces of the felt. Some of the expressed water then may return to the sheet (“rewetting”) in the expanding side of the nip (Bergström 1959; Sweet 1961; MacGregor 1989; McDonald and Kerekes 1995; McDonald *et al.* 2013; McDonald and Kerekes 2018).

There has been much discussion related to components of the pressure that resists the applied mechanical pressure within a wet-press nip (MacGregor 1989; Paulapuro 2000, 2001; Rogut 2009). According to Wahlström (1960, 1969), the resisting pressure can be described as the sum of structural pressure and hydraulic pressure. The concept appears to have been originated by Terzaghi (1943, 1960), who was modeling the flow of water through soil, which is often dominated by relatively incompressible matter such as sand particles. To apply such concepts to papermaking, by suitable experimental design, it has been possible to measure what appears to be the hydraulic component of pressure during simulated wet-pressing (Carlsson *et al.* 1977; Chang 1978; Carlsson 1984; Szikla and Paulapuro 1989). In general, higher components of hydraulic pressure have been observed or predicted in cases where the fibers had been refined, thus making them more resistant to dewatering.

The validity of applying the Tezaghi principle to paper webs has been questioned (McDonald *et al.* 2000; McDonald and Kerekes 2017b). Application of the Tezaghi principle to paper implicitly assumes that fibers support pressure in a manner that shields water from pressure. This is a misconception because the fibers are filled with a considerable amount of water, and the cell walls of the fibers are flexible and offer little mechanical resistance. Pressure applied in the press nip is exerted on both water between the fibers and water within the fibers. The rate of water removal is determined by the applied pressure and the average permeability of the fiber network. As dewatering proceeds, water is forced from smaller openings between and within fibers, making removal more difficult because of decreasing permeability, not diminishing hydraulic pressure. This concept is embodied in the Decreasing Permeability (DP) model (McDonald *et al.* 2000; Kerekes *et al.* 2013; McDonald and Kerekes 2017a,b). The applicability of Terzaghi's principle for soft porous media was assessed experimentally for highly compressible fibrous media by Kirmanen *et al.* (1994). The authors presented results showing deviation from Terzaghi's principle and proposed a phenomenological formula for a generalized effective stress under one-dimensional static compression.

Carlsson *et al.* (1983a,b) suggested that the resisting pressure ought to be regarded as a "mixture" of hydraulic and structural pressure. Also it has been suggested that what may appear, based on experimental findings, to be evidence of structural pressure may at least partly be due to water that is at least momentarily entrapped within such spaces as fiber lumens, the mesopores within fiber cell walls, or maybe also in isolated places between fibers that have been blocked off from flow (Kerekes and McDonald 1991; Paulapuro 2001). The ultimate possible dryness is a function of the surface tension of water in the pores of the fibers (Kerekes and McDonald 2020).

There is evidence that when water is forced out of the cell wall of a refined kraft fiber by means of applied pressure, there can be a permanent loss of swelling ability, an effect that has been called hornification (Han 1969; Carlsson 1983; Carlsson *et al.* 1983a,b; Weise *et al.* 1996; Maloney *et al.* 1999).

Though clearly there is substantial flow of water from a wet web into the felt during wet-pressing, there also can be flow within the plane of the sheet. This results when high hydraulic pressure develops within the material when it is highly pressed. As a result of the buildup of pressure within the material, some of the water within the central part of the wet web is delayed in its entrance into the nip in comparison to the outer layers of the wet web (MacGregor 1983b; Kataja *et al.* 1992). When the phenomenon becomes unstable and is sufficient to cause recognizable damage to paper properties, it is called "crushing" (Wahlström 1969; Francik and Busker 1986; MacGregor 1989). Damage is expected in situations where the hydrodynamic forces exceed the structural integrity of the web, as in the case where the incoming moisture content is excessive relative to other parameters (Wahlström 1969).

Wet-press (double-felted)

One very promising way to overcome the two-sidedness problems often associated with wet-pressing is to employ a pair of felts, *i.e.* using a double-felted nip (Bergström and Kolseth 1989). In addition to providing symmetry, such practices can effectively double the capacity for accommodating the removed water within the voids of the felts. However, double-felting for lightweight paper can sometimes lead to a wetter web because of rewetting on both sides of the paper (McDonald and Kerekes 2017a).

Wet-press (extended nip)

Another approach to being able to remove more water from a paper web with less distortion of the structure is to employ a nip that is longer in the machine direction, *i.e.* an extended nip press. The development and implementation of extended-nip technology has been one of the most important contributions to paper machine speed and efficiency in recent decades (Paulapuro and Nordman 1991; Schlegel *et al.* 1997; Cedra 1999; McDonald *et al.* 2013; McDonald and Kerekes 2017a). In principle, by increasing the area of pressing, the force applied per unit area does not need to be as high and the water has more time to permeate outwards. In addition, the press impulse (the product of pressure and time) can be high enough to achieve higher levels of dewatering in comparison to conventional wet-presses.

RATE-LIMITING MECHANISMS AND SUPPORTING EVIDENCE

After having, in the previous section, reviewed aspects of unit operations that remove liquid water from paper during its manufacture, the present section will consider mechanistic aspects of those processes. The focus will be on factors and mechanisms that tend to impede dewatering.

Generalized Cause: Relative Motion among Solids

Table 2 in the Introduction to this article presented a series of working hypotheses, of which the first and most general was as follows: It is proposed that changes in the relative positions of solids in the wet web, in response to hydrodynamic and other forces, including changes in density *vs.* position, can play a major role with respect to dewatering rates in various unit operations of papermaking. Relative motion can take several forms. For instance, as noted in the previous section, densified layers can be expected to form within the wet web of paper adjacent to where water is passing into a forming fabric (in the case of a vacuum box) or felt (especially in the case of a single-felted wet-press (MacGregor 1989). The distribution of fine materials can shift as a result of dewatering operations (Tanaka *et al.* 1982; Räisänen *et al.* 1995b). And the pressing-together of conformable fibers at the surface of a forming fabric can create a sealing effect (Sjöstrand *et al.* 2019); such an effect was highly apparent when using highly swollen dialcohol cellulose fibers. So the general hypothesis motivating this discussion is that these mechanisms, each related to relative motion among solid components of the wet-web of paper, can contribute significantly to the slowing down of dewatering rates. The question at hand is to what degree there is evidence to support such mechanisms as playing an important role during ordinary papermaking.

To begin the discussion, Fig. 4 provides simplified illustrations of several of the hypothesized mechanisms that have been proposed as being important in at least some cases in significantly impeding dewatering on a paper machine.

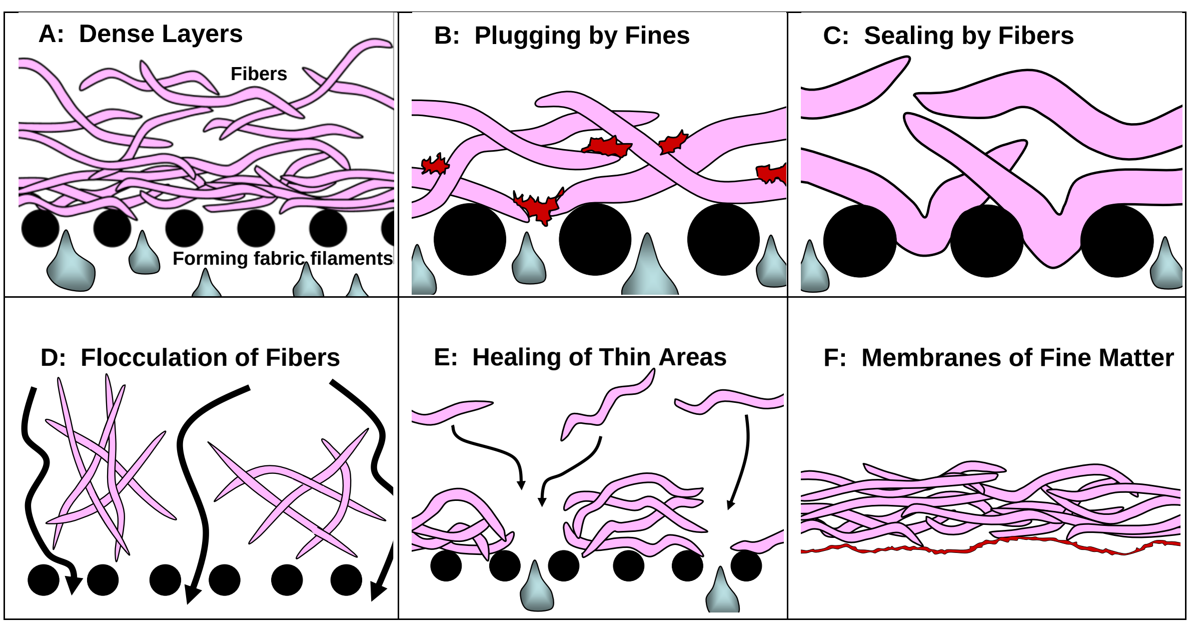

Fig. 4. Simplified schematics for six reported phenomena that appear to underlie various aspects of resistance to the dewatering of paper webs

Briefly stated, some of the factors associated with slow dewatering or resistance to vacuum or pressing can be described as involving dense layers, the plugging of drainage channels in the wet web by cellulosic fines, various sealing effects associated with the conformability of fibers, especially well-refined kraft fibers, inefficient response to vacuum due to flocculation, repairing of thin areas of paper by a healing mechanism, and finally the rarely-reported phenomenon of a thin membrane that may form on the surface of paper facing a wet-press felt. These and other phenomena will be considered later in this section, along with discussion of supporting evidence.

Typical Composition of Headbox Stock

The intent of this subsection is to provide sufficient background to facilitate discussion of mechanistic discussions that come later. This is intended especially for readers who don't have extensive experience with the composition and behavior of the fibers and other materials used in papermaking. This subsection might be skipped by other readers.

The amount of water that needs to be removed from solid matter during the preparation of a paper sheet cannot be overemphasized. Figure 5 illustrates the proportions of water, compared to solid matter, at various points of typical paper machine systems that produce a variety of paper products. Background information related to these unit operations, including discussion of hydrodynamic aspects, has been provided by Zhao and Kerekes (2017).

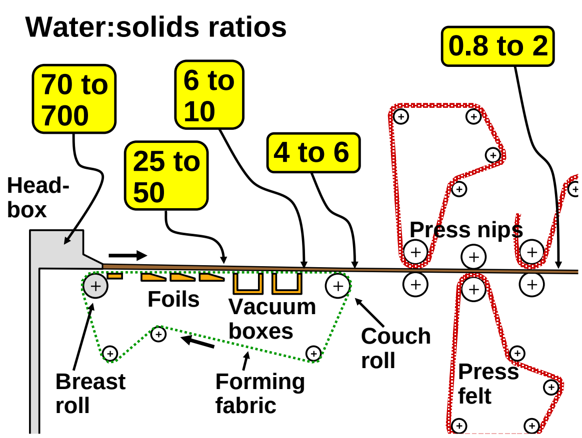

Fig. 5. Simplified schematic of a typical paper machine system, indicating the ranges of water content in the paper web, compared to solid matter, at different points in the process

The filtrate collected during formation of a paper sheet, *i.e.* the "white water," also will contain some solid matter. Those solids are together known by the term "fines". Depending on the paper grade, much of that material is likely to consist of parenchyma cells, as well as fibrillar material separated from fibers during refining, *i.e.* cellulosic fines. According to TAPPI standard T 261 cm-94, cellulosic fines are expected to be able to pass through a circular opening of 76 µm. The cellulosic fines that are generated during mechanical refining of pulp fibers tend to have high aspect ratios and high surfaces areas (Brecht and Klemm 1953; Marton 1980a,b, 1982). They are especially of interest in this paper, since high levels of such fines, especially when making paper products of relatively high basis weight, have been shown to slow down rates of dewatering in laboratory tests (Hubbe 2002; Cole *et al.* 2008; Hubbe *et al.* 2008; Chen *et al.* 2009).

In addition to cellulosic fines, again depending on the grade of paper and local practices, there may be a substantial amount of mineral fillers, including calcium carbonate, clay, or other inorganic particles. During commercial-scale papermaking, depending on chemical additives and many other factors, a substantial proportion of the fines will be retained in the paper during each pass through the paper machine process.

Upwards of 70% of the solid matter contained in the jet of furnish coming from the headbox of typical paper machine systems will consist of cellulosic fibers. The nature of such fibers, as well as how they are processed, can have a large effect on dewatering rates. Most of the paper in the world is produced with fibers from trees. Softwood (conifer) trees that are used commonly for papermaking yield tracheids (fibers) that have lengths of about 3 to 4 mm and widths generally in the range of 30 to 50 µm (Nanko *et al.* 2004). Such fibers are especially used in fabrication of containerboard, fluff pulp for absorbent products, paper bags, and as reinforcement to achieve the needed tear strength in other paper products. Hardwood (deciduous) trees have lengths typically near to 1 mm and widths of 15 to 30 µm. In temperate zones a large contrast in cell-wall thickness can be expected when comparing fibers formed in the springtime (earlywood) and those formed in the summer and autumn (latewood). The earlywood fibers have much thinner walls and larger void spaces (lumens) in their centers. This difference means that the earlywood fibers tend to be much more collapsible, especially after kraft pulping and mechanical refining. Another contribution to nonuniformity of fiber properties comes from the age of the tree when different fibers were formed (Burdon *et al.* 2004). Juvenile wood, which is produced by trees when then are young (often less than ten to 20 years) has fibers that are shorter and thinner than mature wood, which constitutes the outer wood of an older tree.

The kraft pulping process is the most dominant method of converting wood to pulp fibers (Gullichsen and Fogelholm 1999). By breaking down and solubilizing much of the lignin, which functions as a binder between the fibrillar cellulosic domains in the fiber, the kraft process leaves mesopore spaces. Subsequent refining of the pulp tends to delaminate the fibers, including within the dominant S2 sublayer of the fibers. As has been demonstrated by suitable tests, such refining renders the fibers more conformable (Tam Doo and Kerekes 1982; Paavilainen 1993). Conformability of the fibers tends to increase with increased completion of delignification, *i.e.* with decreasing yield (Tam Doo and Kerekes 1982). Thus, high-yield pulps, such as those obtained by thermomechanical pulping (Wang *et al.* 1998; He *et al.* 2011) or with relatively high-yield kraft pulping tend to be stiffer and less conformable (Broderick *et al.* 1996; Nordström 2014). It also has been reported that higher-yield pulps of the same type tend to give higher dryness after pressing (Opherden and Rudolph 1980). Also, fibers that have been dried during a previous cycle of papermaking, and thereby hornified, tend to be less conformable, thus contributing to lower relative bonded area and lower strength of the resulting paper (Jayme 1944; Paavilainen 1993; Weise and Paulapuro 1999; Somwang *et al.* 2001; Zhang *et al.* 2002). Kerekes and Tam Doo (1985) have provided a chart of fiber stiffness, showing how fiber stiffness differences can be estimated based on species, yield, chemical treatment, and refining.

The mechanical refining of pulp fibers, which usually happens by means of shearing and compression of 4 to 6% consistency pulp between a rotor and stator with raised land areas (bars), has a profound effect on all aspects of removal of liquid water from paper. The basics of the procedure and its effects have been reviewed (Gharehkhani *et al.* 2015). Evidence of such effects includes the fact that the extent of refining is almost universally monitored by standard tests of the drainage rates of the refined fiber suspensions (*e.g.* TAPPI Method T 227 om-94). Such a practice is counterintuitive, since the most usual goal of papermakers is to increase strength properties of paper, whereas decreasing the freeness of pulp typically is associated with lower rates of production on drainage-limited paper machines (Ingmanson and Andrews 1959; d'A Clark 1970; Attwood and Jopson 1998b) and in wet-pressing operations (Carlsson 1983; Carlsson *et al.* 1983a; Paulapuro 2000).

Especially when one considers removal of water in a wet-pressing operation, the water located within the cell walls of fibers appears to play an important role (Wahlström 1990; Maloney *et al.* 1999). The amount of such water present in a wet pulp specimen is the water retention value (WRV), which can be determined by a centrifugation test (*e.g.* TAPPI Useful Method UM 256 or SCAN-C 60:00). In such tests, the pulp slurry consistency is first adjusted to an initial range, usually near to 10% solids. Then the material is subjected to a standard acceleration and time. The mass of the material after the centrifugation is compared with that of the same specimen after it has been fully dried in an oven. The difference in mass, divided by the dry mass, is reported. The SCAN test is sometimes preferred over the TAPPI test because it employs a higher acceleration (3000 rather than 900 gravities) and hence can be expected to remove more of the excess water located between the fibers and at their surfaces. For precise, theoretical work, some researchers prefer the employ results of fiber saturation point tests (Scallan and Carles 1972; Maloney *et al.* 1999), which are based on measuring the concentration of very-high-mass dextran molecules, which are generally too large to enter the mesopores within a typical pulp fiber. The amount of water within the cell walls of kraft fibers is expected to increase with increasing extent of mechanical refining. Cell-wall water is believed not to be removed from a wet web to a significant extent in the forming section of the paper machine (Gruber *et al.* 1997). On the other hand, strong correlations have been observed between water retention value and the moisture still in remaining in paper after high-vacuum dewatering (Sjöstrand *et al.* 2019) and after wet-pressing (Rousu *et al.* 2010). As noted by Carlsson (1983), though the cell-wall water may be difficult to remove from fibers during the very brief exposures of the wet web to pressure within a press nip, some of it is removed. This hard-to-remove water in the fiber wall ultimately limits the amount of water that can be removed by pressing (Kerekes and McDonald 2020). A certain portion of the water in the cell wall appears to be sufficiently strongly associated with the cellulosic material that its properties differ from those of bulk water, *e.g.* such as not having a freezing point or being more difficult to remove (Weise *et al.* 1996; Maloney and Paulapuro 1999; Park *et al.* 2006, 2007). In line with some of these findings, Jönsson and Jönsson (1992a) developed a model of the dewatering process for incompressible media in which 0.3 parts of water per mass of cellulosic matter was assumed not to move at all relative to the solids.

Near the end of this article, in the context of strategies to increase rates of water removal, some attention will be paid to chemical effects. Since some of the effects may be related to mechanisms of dewatering, some brief background will be provided here. First it is worth noting that the extent of swelling, including the WRV levels of pulp fibers, will be affected by anything that changes the charge properties of the furnish. Such issues are covered in more detail in an earlier review (Hubbe and Heitmann 2007).

As shown by Lindström and Carlsson (1982), much of the tendency of kraft fibers to swell with water can be attributed to the negatively charged ionic groups within them, especially the carboxylate groups associated with hemicellulose. The osmotic pressure promoting swelling of the fibers with water is suppressed to an increasing extent with increasing ionic strength (salt content) in the water phase. In addition, swelling can be decreased either by lowering the pH (in the range of about 6 to about 3) or by adding multivalent positive ions. In addition, it is well known that dewatering rates, especially early drainage, can be promoted by the addition of cationic polymers (Britt and Unbehend 1980, 1985; Stratton 1982; Wegner *et al.* 1984; Allen and Yaraskavitch 1991; Räisänen *et al.* 1995a; Hubbe *et al.* 2008).

Models to Estimate Resistance to Flow

For a concise overview of mathematical models related to rates of the release of water from paper, readers are referred to a review article by McDonald and Kerekes (2017b). The article covers the most important historical developments in such models, as well as emphasizing some visco-elastic effects that are highly relevant here. To start off, Table 4 provides a summary of some key publications related to the modeling of dewatering rates of paper in various unit operations.

Table 4. Advances in Mathematical Models to Predict Rates of Release from Wet Webs of Paper Subjected to Vacuum or Pressure

Type of System	Findings	Citation
Basic packed bed	Flow = delta pressure * constant / (viscosity coeff.), or $Q = [(kA)/(\mu L)]\ \Delta P$ in integrated form.	Darcy 1856
Rigid packed bed	Related flow resistance to surface area and porosity of a packed bed, with laminar flow characteristics.	Kozeny 1927
Rigid packed bed	Considered a mixture of two particle sizes; also determined specific surface area.	Carman 1937, 1939
Granular bed	Added an inertial term (for high Reynolds number) to the Kozeny-Carman analysis.	Ergun 1952
Wet press	Model is based on separation of hydraulic and structural resistance to applied pressure difference.	Wahlström 1960
Fiber mats	Flow resistance is calculated based on multi-body drag, based on Happel, rather than capillary friction.	Meyer 1962
Fiber mats	Model calculations are able to predict the squeezing of water from a compressible mat.	Ingmanson 1964
Fiber mats	Differences in results are attributed to differences in compressibility of fibers.	Han & Ingmanson 1967
Wet press	Effects of refining and whether the web becomes drier after the midpoint of the nip were considered.	Larsson & Nilsson 1968; Nilsson & Larsson 1968
Fiber mats	Bending, slipping, and conformation of fibers were considered; permeability decay and fiber deswelling.	Han 1969
Forming section	Numerical modeling of forces, which are assumed to be proportional to the square of drainage velocity.	Victory 1969
Wet press	Review of model based on separating hydraulic and structural resistance to applied pressure difference.	Wahlström 1969
Fibrous bed	Flow through random packed bed; effective pore model, Reynolds number, and predicted dead space	Kyan *et al.* 1970
Initial filtration	Effects of accumulation of cake filtration material are considered in model.	Smiles 1970
Granular packed bed	Complex interactions among parameters makes it impractical to model filtration with a series equation.	Payatakes *et al.* 1973
Wet press	Regression analysis was carried out based on paper and felt incoming moisture, pressure, time.	DeCrosta & Paisted 1978
Packed bed: binary sizes	The mixtures gave much lower permeability, in agreement with theoretical fits.	Abe *et al.* 1979

Wet press	Pressing permeability decreases due to the compressing of fiber, deviating from Darcy's law.	Luey 1979
Table rolls, blades	Models were based on hydropulse of the drainage element, pulp compressibility, and Kozeny-Carman.	Cadieux 1983
Wet press	Kelvin (spring and dashpot) with Deborah number (retardation time divided by test duration)	Carlsson *et al.* 1983b
Wet press	Wet-press simulator results were fit to a stress-strain model.	Davis *et al.* 1983
Mat of stiff fibers	3D models with parallel or perpendicular rods gave reasonable agreement with data and Darcy's law.	Jackson & James 1986
Vacuum jar test	Specific filtration resistance was determined based on dewatering test results; effects of turbulent flow.	Pires *et al.* 1988
Wet press	Modeling with a Kelvin model (spring and dashpot) was compared to results from a wet-press simulator.	Springer *et al.* 1989
Binary bed with 2 fiber sizes	A creeping flow model showed lower permeability than predicted by Darcy's law.	Ethier 1991
Wet press	The Kozeny-Carman equation was modified with compressibility, permeability, and press impulse.	Kerekes & McDonald 1991
Wet press	Data from a commercial paper machine were fit to model, including temperature effects, paper grades.	McDonald & Kerekes 1991
Wet press	The structural and hydraulic pressure were modeled based on pressing time, distance, and impulse.	Pothmann 1991
Wet press	Numerical simulations were done with attention to pore-size distributions.	Roux & Vincent 1991
Vacuum flatbox	The model related the dewatering parameters to web pore size.	Skalicky *et al.* 1991a
Compressible media	Steady-state flow through porous media gives cumulative pressure & compression, affecting flow.	Jönsson & Jönsson 1992a,b
Wet pressing	The hydrodynamic model considers transverse flow of both water and air.	Kataja *et al.* 1992
Filter cake of pulp	A cake filtration model for pulp was similar to diffusion for compressible and incompressible mats.	Nordén & Kauppinen 1994
Wet pressing	A term was added to the decreasing permeability model to account for rewetting.	McDonald & Kerekes 1995
Vacuum flatbox	A model based on pilot trial data showed diminishing dewatering rate with passage of time.	Neun 1995
Drainage test device	The ability of the fibers to pack correlates with drainage resistance.	Sampson & Kropholler 1995
Fiber mats	Proposed micromechanical theories of flow through compressible fiber beds of homogeneous layers.	Zhu *et al.* 1995
Nylon fibers and beads in beds	Permeability could be modeled linearly and fit well to the Kozeny-Carman equation.	Chan *et al.* 1996
Fines in a paper sheet	Model considered bridging, blocking, or filling by fines; no flow predictions made, just density, *etc.*	Görres *et al.* 1996
Freeness test	Modeled freeness test, including changing head of gravity, mat compressibility, and surface areas.	Kumar *et al.* 1996
Cake filtration with gravity	Model predicts that pressure, consistency, and filtration resistance will go through a maximum.	Ramarao & Kumar 1996
Twin-wire forming	Linear numerical modeling of effects of a blade of arbitrary shape with incompressible, inviscid fibers.	Zahrai *et al.* 1997
Wet press	Grey-box modeling that combines physical models with disturbances, thereby getting good predictions.	Funkquist & Danielsson 1998
Wet press	A capillary flow model, with consideration of decreasing passages due to applied pressure.	Holstege 1998
Vacuum flatbox	Assumed compressible porous media with surface tension forces in the pore structure.	Jones 1998

Twin-wire forming	Force and mass balances were applied, with application of Darcy's law.	Martinez 1998
Jet impingement & early drainage	Simple filtration model of paper forming, analogous to handsheet forming; mat phase & dilute phase.	Herzig & Johnson 1999
Vacuum flatbox	Assumed zero compression of web and all removal being due to air flow through the web.	Tarnopolskaya *et al.* 1999
Vacuum flatbox	Modeled pulsating vacuum suction with one-dimensional, 2-phase (air and water) model.	Mitchell & Johns-ton 2000, 2003
Hydrofoils	Activity generation was modeled in terms of Z-directional changes in fluid velocity on the table.	Sodergren & Neun 2000
Handsheets; varied refining	Flow simulations based on 3D imaging and Kozeny-Carman equation to relate permeability to porosity.	Aaltosalmi *et al.* 2003
Twin-wire forming	The model considered a sealing mechanism and plugging of pores in the mat by fines.	Wildfong *et al.* 2003
Twin-wire forming	Pressure profiles are modeled through a twin-wire forming section.	Lobosco *et al.* 2005
Wet press section	Modeling of when to exchange press felts and the sequence of paper grade production, *etc.*	Drummond *et al.* 2009
All the dewatering sections of PM	Sequential modeling of all dewatering operations of a paper machine to fit and reduce steam demand.	Afshar *et al.* 2012
Vacuum flatbox	Filtrate per unit area is proportional to the square-root of suction time.	Roux & Rueff 2012
Initial dewatering	Model of fiber-forming fabric interactions, including bending of fibers and surface roughness of paper.	Li & Green 2012
Rheometer dewatering test	Shear-thinning behavior of furnishes that contained nanofibrillated cellulose fit the Oswald model.	Dimic-Misic *et al.* 2013
Wet press	Press felt structure's effect on dewatering was modeled with the decreasing permeability model.	McDonald *et al.* 2013
Wet press	An equilibrium term was added to the Decreasing Permeability model for highly pressed webs.	Kerekes *et al.* 2013
Vacuum flatbox	Model considers the effect of the forming fabric, using volume forces in the model.	Rezk *et al.* 2013
Vacuum flatbox	Air flow sucked through the wet web was incorporated into the model.	Nilsson 2014a
Vacuum flatbox	Two-phase flow was modeled using a level-set approach in a 3D environment.	Rezk *et al.* 2015
Vacuum flatbox	Dewatering predictions were fitted based on the fiber width and length data.	Stenström & Nilsson 2015
Initial dewatering	Pressure profiling was used to determine flow resistivity from the instantaneous response to pressure on the former.	Koponen *et al.* 2016
Vacuum flatbox	Numerical modeling, with attention to forming fabric structure.	Sjöstrand *et al.* 2017
Wet Pressing	Mathematical model of rewetting that accounts for both in-nip and separation rewetting.	McDonald and Kerekes 2018
Vacuum flatbox	Numerical modeling, with attention to moisture ratio and penetrated air volume.	Sjöstrand *et al.* 2020
Wet pressing	Equilibrium moisture m_e depends on the pore size distribution of the fiber wall.	Kerekes and McDonald 2020

Darcy's law

Other sources give a fuller explanation of hydrodynamic principles and factors acting to resist flow (Hubbe and Heitmann 2007; Guyon *et al.* 2015). Some topics, however, need to be summarized here, since they will be mentioned repeatedly in discussions that follow. One such topic is called Darcy's law (Darcy 1856). This relationship can be expressed as in Eq. 1,

$$V = \frac{k \cdot P}{\mu\, L} \tag{1}$$

where V is the superficial velocity (*i.e.* the porosity times the real velocity within the pores), k is the permeability coefficient, P is the pressure difference across a uniform bed, μ is the viscosity, and L is the height of the bed. The relationship can be expressed equivalently in terms of the volume of flow as,

$$Q = \frac{k\, A}{\mu\, L} \Delta P \tag{2}$$

where Q is the volumetric flow and A is the area of the face of the bed or pipe within which the material is packed. Notice that for Darcy's law to provide reasonable predictions, the particles and packing within the bed need to be sufficiently uniform (McDonald and Kerekes 2017b). For fiber networks, a classical review on permeability models and measurements can be found in Jackson and James (1986).

For practical purposes Darcy's law is sometimes written in the form,

$$V = \frac{\Delta P}{Kb\mu} \tag{3}$$

where b is the mass of the sheet per unit area (*i.e.* basis weight) and K is the specific filtration resistance or the resistivity of the filtered sheet. This form is useful when the sample thickness is not known, as is the case in many practical cases. Note that there is the following relation between the sheet permeability and resistivity, where ρ is the density of the porous material:

$$K = \frac{1}{k\rho} \tag{4}$$

Though Darcy's law deals only with flow *through* rather than *from* a porous medium (the latter of which is the interest of papermakers), it has provided a reference point or a starting point for many modeling efforts by papermakers (Campbell 1947; Meyer 1962; Luey 1979; Jackson and James 1986; Ethier 1991; Jönsson and Jönsson 1992a; Kataja *et al.* 1992; McDonald and Kerekes 1995; Funkquist and Danielsson 1998; Martinez 1998). An obvious problem that needs to addressed is that during water removal, the permeability k in Darcy's law is not a constant but decreases as water is removed from the web and the web is compressed (Kerekes and McDonald, 1991; McDonald *et al.* 2000; McDonald and Kerekes 2017b).

The most important advance to build upon Darcy's contribution was achieved by Kozeny and Carman (Kozeny 1927; Carman 1937, 1938). These authors figured out a way to estimate the value of the permeability coefficient k in Darcy's equation. The most useful form of the Kozeny-Carman equation is as follows (Carrier 2002),

$$k = \frac{\varepsilon^3}{k_c S^2 (1-\varepsilon)^2} \tag{5}$$

where ε is the fractional void volume (or porosity) of the packed bed, k_c is essentially a correction factor, which includes *e.g.* the effect of tortuosity, and S is the specific surface area of the solids. Kozeny-Carman law has been a starting point or a comparison point for many analyses of the flow resistance during dewatering of paper webs (*e.g.* Campbell 1947; Ingmanson 1952, 1953; Carlsson *et al.* 1983a; Kerekes and McDonald 1991). Notice that for dilute fiber networks the Kozeny-Carman equation does not work well and one should use correlations developed specifically for dilute systems, such as that of Jackson and James (1986),

$$k = \frac{3d^2}{80(1-\varepsilon)}\left[-\ln(1-\varepsilon) - 0.931\right] \quad (6)$$

where d is the diameter of fibres.

While permeability models, such as Eq. 5 (Kozeny-Carman), can be used for general description of the permeable behavior of fiber networks, the irregular shape of the fibers and effects related to their compressibility usually prevent accurate prediction of permeability *a priori*, *i.e.* without supporting experiments. Such experiments are technically rather straight-forward to perform, and there are numerous papers on them in different porosity regions (Carlsson *et al.* 1983a; Chan *et al.* 1996; Lindsay and Brady 1993a,b). Recently, the developments of X-ray tomographic imaging and computational fluid dynamics have enabled quantitative determination of the permeability of pulp fiber networks also without explicit flow measurements (Koivu *et al.* 2009a,b). This approach has made it possible to develop more accurate permeability models for fiber networks that take into account the real structural details, such as local thickness distribution, of the network (Koponen *et al.* 2017).

An important implication of the models considered up to this point is that the permeability of a paper mat can be expected to decrease as the mat becomes more densified. With less void volume and with smaller channels of water between fibers or particles of solid material, there is higher frictional resistance to flow. Notably, this conclusion can be reached even without considering effects due to non-uniform densification or any details of packing of the solids within a paper mat.

Simple linear model for the sheet flow resistivity

According to Sayegh and Gonzalez (1995) and Koponen *et al.* (2016) the dependence of the water flow resistance through pulp fiber sheets was studied as a function of pressure. It was found that the resistivity of the fibre sheet could be described in the pressure range of 5 to 70 kPa with a good accuracy by a linear model,

$$K = \beta\Delta P + \alpha I + \gamma, \quad (7)$$

where I is impulse density (integral of pressure over time), and β, α, and γ are pulp-dependent material parameters. In most practical cases dewatering takes place so quickly that the term αI in Eq. 7 can be eliminated. Equation 7 suggests that the effect of increased pressure is mostly lost due to simultaneously increasing flow resistance. So, in addition to leading to potential sheet sealing, high pressure levels may lead to a waste of energy without giving major benefits in the initial dewatering.

A widely used application of the Kozeny-Carman equation has been in the characterization of the hydrodynamic surface area of particulate or fiber materials (Sullivan and Hertel 1940, 1942; Ingmanson and Andrews 1959; Kumar and Ramarao 1995). Such approaches, as well as the results from such analyses, need to be viewed with caution in the case of compressible and deformable materials such as papermaking fibers. According to the initial assumptions, the particulate material in a Kozeny-Carman analysis ought to have no dependency of the shape or the spaces between particles as a function of applied pressure. Also, the representation of the packed bed as being uniform needs to be justifiable.

Binary mixtures

It is well known that a higher density of loosely packed material generally can be achieved if a fraction of the particles have a smaller size (Santiso and Müller 2002; Brouwers 2006). Accordingly, it has been shown, with application of the Kozeny-Carman analysis, that bimodal mixtures of particles present greater resistance to flow (Carman 1937; Ethier 1991; MacDonald *et al.* 1991; Andrade *et al.* 1992). As pointed out by Andrade *et al.* (1992), the details of topology can be expected to play a significant role, which tends to place limits on the precision of predictions based on uniform packed bed models. These considerations are highly relevant to papermaking systems, in which there can be a range of sizes of fibers, cellulosic fines, and other particles. For example, Görres *et al.* (1996) described how different placement of fines within a paper sheet formed from mechanical pulp fibers and fines can achieve a range of densities, depending on whether the fines are engaged in bridging, blocking, or the filling of places within the structure. Likewise, Sampson and Kropholler (1995) found a strong correlation between the packing ability of solids in the furnish and both drainage resistance and mat density.

Lucas-Washburn analysis

The Lucas-Washburn analysis of rates of wetting of porous materials is relevant to the dewatering of paper for two reasons. First, it presents an alternative, and possibly equivalent way to estimate the viscous resistance to flow through porous material. Second, it provides a way to predict certain contributions to resistance to flow imposed by the presence of an air-water meniscus within or at the entrance to an individual pore. In the Lucas-Washburn analysis, the viscous resistance to flow is estimated based on the model of a single, uniform, cylindrical pore, using the Hagen-Poiseuille equation (Sutera and Skalak 1993). The viscous force was envisioned as providing the main resistance against flow of liquid into a porous solid. Lucas (1918) and Washburn (1921) proposed that the force motivating the liquid to enter a porous solid is provided by interfacial tension. The physical situation can be modeled as shown in Fig. 6, where the porous material is represented as a single cylindrical pore of uniform cross-section.

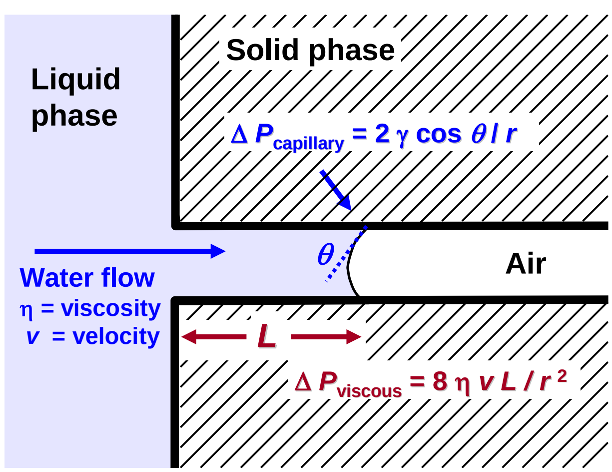

Fig. 6. Representation of model envisioned by Lucas and Washburn for estimating the rates of penetration of liquids into porous solids based on capillary forces and viscous resistance to flow

The most important result from the analysis of Lucan and Washburn is a prediction that the amount of liquid adsorbed ought to be dependent on the square-root of time that has passed after the moment of wetting (see Eq. 11). This relationship has been found to be applicable to wetting of paper by non-aqueous fluids, but there can be large deviations in the case of water (Bristow 1967; Aspler *et al.* 1987). The following four equations show, in turn, the anticipated meniscus force, the viscous force that is expected to resist penetration, and the expressions that result when the opposing forces are set equal to each other. In these equations, ΔP is a change in pressure, γ_{LV} is the interfacial tension between water and its vapor phase, θ is the angle of contact (drawn through the liquid phase), r is the effective radius of a capillary (modeled as being cylindrical), μ is the fluid viscosity, v is the velocity of fluid entering the pore, and L is the wetted length of the pore at time equal to t.

Capillary force equation

$$\Delta P_{\text{capillary}} = 2\gamma_{LV} \cos \theta / r \tag{8}$$

Viscous retarding force, Poiseuille's equation

$$\Delta P_{\text{viscous}} = 8\mu v L / r^2 \tag{9}$$

Lucas-Washburn equation in differential form

$$\mathrm{d}l/\mathrm{d}t = \gamma_{LV}\, r \cos \theta / (4\mu L) \tag{10}$$

Lucas-Washburn equation in integrated form

$$L = [(2r\, \gamma_{LV} \cos \theta\, t) / (4\mu)]^{1/2} \tag{11}$$

In the context of water removal from paper, the Lucas-Washburn approach points to the possibility of using the Poiseuille equation as a relatively simple way to estimate resistance to flow in a porous material, replacing the complication of a packed bed structure with simple equivalent cylindrical pores. But it also provides a way to begin to account for effects of an air-water meniscus at the entrance to a pore or at other places within a porous structure. Related approaches have been used to some extent to understand and predict aspects of the dewatering of paper, especially when considering the vacuum flatbox or when predicting flow through compressed beds (Sullivan and Hertel 1942; Carlsson *et al.* 1983a; Brundrett and Baines 1996). Notably, in the context of water removal from paper, a meniscus generally will act to completely prevent flow at the phase boundary until such point that the difference in pressure exceeds the capillary pressure, which depends on the radius of the pore, the contact angle, and the interfacial tension.

Non-laminar flow resistance

The predictions of the Darcy's law can be expected to show deviations when flow rates are sufficiently high to induce significant inertial contributions to flow resistance (Carman 1937; Sullilvan and Hertel 1942; Ergun 1952; Ingmanson and Andrews 1959; Kyan *et al.* 1970; Kufereth 1982a,b; Norman 1989; Polat *et al.* 1989; Sjöstrand *et al.* 2017). Especially during initial dewatering, when the filtered fiber network is still dilute, flow resistance is low and the flow rate inside the network is high. Ergun (1952) proposed the idea of including a term from Burke and Plummer (1928) to Darcy's law to account for the inertial component of resistance to flow through a packed bed:

$$\frac{\Delta P}{L} = \frac{\mu}{k} Q + C\rho Q^2 \qquad (12)$$

The second term in Eq. 12 is also called the Forchheimer term. The quantity ρ is the density of the fluid and

$$C = \alpha \frac{1-\varepsilon}{d\,\varepsilon^3} \qquad (13)$$

is a parameter that depends on the medium geometry (here d is the effective diameter of the particles and parameter α is 1.8 for smooth-walled particles and 4.0 for rough-walled particles). Notice that the formula for parameter C has some similarity with the Kozeny-Carman equation.

Usually the effect of turbulence is omitted in the analysis of initial dewatering. When this simplification is justified is currently unclear. The flow coming from the headbox is fully turbulent, which could affect the filtration resistance if the Kolmogorov scale of the turbulence is smaller than the pore size of the filtered sheet. Moreover, the flow rates during early initial dewatering could sometimes be high enough to generate turbulent eddies inside the fiber network.

Compressibility incorporated into models

As already mentioned in passing, effects related to compressibility and deformability of the solids are not accounted for in the models provided by Darcy and Kozeny-Carman. Work to incorporate compressibility effects into experimentation and analysis suitable for paper dewatering system has been undertaken by several researchers (Ingmanson 1953; Nordman 1954; Ingmanson and Andrews 1959; Jones 1963; Chang 1978; Kerekes and McDonald 1991; Roux and Vincent 1991; Jönsson and Jönsson 1992a,b; Nordén and Kauppinen 1994; Zhu *et al.* 1995; Vomhoff and Schmidt 1997; McDonald *et al* 2000). In general, compression of a fiber mat can be expected to increase the resistance to flow through the compressed layer (Gruber *et al.* 1997; Kerekes and McDonald 1991; Jönsson and Jönsson 1992a,b; McDonald *et al* 2000). In response to applied pressure, fibers can be expected to bend, slide relative to each other, and to be individually compressed (Gurnham and Masson 1946; Jones 1963; Han 1969; Zhu *et al.* 1995).

After a mat of fibers is compressed and the pressure is released, it may not immediately snap back to its expanded state. Jones (1963) suggested that such behavior can be regarded as a form of viscous creep, *i.e.* a gradual change in shape when an elastic force of recovery is applied over time. There are hydrodynamic factors too, which can be considered in accounting for delayed re-expansion. The compared mat initially is likely to be saturated with water, and the necessity of flow through the narrow channels among compressed fibers will require time. As just discussed, there also may be significant capillary resistance due to an air-water meniscus at openings of pores leading into the fiber mat.

Separation of pressure components

When pressure is being applied to a wet web of paper, it makes sense to expect that at least some of the applied pressure will be borne directly by the strength of the solid material, as can be predicted from its elastic modulus and detailed structure. In other words, one assumes that there will be a structural component of resistance to the applied pressure.

Wahlström (1960, 1969), who based his analysis on principles set forth by Terzaghi (1943) for soil mechanics, proposed that the resistance to compression during wet-pressing of paper can be divided into two parallel components, of which the other consists of hydraulic pressure.

There are reasons, however, to suspect that the actual contribution of mechanical structural forces may be relatively small. The first reason is the relatively high proportion of water that is present, especially when considering the parts of the dewatering process prior to wet-pressing. In addition, pressing on a water-swollen kraft fiber might be compared to squeezing a leaky water balloon; what appears to be structure could just be the effect of water that is slow to escape from a fully or partially blocked area (Paulapuro 2000, 2001). Accordingly, Campbell (1947) predicted that at no time during the papermaking process would the structure of the paper web carry the full load of the applied pressure during in dewatering. Kataja *et al.* (1995) set out to determine whether there is justification to distinguish between hydraulic and structural forces in a wet-press nip. They concluded that such a model cannot be justified in the case of deformable materials, which tend to form finite areas of contact when pressed together. In an early version of their decreasing permeability model, Kerekes and McDonald proposed that at least during the initial stages, the pressure is dominated by hydrodynamics, *i.e.* rate-dominated pressures resisting the applied pressure. Based on that they developed a more comprehensive mathematical model, which shows promise for accounting for results of wet-pressing over a range of conditions (McDonald and Kerekes 1991; McDonald *et al.* 2000; Kerekes and McDonald 2013). Jaavidaan *et al.* (1988) reported that the hydraulic pressure component usually followed the applied pressure quite closely.

Viscoelastic elements in modeling

If pressure is applied to paper for a longer time, more water generally will be released, even if very short impulses of pressure appear to be opposed by forces that resemble solid-like elasticity. This contrast between short-term solid-like behavior and long-term ability to flow means that the wet web is acting like a visco-elastic material (Carlsson 1983). The validity of this statement is evident in the wide-spread commercial success of extended-nip wet-presses, which can greatly exceed the dewatering capacity of conventional wet-press equipment, despite the fact that they generally apply lower peak levels of pressure (Wicks 1983; Paulapuro and Nordman 1991; Pikulik 1999; Lange and Meitner 2006). In light of such practical evidence, it makes sense to employ visco-elastic models in modeling of what happens in a wet-press nip. Accordingly, Carlsson *et al.* (1983b) and Springer *et al.* (1989) employed a simple Kelvin model (a parallel spring and dashpot) in their model of wet-pressing. Davis *et al.* (1983) explicitly evaluated the viscoelastic response of paper during simulated wet-pressing. Dimic-Misic *et al.* (2013) found evidence that shear-thinning behavior of highly fibrillated cellulose affects its dewatering behavior when it is present in a wet web of paper.

Although shoe presses may apply a lower peak pressure than roll presses, they apply a higher line load, which gives a greater press impulse (line load/speed or dwell time multiplies by pressure). Press impulse has been shown to be the dominant factor in press section water removal (Busker and Cronin 1984; Kerekes and McDonald 1991; McDonald et al 2005). The fact that the Kelvin model only predicts this at vanishing small dwell times, indicates that the spring and dashpot concept is flawed.

Advances in Experimental Devices

The tests that enabled many of the advances in models of water-removal operations, as just described, were obtained when using laboratory equipment, such as drainage jars and wet-press simulators. Equipment for evaluation of dewatering by gravity and vacuum was described in an earlier review article (Hubbe 2007). Some of these devices were compared in a series of tests carried out by TAPPI (Kerekes and Harvey 1980). Some notable advances in such technology are listed in Table 5. Likewise, Table 6 lists some of the wet-press simulation devices that have been reported.

Table 5. Dewatering Devices based on Gravity or Vacuum

Main Force	Key Details and Findings	Citation
Dynamic vacuum	Vacuum was applied in a narrow slot below a spinning wet paper handsheet. High fines slowed dewatering.	Nordman 1954
Constant rate filtration	Filtration resistance increases by a factor of about 3 from the breast roll to the end of the forming section.	Ingmanson 1957
Pulsed drainage	Short pulses gave the biggest benefits to dewatering.	Persson & Österberg 1969
Pulsed drainage	The dewatering of more highly beaten pulps benefited from the pulsation.	Lindberg 1970
Constant rate filtration	Faster dewatering flow yields a denser mat.	Fleischer *et al.* 1978
Freeness test & handsheet test	The two types of test were compared relative to evaluation of drainage rates (one page).	Yan & El-Hosseiny 1978
Drainage jar; gravity & vacuum	If chemical additives induce fiber flocculation in lab tests, they can adversely affect vacuum dewatering.	Britt & Unbehend 1980
Vacuum dewatering	The G/W system device gives a vacuum *vs.* time output that can be correlated to vacuum box responses, *etc*.	Gess 1983, 1984
Drainage by gravity, vacuum	Retention chemicals increased early dewatering but decreased the effectiveness of vacuum dewatering.	Wegner *et al.* 1984
Turbulent pulse sheet former	Wet-end chemicals were evaluated under conditions that better simulated forming on a commercial machine.	Staib 1991
Continuous freeness tester	The pulp drainage analyzer (PDA) senses how soon air flows through the pad when vacuum is applied.	Kaunonen & Luukkonen 1992
Drainage/vacuum retention tester	Fillers adversely affected dewatering.	Springer & Kuc-hibhotla 1992
Gravity drainage with level sensor	A maximum in filtration resistance was observed at 0.5% consistency. Fines above 15% slowed drainage.	Mantar *et al.* 1995
Modified Schop-per-Riegler	Freeness tests with continuous mass detection provide a full drainage curve.	Sampson & Kropholler 1995
Moving belt with vacuum slots	Effects of basis weight and freeness were shown. Drainage got faster with increasing temperature.	Räisänen *et al.* 1996
Pulsating drainage	Foils rotating below a screen imparted effects similar to hydrofoils. Microparticle additives were demonstrated.	Sutman 2000
Constant pressure filtration	Drainage resistance increased out of proportion with basis weight, which was attributed to fines entrapment.	Wildfong *et al.* 2000a,b
Moving belt drainage former	Air flow rate and vacuum could be measured. Formation and strength properties were evaluated.	Xu and Parker 2000
High drainage rate tester	Drainage resistance increased out of proportion with basis weight, which was attributed to fines entrapment.	Paradis *et al.* 2002, 2003
Vacuum dewatering	Vacuum dewatering with short dwell times (>0.5 ms) and ability to use commercial forming fabrics.	Granevald *et al.* 2003
Pressure filtration	Addition of a debonding agent promoted flow channels in the wet web and sometimes gave a drier sheet.	Kugge *et al.* 2005

Pulsation during dewatering	Application of pulsations resulted in lower retention of fine particles during dewatering.	Hubbe *et al.* 2006
Vacuum dewatering	Air and water flows through the sheet were detected with a slot opening below a rotating disc of wet paper.	Pujara *et al.* 2008a,b
Oriented gravity handsheets	The fibers interacting with the fabric appeared to have a disproportionate effect on overall permeability.	Xu *et al.* 2010
Initial dewatering	The sheet solids content depends on the magnitude and shape of the pressure profile.	Koponen *et al.* 2015, 2016

Table 6. Wet-press Simulation Devices

Type of Device	Key Details and Findings	Citation
Static pressing	Dynamic tests were not yet available.	Campbell 1947
Rapid hydraulic	Hydraulic force was a significant proportion of total.	Chang 1978
Anvils & force transducer	Load *versus* moisture curves were generated.	Zotterman & Wahren 1978
Anvils & force transducer	Additives can increase solids after the press.	Stratton 1982
Falling weight	Additives had both positive and negative effects.	Davis *et al.* 1983
Rapid hydraulic	Hydraulic force was a significant proportion of total.	Carlsson 1984
Falling weight	Thickness of the sheet and water's distribution were determined. Substantial water remains in the sheet.	Burns *et al.* 1989
Hammer & anvil	Hot conditions gave faster dewatering.	Link *et al.* 1995
Rapid pulse: plate & screen	Highly fibrillated cellulose impeded press-dewatering, especially at higher basis weights.	Rantanen & Maloney 2013

Average Alignment of Fibers

It is well known that, on many paper machines, there is a preferential alignment of fibers in the machine direction (Kufereth 1982a; Parker 1972). Since such orientation is highly influenced by events at the very start of the dewatering process – including some alignment of fibers already in the jet of stock coming from the headbox – it makes sense to place a priority on considering whether or not such alignment of fibers will affect rates of dewatering.

Aspects of the hydrodynamics of flow within the headbox slice and immediately thereafter, in the free jet heading toward the forming fabric, have been explained and mathematically described by Aidun (1998). Within the converging flow of a hydraulic headbox the overall situation can be understood as being a combination of shear flow and extensional flow, with constraints imposed by the stationary metal surfaces on each side of the moving suspension. This converging flow, even in the absence of other factors, will tend to align fibers in the machine direction to a significant degree, in comparison to random orientation (Stover *et al.* 1992; Ulmar and Norman 1997; Hubbe 2007). Preferential orientation of fibers in the machine direction is often further augmented, during commercial papermaking, by maintaining slightly unequal speeds of the jet of furnish and the forming fabric or fabrics (Svensson and Österberg 1965; Parker 1972; Swerin and Mähler 1996). As was noted earlier, such speed differences give rise to oriented shear and a rotational motion of the elements of fluid, which has the effect of aligning fibers.

Paradis *et al.* (2002, 2003) obtained experimental evidence supporting a hypothesis that alignment of fibers will increase resistance to flow through a wet web of paper. The results were achieved by use of a unique drainage jar device in which the furnish was subjected to low-velocity shearing from a ten-degree-angle conical rotor during formation of the paper on a screen. Such conditions resulted in higher resistance to dewatering.

Higher velocities of shearing merely disrupted formation of a paper mat. Related effects, also supporting increased resistance to drainage in the presence of gentle oriented shear, were reported by Forsberg and Bengtsson (1990).

Another factor that can be expected to affect fiber orientation is the consistency of the stock. A higher consistency, which induces more crowding and flocculation among the fibers (Kerekes 2006), can be expected to result in less orientation and often a higher component of fibers with significant z-directional orientation, *i.e.* with parts of a fiber spanning the thickness dimension of the fiber. Lindsay and Brady (1993a) found that higher consistency yielded higher permeability of the paper structure in the thickness direction. Such results, though suggestive, cannot be regarded as convincing evidence, since the flocculation of fibers often implies that there are thin areas in the paper, through which water or air can flow more easily.

Published evidence suggests that the first layer of fibers interacting with the forming fabric has a disproportionate influence on dewatering (Li and Green 2012). Such fibers would logically tend to be the most affected by the fiber-aligning tendencies due to headbox slice effects and jet-to-wire speed differences, since their orientation would be subsequently restrained by their being held against the fabric surface. Puurtinen *et al.* (2010) found that changing the jet/wire speed ratios did not cause any measurable differences in the dewatering rates of a shoe gap former.

Healing

Especially in cases where the mass per unit area (*i.e.* the basis weight) of a sheet of paper is very low, the resistance to flow through the sheet can be expected to be much lower in thin areas, especially if there are open channels such as pinholes through the whole thickness of the sheet. It has been proposed that, during the formation of paper from a sufficiently dilute suspension, there is a natural tendency of fibers to assemble themselves in a somewhat more uniform way, particularly with respect to dimensions less than a fiber length. Such a tendency would be suggested by two principles. First, two solid objects cannot occupy the same position simultaneously. Second, the predominant flow of water leaving the paper during dewatering can be expected to draw any individually suspended fibers toward void areas in the mat (see part E of Fig. 4) (Wrist 1962; Egelhof and Bubik 1994; Sampson 1997). Accordingly, Norman *et al.* (1995) suggested that a paper handsheet can be expected to often have a higher uniformity than would be predicted based on a purely random distribution. As a counter-point, however, it is worth noting that, to the extent that fibers have become formed into flocs due to mechanical or chemicals effects, even a handsheet may have lower uniformity than would otherwise be expected (Sampson 1997). Fine-scale uniformity of paper can be expected to affect dewatering of paper in two ways. As already mentioned, the thin areas of a paper sheet provide easier paths for water to leave a wet web during dewatering. But in addition, once much of the water has been removed from the web, vacuum dewatering can suffer. This is because the vacuum will tend to get wasted in the sucking of air through the thin or open areas, while water may remain in the thicker areas of a non-uniform paper web. These last issues will be probed more deeply in the next subsection.

The healing mechanism has been mainly considered in the literature as a way to account for paper's tendency to have enhanced fine-scale uniformity as a result of an initial forming process. However, it can also be considered in the context of the effects of hydrofoils, which can periodically cause upward components of flow, *i.e.* microturbulence.

Figure 7 shows, in principle, how such periodic flows may be expected to contribute to a healing process.

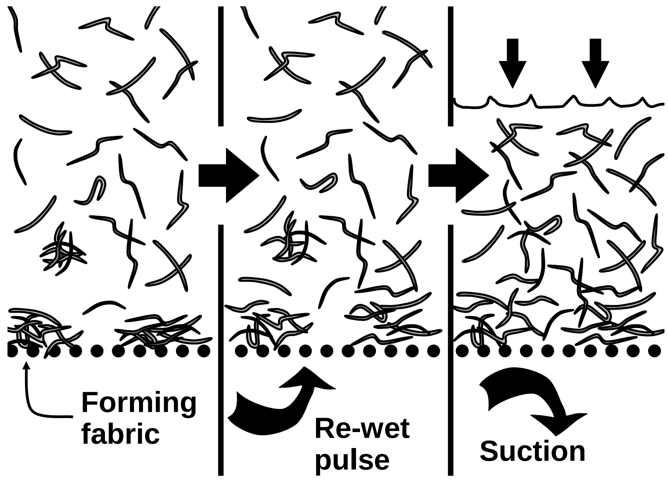

Fig. 7. Schematic diagram showing hypothetical healing effect brought about by the occasion of flow back into paper after its compression by vacuum

Singh and Green (2015) provided some highly persuasive support for the healing mechanism in an unusual way. They correlated the amounts of cellulosic fines present in different microscopic locations within the paper, relative to microscopic locations where different parts of the forming fabric had earlier been in contact with the wet sheet. The least amount of fines were present in the knuckle areas, at which flow into the forming fabric would have been completely blocked by a solid plastic strand. An intermediate concentration of fines was found over the horizontal filaments of the fabric. The highest concentration was found adjacent to the void areas of the fabric, which is consistent with fines following the flow of water and becoming filtered by the fiber mat in those locations. Though it has not been reported, a similar mechanism may be responsible for some of the effects achieved by traditional water-mark systems, in which patterns are conveyed to the paper by relatively large wires, and the effects can be viewed in transmitted light through the paper (Boniface 2000; Hubbe and Bowden 2009).

Uniformity of Formation

Crowding number and floc formation

Factors affecting the uniformity of formation of paper were considered more fully in an earlier review (Hubbe 2007). A couple of key points from such analysis are worth highlighting here: First, the inherent tendency of wood-pulp fibers to become mechanically flocculated can be predicted by the crowding number N (Kerekes and Schell 1992; Kerekes 2006). The value of N is related to the square of the predominant ratio of length to width of the fibers (the aspect ratio) and linearly related to the consistency. Celzard *et al.* (2009) discuss how the crowding number can be used to differentiate situations when fibers in suspension come into frequent contact ($N = 1$), tend to become connected ($N = 16$), and tend to form a relatively rigid structure ($N = 60$). Papermaking headbox stock is often in the range of $16 < N < 60$. Fiber flocs tend to be formed when tiny eddies of flow cause momentary bending of the fibers, which then can get trapped as self-sustaining flocs when the elastic forces act to straighten out the fibers (Parker 1972; Norman 1989). In addition, flocculation can be increased by certain chemical additives (Hubbe 2007). In general, a less uniform or flockier formation has been found to give rise to more rapid initial dewatering (Helmer *et al.* 2006). However, initial dewatering is not the only important goal of papermakers. As noted by Kiviranta (1993) the three important goals of formation uniformity, retention of fine particles in the sheet during formation, and rapid initial dewatering cannot be achieved simultaneously. In general, a web with more uniform formation has been found to dewater more effectively during vacuum application (Baldwin 1997). This finding is consistent with a compression-dependent mechanism of dewatering, for which air leakage through the sheet is to be avoided.

Effects of flocculants, etc.

The kinds of chemical additives that tend to have the greatest effect in promoting flocculation of the fibers are the very-high-mass acrylamide copolymers, *i.e.* the retention aids (Wegner *et al.* 1984; Hubbe 2007). Related effects also can be produced, to some extent, by highly cationic, intermediate molecular mass polymers (Gruber *et al.* 1997) and by cationic starch products (Roberts *et al.* 1986). Some of the most dramatic results showing the effects of such additives on rates of dewatering were those of Britt and Unbehend (1980, 1985). Their results showed that gravity drainage was promoted, to increasing extents, by treatment of bleached kraft furnish with (a) rosin and alum, which would work by a charge neutralization mechanism, (b) poly-ethyleneimine (PEI), which would work by a charged patch mechanism, and (c) successive addition of PEI, then very-high-mass anionic polyacrylamide (aPAM) retention aid, which would work by a an aggressive polymer bridging mechanism. But when exactly the same treatments were compared using the application of vacuum, the results were reversed. The most effective vacuum dewatering was achieved in the case of the blank, untreated stock. The wettest sheets at any point during vacuum dewatering were those prepared with the two-part flocculant system. Such results are consistent with the channeling of either water (early in the dewatering process) or air (later in the dewatering process) around fiber flocs, which would tend to retain their water. Water present within the flocs might be regarded as being relatively “unavailable” in terms of the flow of water from the sheet (Kyan *et al.* 1970; Lindsay 1994; Jones 1998). Fortunately, the same researchers found a practical way to overcome the problem. By applying sufficient hydrodynamic shear to the mixture prepared with the two-part flocculant treatment, they achieved the most promising results of all for both early dewatering and vacuum dewatering in the course of tests on a pilot paper machine (Britt and Unbehend 1980).

The idea of applying hydrodynamic shear to overcome the undesired flocculating effect of retention aids can prompt the following critical question: Would such shearing merely reverse any benefits contributed by such treatments in promoting the retention of fine particles during paper formation? Fortunately, it appears that by appropriate adjustment of chemical dosages relative to the prevailing hydrodynamic shear levels, one can achieve the favorable combination of relatively uniform retention, increased retention efficiency of fine particles, and enhanced dewatering (Britt 1991). The mechanism can be traced to an inherently greater intensity of shear stress that is required to remove smaller rather than larger particles adhering to surfaces (Hubbe 1985). A practical way to achieve such effects during commercial papermaking can involve addition of the high-mass retention aid before the pressure screen rather than after the screen of a typical paper machine system (Hubbe and Wang 2002).

Thickening and Refluidization

When envisioning what happens during dewatering of paper, two contrasting simplified models are filtration and thickening (Whitney *et al.* 1955). These two limiting models are illustrated in Fig. 8. The filtration model can be well understood by considering the formation of a handsheet from a highly dilute fiber suspension. In that case, as water is drained through a screen, a mat gradually accumulates on the screen. Above the mat, the suspension will resemble the original suspension, before drainage started. The thickening mechanism, in its pure form, envisions that the distribution of solids remains uniform during dewatering. Such a situation would be expected to be favorable for dewatering, since then there would be no dense layer adjacent to the screen. But the more challenging issue consists of figuring out practical ways to achieve such an effect. During initial dewatering, filtration dewatering is likely to dominate, as the used pressure levels easily compress the filtrating fiber suspension; for consistencies lower than 15% the structural pressure of pulp fiber networks is typically clearly below 1 kPa (Kataja *et al.* 2008).

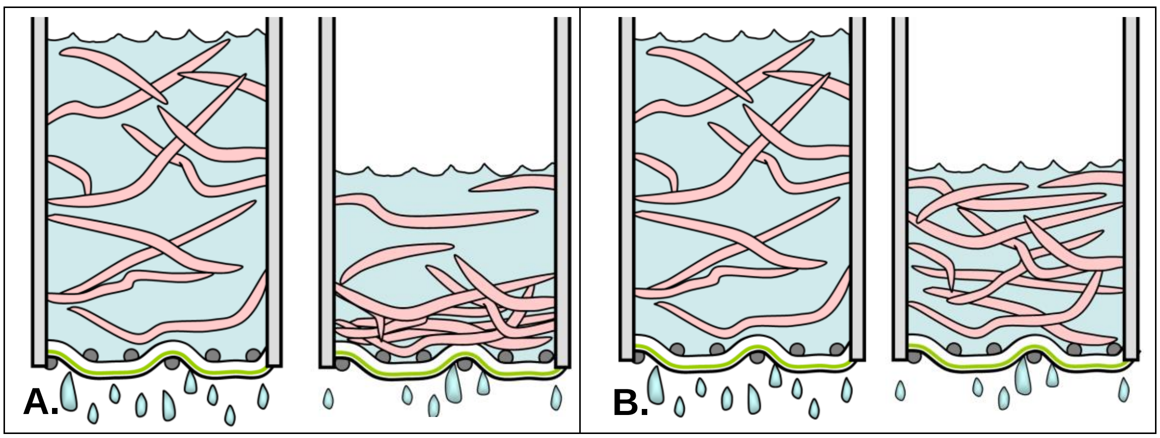

Fig. 8. Schematic depiction of (A) filtration dewatering and (B) thickening dewatering

One way to encourage a more uniform distribution of solids during a dewatering process is to periodically reverse the flow, perhaps in tiny increments (Persson and Österberg 1969; Britt *et al.* 1986; Norman 1989; Unbehend *et al.* 1989; Giles 1990; Staib 1991; Sutman 2000). On a commercial paper machine, such effects can be achieved by selection and adjustments of hydrofoils and drainage blades (Kapoor 1986; Eames 1993). A similar effect has been documented at the leading edges of flatboxes, especially for the earlier flatboxes on a paper machine (Attwood 1960, 1962; Miller 1998; Mitchell and Johnson 2000). Though efforts to refluidize the wet web, by means of hydrofoil pressure pulses, generally tend to promote a uniform appearance of paper and more rapid dewatering, excessive application of this approach can be expected to hurt paper strength. For instance, decreases in strength were observed when excessive levels of forming blade action were applied during twin-wire forming on a pilot paper machine (Nordström and Norman 1996; Nordström 2006). The mechanism of formation improvement in twin-wire blade forming differs from the re-fluidization discussed thus far, which is from spouting motions in Fourdrinier formers. By contrast, blade action in twin-wire formers creates a relative flow in the MD direction between undrained stock and the formed mat. This moves parts of flocs not anchored in the mat over a bit, thereby improving formation uniformity. Though this leads to lower strength, in particular internal bond strength, it also leads to some increase in MD fiber orientation. This formation improvement mechanism is described in Kerekes *et al.* (2007).

Plugging of Drainage Channels

Explanation of the concept

It is well known that high levels of cellulosic fines tend to slow down most phases of dewatering of paper, especially when the basis weight is relatively high. This can be demonstrated dramatically when kraft pulp is heavily refined, then processed with a Bauer-McNett classifier to remove the cellulosic fines. The initial refining will greatly decrease the freeness of the pulp. But after the fines fraction has been removed, the freeness typically will again resemble that of unrefined or slightly refined pulp.

The explanation for the effect, as described in various earlier articles (Britt *et al.* 1986; Szikla 1986; MacGregor 1989; Patel and Trivedi 1994; Kumar *et al.* 1996; Räisänen 1996; Gruber *et al.* 1997; Hubbe 2002; Wildfong *et al.* 2003; Hubbe and Heitmann 2007; Chen *et al.* 2009; Hubbe *et al.* 2009; Rantanen and Maloney 2013; Sjöstrand *et al.* 2019), is illustrated in Fig. 9.

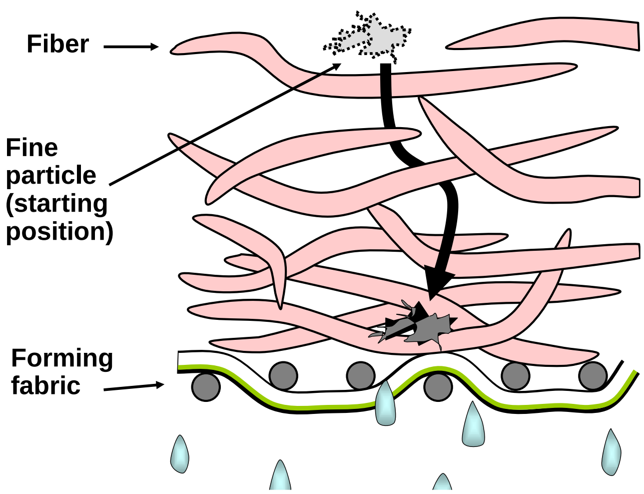

Fig. 9. Schematic diagram depicting plugging of a drainage channel by a cellulosic fine particle that is not well attached to a fiber in the wet web

Briefly stated, the channel-plugging mechanism can be described as being a consequence of the presence of fine particles that are not firmly attached to fiber surfaces, small enough to be transported by flowing liquid, but large enough to become trapped, especially if there are densified layers of the fiber mat (Hubbe and Heitmann 2007). Because the plugging mechanism depends on there being enough fines to effectively plug up a finite number of effective channels, dependencies can be expected on such factors as the amounts of fines and their sizes.

Though some aspects of the problem under consideration are specific to the dewatering of paper, it is worth noting that relating phenomena have been reported in other fields, such as in groundwater flows or in enhanced oil recovery from porous rock strata. In such cases, as noted in an earlier review article (Hubbe *et al.* 2009), relatively small amounts of fine particles can sometimes come loose from their resting places and effectively seal up strata in deep underground locations, effectively stopping useful amounts of flow. The science of such plugging mechanism has come to be known as the percolation theory (Broadbent and Hammersley 1957; Berkowitz and Balberg 1993), as suggested by the flow of water through a bed of coffee grounds. A key principle of such theory, as well as many developments in mathematical models, is that flow can take place only if there is at least one contiguous open channel between the defined input and output surfaces.

Dependencies of plugging on fines content, basis weight, or type of fines

Some support for the mechanism shown in Fig. 9 is related to effects of the fines content, the types of fines, and the basis weight on the dewatering of paper sheets. First, it is well known that increased levels of fines in paper stock tend to slow down drainage, as shown in freeness tests and related devices (Nordman 1954; Ingmanson and Andrews 1959; Steenberg *et al.* 1960; Molina *et al.* 1984; Ormerod 1984; Britt and Unbehend 1985; Britt *et al.* 1986; Szikla and Paulapuro 1989; Gess 1991; Mantar *et al.* 1995; Gruber *et al.* 1997; Wildfong *et al.* 1999, 2000b; Hubbe 2002; Chen *et al.* 2009; Rousu *et al.* 2010).

The type of fine material can play a key role. Highly fibrillar cellulose fines, as formed in the course of mechanical refining of kraft pulps, have been shown to have much greater adverse effects on dewatering in comparison to parenchyma cells already present in a kraft pulp suspension before refining (Hubbe 2002; Cole *et al.* 2008; Hubbe *et al.* 2008; Chen *et al.* 2009). In addition, the finer the size fraction, in general, the greater usually will be the adverse effect on dewatering (Steenberg *et al.* 1960; Przybysz and Szwarcsztajn 1973; Patel and Trivedi 1994; Liu *et al.* 2001; Htun and de Ruvo 1978). The general trends shown in these studies are consistent with either or both of two mechanisms. One is the Kozeny-Carman equation (consistent with the high specific surface area of the fibrillar fines), and the other is the plugging of drainage channels (consistent with the tendency of fibrillar fines to be stuck and thereby block drainage channels).

Effects of basis weight also can be used as evidence with respect to the mechanism of plugging of drainage channels. As depicted in Fig. 9, effective plugging is much more likely if there is a lot of material, a lot of fine matter, and self-filtration of the fine matter by densified layers adjacent to a forming fabric. The following studies showed increases in fines-sensitivity of dewatering with increasing basis weight (Brundrett and Baines 1966; Gess 1991; Wildfong *et al.* 2000a,b; Paradis *et al.* 2002). Chang (1978) found that the hydraulic pressure generated during simulated wet-pressing increased strongly with basis weight, which is consistent with the proposed mechanism. In related work, it has been shown that higher basis weight can lead to more effective filtration of fine particles during the formation of paper (Athley *et al.* 2012).

Z-directional fines distribution

Additional support for the mechanism depicted in Fig. 9 comes from studies that have characterized the z-directional distribution of fine particles in paper (Britt 1981; Tanaka *et al.* 1982; Egelhof and Bubik 1994; Zeilinger and Klein 1995; Wei *et al.* 1996). An important point to bear in mind is that the distributions of fines or fillers in paper can be dramatically changed by the action of hydrofoils, which tend to wash fine particles from the wire side of the paper (Zeilinger and Klein 1995). Pertinent to the topic of the following subsection, it should be noted that addition of retention aids has been shown to render the z-directional distributions of fine particles much more uniform (Tanaka *et al.* 1982; Serles and Green 2013; Singh and Green 2015).

Retention aid effects

A key strategy to overcome the effects of the mechanism depicted in the previous figure is to use an effective retention aid program. The idea is to attach each of the fine particles securely to a fiber surface. The concept is illustrated in Fig. 10.

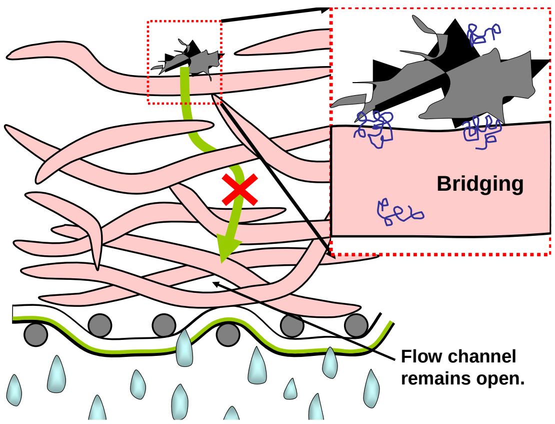

Fig. 10. Concept of using a retention aid system to hold fines onto fibers and thereby prevent them from plugging up drainage channels in a wet web of paper

The mechanism depicted in Fig. 10 is consistent with beneficial effects of retention aid usage in many papermaking systems where there are substantial amounts of fines present (Britt and Unbehend 1980; Davis *et al.* 1983; Räisänen 1996). In the case of the work by Britt and Unbehend (1980), it is important to point out that the benefits were seen only after the treated furnish had been agitated sufficiently to break down the fiber flocs and achieve sufficiently uniform formation of the sheet. The work by Davis *et al.* (1983) is notable because it represents a very rare case in which researchers have clearly demonstrated a beneficial effect of chemical addition on the removal of water under simulated wet-pressing conditions.

Further support for the concept shown in Fig. 10 is provided by some studies based on retention of materials other than ordinary cellulosic fines. For instance, Balea *et al.* (2019) studied the effects of nanofibrillated cellulose on the dewatering of paper. In that work the nanocellulose slowed down the drainage, but the effect could be overcome by optimizing the retention aid system. Athley *et al.* (2012) employed quartz particles having sizes in the range between a few µm to about 100 µm. Retention increased linearly with particle size, which is consistent with a mechanical filtration mechanism, as depicted in Fig. 9.

Contrary evidence and alternative explanations

Not all studies that have considered the subject have found evidence to support the channel-plugging mechanism. For example, Szikla (1986) concluded that such a mechanism was not important for the wet-pressing systems that they studied.

When seeking other ways to account for effects of fines on dewatering, other than the channel plugging mechanism, a likely candidate would be the Kozeny-Carman equation. This relationship predicts that the resistance to dewatering increases as the square of specific surface area. Practical studies reported by Marton (1980a,b, 1982) have shown that cellulosic fines typically behave like they have specific surface areas in the range of about 2 to 20 times larger than typical kraft fibers in the same mixture.

Sealing Phenomena

When addressing the topic of sealing, it may be important to distinguish two levels of focus – a general focus, and a specific focus related to the permeability of the forming fabric, as affected by an initial layer of fibers.

General sealing effects

As a general definition, sealing means that a material is able to deform under pressure in a manner that closes off possibilities for flow of a fluid. In general, sealing behavior can be expected to increase with increased deformability of fibers, which is often associated with the increased refining of kraft fibers. Thus, Paulapuro (2000), in his chapter, stated that easily conformable materials can be expected to form structures having low permeability. This is consistent with the term "ability of the furnish to pack," as used by Sampson and Kropholler (1995) to characterize systems of high resistance to drainage. Modelling of sheet sealing is challenging; continuum models tend to overestimate the effects of sealing, as the relation between the network density and its flow resistivity is highly non-linear (see Eqs. 5 and 6). Experimental evidence for the effect of fiber flexibility and strength of initial dewatering on sheet sealing was given by Koponen *et al.* (2015), where sealing was studied by using a filtration device that enabled profiling with pressure levels that were comparable with those used in real life paper machines. For (on the average) more flexible LWC fibers and NSSC fibers, the solids contents of the filtered sheets were 1.5% and 0.5% higher with gradually increasing pressure profiles, respectively, when compared to constant pressure profiles. Kataja *et al.* (1995), in their study of compressed paper webs, noted that compressible materials tend to form relatively large areas of close content between adjacent solid entities, and such a characteristic seems consistent with a sealing mechanism. In dynamic wet-press simulators of the type where a hydraulic component of pressure is evaluated (Wahlström 1969; Chang 1978; Carlsson 1984; Szikla and Paulapuro 1989), one might anticipate that sealing effects would tend to show up as a high ratio of apparent hydraulic pressure relative to the total applied pressure. However, lower values of that ratio also could be possible if a sufficiently aggressive sealing effect at the entrance to the pressure-sensing space, where the transducer would be located, also affected the measurement of hydraulic pressure.

The expected correlation between fiber conformability and resistance to dewatering at the wet press, consistent with a sealing mechanism, has been borne out in several studies (Nordman 1954; Andrews and White 1969; Attwood and Jopson 1998a,b; Sjöstrand *et al.* 2019). Nordman (1954) reported cases in which continued dewatering by application of air pressure resulted in no additional passage of water when the pulp had been refined to the relatively high level represented by 80 degrees of Schopper-Riegler. Likewise, Sjöstrand *et al.* (2019) documented relatively high amounts of water retained in sheets containing highly conformable dialcohol cellulose fibers after they had been subjected to vacuum dewatering. However, both sets of results just mentioned don't necessarily imply a sealing effect. Rather, they also could be explained based on the high water retention value of the dialcohol cellulose fibers or by channeling of the lower viscosity fluid (air) through the porous media.

There are many factors that can be expected to affect sealing behavior. For instance, sealing behavior might be facilitated by an ability of the material to slide when in contact with other solid surfaces, thus facilitating the formation of dense layers (Hubbe and Heitmann 2007). Also, it has been proposed that shorter fibers may be more easily forced into dense structures (Jones 1963). Kerekes and McDonald (1991) in their decreasing permeability model, raised the possibility that rather than complete blockage, the situation may be modeled as compression of the material such that potential drainage channels around or through the fibers become progressively smaller with increasing applied pressure.

Sealing related to the forming fabric

Results of several studies have suggested that interactions between an initial layer of fibers and a forming fabric can have a decisive effect on the apparent permeability of the system and hence on the effectiveness of dewatering (Andrews and White 1969; Fleischer *et al.* 1978; Jong *et al.* 1999; Xu *et al.* 2010). In other words, the permeability of the forming fabric by itself can be a poor predictor of the apparent permeability when a layer for fibers interacts with it (Kufereth 1982c; Sjöstrand *et al.* 2017). A commonly recommended approach to avoid such situations is to minimize the volume of early drainage (Giles 1990). This is consistent with a view that fabric sealing might be a consequence of fibers being driven against the forming fabric with high pressure. Consistent with this idea, Miller (1998) suggested that fabric sealing happens when rapid drainage causes fibers to become compressed into or within the fabric at an accelerated rate, leading to higher than expected resistance to dewatering. Sealing would thus be due to inertial effects. Jong *et al.* (1999) showed evidence of fabric-fiber interactions in the form of deviations from Darcy's law.

Important evidence regarding the mechanism is provided by studies in which significant differences in dewatering were achieved just by flipping a forming fabric over and utilizing the reverse side (Fleischer *et al.* 1978; Kufereth 1983). The fact that the dewatering results are often very different indicates that such effects cannot be attributed to the permeability of the fabric by itself, but rather that fabric-fiber interactions are important.

An intriguing conceptual model to explain fabric sealing and also a potential strategy to minimize such effects was shown by Kufereth (1983). Figure 11 is inspired by a graphic in the cited work.

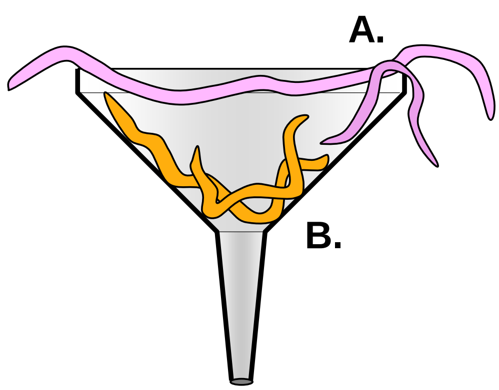

Fig. 11. Concept of a funnel to represent two limiting ways in which the first layer of fibers might interact with a forming fabric, thus resulting in differences in the apparent permeability of a system comprising the forming fabric and the first layer of fibers, *i.e.* fabric sealing

As shown, one envisions the surface of the forming fabric as acting like a series of funnels. In each case there are two limiting possibilities. First, if the fibers mainly end up bridging the outer, wide parts of each conceptual funnel ("A" in the figure), then a relatively high permeability of the system including the fabric is expected. However, if cellulosic material gets wedged into the throats of the funnels ("B" in the figure), perhaps representing the minimum dimensions as water passes into the first layer of the fabric, then a fabric sealing effect, negatively affecting the permeability of the system, will be expected.

Another potential source of information about the mechanism of fabric sealing might be based on the detection of wire-mark in the resulting paper. An example of this is provided by Sjöstrand *et al.* (2019). They reported a very pronounced wire-mark for a sheet containing highly conformable di-alcohol cellulose.

Air Breakthrough

Water displacement by air

When vacuum is used to remove water from the wet web of paper, initially it might be sufficient just to assume that only two phases are present within the material itself, *i.e.* the fiber solids and water. In support of this view, Sjöstrand *et al.* (2019) found this to be true during the first millisecond of vacuum dewatering, consistent with a water-saturated web of paper. But in order for the process to have approached its full potential, eventually at least some of that water ought to be displaced by air. Campbell (1947) posed the question, "at what stage does air pressure begin to blow through the sheet after having shoved the water ahead of it through the porous mass?" Until that point, the vacuum can be expected to be acting more effectively to compress the sheet. After than point, the sheet is expected to expand (Nordman 1954). Brundrett and Baines (1996) envision a process by which a succession of smaller pores become relatively free of water with increasing levels and durations of applied vacuum. Any ineffective sucking of air by vacuum pumps is of concern due to the cost of electricity for operating the vacuum pumps (Nilsson 2014b). However, Pujara *et al.* (2008b) observed a positive correlation between the flow of air and the final solids. Tarnopolskaya *et al.* (1999) modeled a mixed system in which both water and air were assumed to be present in a wet web subjected to vacuum dewatering.

Predicted capillary resistance

One kind of force that can be expected to oppose the entrance of air into a wet web of paper subjected to vacuum dewatering can be attributed to the presence of a meniscus at the surface of pores, where the internal water phase present in the interior meets air. If the size of the capillary is known, and if it is modeled as an ideal cylinder, then the maximum pressure can be estimated from the capillary equation,

$$\Delta P = 2\,\gamma / R \tag{14}$$

where γ is the interfacial tension and R is the effective radius used to model the interaction. However, the limitation of capillary models for the analysis of vacuum dewatering is the fact that fibrous networks at this stage of dewatering have still quite high porosity, are very heterogeneous relative to their thickness and have a void structure composed of multi-connected pores. The air has a high relative freedom of choosing the optimal flow path in the structure, and the pressure gradients developed around the water droplets inside the sheet are often smaller than those calculated from the average pressure loss over the sheet.

The principles just described have been used as a way to characterize the distributions of pore sizes within textile specimens (Miller and Tyomkin 1986). This is accomplished by applying a hydrostatic suction, which can be adjusted by changing the elevation of the damp specimen above the level of water in a receiving vessel resting on an automatically recording analytical balance. The first increase in recorded mass provides information about the largest capillary size characterizing the fabric. The process is continued at successively higher hydrostatic heads in order to obtain an estimate of the distribution of pore sizes. The cited authors expect that even at the highest pressure applied, some water will remain in the specimen. However it was noted that such water usually represents only a minor portion of what was original present in a typical fabric specimen.

Based on the findings just cited, it is proposed here that a similar effect would be expected when a wet web of paper is subjected to sufficiently high vacuum. Figure 12 depicts a simplified view of what might be expected at the start of such a process, assuming application of a vacuum level that happens to be the maximum that does not yet exceed the critical value needed to pull water from the largest of the capillary openings, as suggested by Eames and Moore (1976) and by Kufereth (1982b). For simplicity, both the pulp fibers (shown as pink ovals) and the strands of forming fabric (shown as green circles) are imagined to be perpendicular to the plane of view. If one makes the additional working assumption that the radii characterizing pore openings near the surface of the fiber mat are nearly equal, then one can expect there to be a critical pressure that permits maximum compression and dewatering of the mat during gradual application of vacuum, such that effects due to viscous flow and time can be ignored.

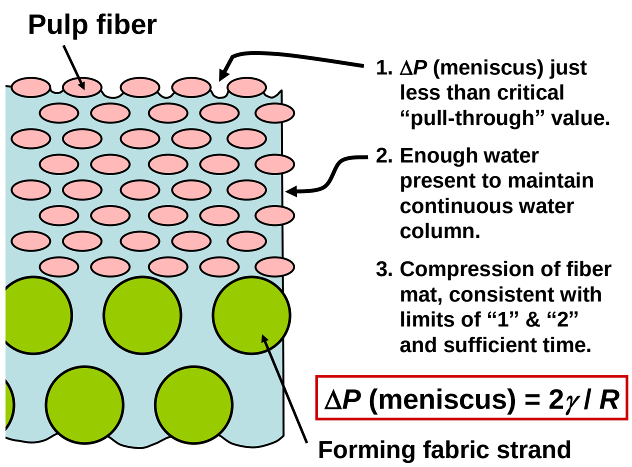

Fig. 12. Concept of capillary resistance to displacement of water by air during application of vacuum, possible contributing to compression of the wet web, especially primary to break-through of air, when the change in pressure exceeds a critical value

Considering the situation shown in Fig. 12, Brundrett and Baines (1966) made estimates of inertial effects, due to the need to accelerate the water from an initial rest state, and estimated that the related forces could be ignored in comparison to capillary forces and viscous forces. The cited authors found a much higher breakthrough pressure for newsprint pulp, in comparison to bleached sulfite. This is consistent with an expected high level of fine particles in the newsprint pulp, giving rise to a low value of R in Eq. 14 and consequently a higher expected breakthrough pressure. Campbell (1947) noted that a model such as that shown in Fig. 12 implies a compressive pressure that can be calculated from the product of interfacial tension times the sum of the perimeters of the fibers in the uppermost layer.

Evidence supporting the action of capillary forces has been presented in various studies. Fleischer *et al.* (1978) observed that during constant rate filtration the pressure would build up to a sharp peak and then decline. Such a peak could represent the highest applied pressure before the start of breakthrough of air. Jones (1998) suggested that the inability of vacuum to remove all water present in paper can be attributed to an inability of air to displace water from the smallest pores, which is also consistent with there being an important role of capillary forces. Tarnopolskaya *et al.* (1999) found evidence that capillary forces of some kind were important for dewatering, but they were not able to clearly distinguish whether those effects were due to meniscus pressures or the viscosity-dependent forces needed to move fluid through narrow passageways in the material.

Effects of surfactants

In view of the form of Eq. 14, it is logical to expect that the resistance to meniscus breakthrough would be decreased if something was done to decrease the interfacial tension. In support of this expectation, Lindqvist *et al.* (2009, 2012) observed increased dryness and decreased dewatering time after vacuum dewatering of fiber suspensions to which a nonionic surfactant had been added. The same effect was obtained in Lehmonen *et al.* (2020) with sodium dodecyl sulfate, which is an anionic surfactant. A related effect might help explain the benefits obtained from higher temperature during dewatering; in addition to decreasing the viscosity of the water, the surface tension also is decreased (Opherden and Rudolph 1980; Powell and Cutshall 1985; Räisänen 2000a). Addition of surfactants during conventional papermaking has not been widely practiced, however, probably due to concerns related to foam stability and adverse effects on hydrophobic sizing.

Membrane use to prevent breakthrough

As a means to evaluate the relative importance of air breakthrough during vacuum dewatering, certain researchers carried out tests with an impermeable membrane placed on the upper surface of a wet web of paper during application of vacuum to the lower surface. Åslund and Vomhoff (2008a,b) observed a lower consumption of air and a similar dryness in comparison to parallel tests in which air was not physically prevented from entering the top surface of the specimen. Similar tests by Brundrett and Baines (1966) showed that breakthrough of air is not essential, up to a point, when the goal is to achieve effective dewatering by vacuum application. When Räisänen (1996) carried out similar tests, he concluded that the passage of air was unfavorable for dewatering under the conditions employed. However, when evaluating a counter-intuitive approach of placing an impermeable membrane to block the flow of liquid into a wet-press felt, Sweet (1961) confirmed the logical expectation that, in that case, there is no point in obstructing the flow of water into a felt.

Viscosity-related forces

As was discussed in the context of the Lucas-Washburn equation (Lucas 1918; Washburn 1921), which predicts rates of wetting of porous solids by suitable liquids, it is reasonable to expect that forces attributable to the viscosity of the aqueous solution will act in parallel to the just-mentioned meniscus forces in impeding flow through a wet web of fibers. In other words, the Poiseuille equation (Eq. 9) is applied, using reasonable estimates for the value of the radius of a typical pore and for the contact angle; a zero value of contact angle can be assumed when perfect wetting is expected (Brundrett and Baines 1966). Han and Ingmanson (1967) estimated that viscous forces have a dominant effect during simple filtration, though they did not consider meniscus effects.

Ineffectiveness of high vacuum beyond a limit

According to tests reported by Attwood (1960), there is no benefit to be expected from applying very high vacuum, above a certain level, *e.g.* 40 kPa. Such an observation is consistent with the concept mentioned earlier that some water present in a damp specimen of paper may be isolated in such places as lumens, cell walls, and blocked-off zones (Kyan *et al.* 1970; Lindsay 1994; Jones 1998). Also, once columns of water are no longer present in the material, the compressive effects of a meniscus will no longer be present, and the viscous effect of the air can be expected to be much less effective in compressing the sheet in comparison to the flow of water, which is much more viscous.

Displacement dewatering

A different set of goals and constraints presents itself when papermakers set out to prepare a highly bulky tissue product, using through-air-drying technology. In such cases, as a means to achieving the lowest practical value of apparent density, the wet web is not subjected to substantial pressing. Rather, hot air dewatering is applied in such a way as to displace water from the sheet and then evaporate the remaining water (Ryan *et al.* 2003; De Assis *et al.* 2018). Lindsay (1992) reported an alternative technology in which the goal is to displace the water by air or steam while the system is under mechanical pressure. The process showed promise for production of specialty grades of paper. The main drawback observed during the testing was that relative long applications of pressurized air were required.

Stratification

Wet-press nips

For many grades of paper, the manufacturer and the client alike would be most pleased if both sides could be exactly the same. But significant deviations from that goal can occur during wet-pressing, and the same factors that lead to such issues also can be expected to affect dewatering. It has been shown that paper tends to be densified in a layer nearest to where water leaves from the wet web (Paulapuro 2000, 2001; McDonald 2020).

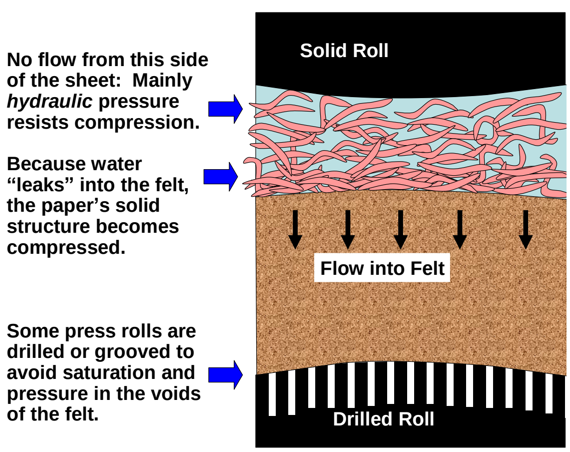

Fig. 13. Schematic diagram of stratification of a paper web within a single-felting wet-press nip

An excellent description of stratification, including a modern-sounding explanation of its causes, was provided by Campbell (1947), who stated that the idea already had been well established in soil mechanics by that time. He attributed densification to the fact that, after water is able to leave the wet web and enter the felt, it is no longer present in the nearest layer of the wet web to support the structure of the fibers. Not being supported by hydraulic pressure, the fibers near to where water exits the sheet are subjected to dewatering of their cell walls and lumens, thus forming a densified layer. From another perspective, the densification of the layer from which water exits the sheet can be attributed to an accumulation of hydrodynamic drag forces on fiber in the direction of drainage. Figure 13 provides a schematic diagram of this situation. This subsection will consider the evidence concerning such changes in density, *i.e.* stratification, in addition to consequences related to rates of dewatering.

The occurrence and extent of stratification in single-felted wet-press nips has been shown in various studies, including in tests with wet-press simulators (Chang 1978; Szikla 1986; Burns *et al.* 1989) and pilot machine trials (McDonald 2020). Chang noted that the densification of the surface layer was especially apparent in cases of relatively low permeability of the material, *i.e.* to an increasing extent with increased refining. Szikla (1986) determined that although the densification of the layer adjacent to the felt was clear, there was no corresponding evidence in the specimens indicating any relative movement of fine materials in relation to the fibers. MacGregor (1983a,b; 2002) presented cross-sectional images of pressed sheets that clearly showed closed-up layers that had been adjacent to the felt during pressing. The cited author noted that such effects may become more prominent when rates of dewatering are high, leading to strong hydrodynamic forces. He also cited an unpublished presentation by Bergström in 1959, which provided further evidence of the phenomena and provided an explanation.

Sealing by a dense layer

Campbell (1947) proposed that a layer with higher density would tend to serve as a barrier to the flow of water. MacGregor used the term "plugs up" to describe the layer nearest to the wet-press felt. Chang (1978) used the term "interface controlled pressing" to describe a situation in which a densified layer provides a sealing effect. In no case, however, did any of these researchers manage to separate layers and separately evaluate their permeability. In fact, it appears that the phenomenon is somewhat delicate. Szikla and Paulapuro (1989) reported that specimens of wet-pressed paper that had been freeze-dried rather than air-dried failed to retain the stratified density structure.

Rewetting

The reality of rewetting

There is quite convincing evidence that significant rewetting of paper webs takes place, for instance right after a high-vacuum flat-box, at the couch (McDonald 1999), or in the outgoing part of the nip, or later, in the case of wet-pressing (McDonald and Kerekes 1995; McDonald *et al.* 2000). However, there have been widely different views not only regarding what might be the primary cause or causes, but also regarding whether the amount of rewetting is significant (Paulapuro 2000). Part of the problem seems to stem from the fact that one usually does not have an independent way to evaluate the true content of water within the wet web during its passage over a vacuum slot or through a press nip. Thus, as stated by Chang (1978), a higher than desired moisture content in the outgoing sheet might be ascribed to rewetting, to inadequate dewatering in the first part of the pressing cycle, or both causes in combination.

Rewetting after a vacuum flatbox has been attributed to picking up water from the forming fabric (Granevald *et al.* 2004; Sjöstrand *et al.* 2015). Because vacuum is able to compress the sheet, it is logical to expect that water may enter back into the sheet when it expands once the vacuum pulse ceases. It is worth bearing in mind that the forming fabric often can hold about 100 to 600 g/m^2 of water (Sjöstrand *et al.* 2015). In addition, the wet web and the forming fabric typically remain together for several more seconds after each vacuum event, providing opportunity for water to pass through narrow passageways back into the paper.

In the case of wet-press nips, Jaavidaan *et al.* (1988) estimated that 30% of the water pressed from a typical sheet in the web will tend to be taken up again by the web of paper. These estimates were made based on thickness measurements on a wet-press simulator, while assuming that the main direction of water movement, on both sides of the center of the nip, is perpendicular to the plane of the sheet. Rantanen and Maloney (1990) showed that pressing of low-basis-weight sheets containing highly fibrillated cellulose resulted in removal of so much water that it could only be accounted for by assuming the squeezing out of water from the cell walls. To account for the final mass, it was necessary to assume that some of the pressed-out water had returned to the paper.

I'Anson and Ashworth (2000) proposed that rewetting is slowed down by a densified layer of fibers on the side(s) of a sheet facing a press felt. Note that this explanation is consistent with the stratification mechanism discussed in the preceding subsection. Thus, water may remain between the batt fibers of the felt and the paper web after the press impulse, but its flow back into the paper web is predicted to be slow.

McDonald and Kerekes (2018) developed a model of rewetting in pressing that consisted of two terms: a "flow" rewet term and a "separation" rewet term. In the expanding nip of the press, as pressure is released, air enters the felt and paper, so that capillary pressures cause water to flow from the felt to the paper. If the felt and the paper remain in contact after the press nip, this flow will continue. This is called post-nip rewet. Both in-nip and post-nip rewet are elements of the "flow" term, which is proportional to the square-root of contact time. When the felt and paper separate, the water at their interface tends to remain with the paper, based on larger surface tension forces. The amount of water is related to the texture of the felt surface and was shown to be proportional the diameter of the batt fibers in the surface layer of the felt. The rewet model equation was shown to be consistent with experimental results from pilot machine trials in the literature.

Elastic re-expansion

Because both vacuum application and pressing tend to momentarily compress the mat, it follows that the damp paper will tend to expand again immediately thereafter in response to its elastic characteristics. For instance, Burton and Sprague (1987) observed immediate spring-back of paper after the midpoint of a wet-press nip to about half of the incoming thickness. Such expansion has been assumed to be responsible for rewetting, whereby the paper web takes up some of the water that had just been pressed out (Wahlström 1969; MacGregor 1989; Jönsson and Jönsson 1992b). Also, it is generally known within the industry that high-yield pulp fibers, including mechanical pulps, tend to have a higher ability to expand again after being compressed.

Paulapuro (2000) argued against the likelihood that elastic expansion can be an effective means of drawing water back into paper after a press nip. This assertion was based on the very tight capillary spaces in the pressed paper web, which implies a low rate of flow. Also, compared to the very high press loads used to expel water from the paper, the restorative elastic forces are expected to be much lower. The fact that densified layers can still be detected after the paper has been removed from a press nip and dried suggests that those layers would remain relatively resistant to rapid uptake of water as a result of expansion. Jones (1963) reported delayed re-expansion of compressed nonwoven fiber mats. Likewise Wahlström (1969) proposed that sheets having a high resistance to seepage, possibly as a result of densification, would be resistant to substantial rewetting related to expansion after the nip.

Another challenge concerns the nature of a typical felt. As explained by Nissan (1954) and Szikla (1991a), felts are designed to be highly permeable. So when they re-expand after a press nip, they become filled by air and water within about 3 ms. In other words, they do not tend to support a vacuum, as would be needed to continue to pull water away from an adjacent paper sheet. Also, the relatively larger sizes of capillary spaces within a typical felt imply a lower capillary forces in comparison to the paper web (see Eq. 8).

Sjöstrand *et al.* (2015) provided support for the re-expansion model, since they found that rewetting after the suction box became relatively large only in cases that the vacuum had been strong enough to compress the sheet. However, the initial rate of rewetting reported by Sjöstrand *et al.* (2015), is higher than the rate of sheet expansion reported by Åslund *et al.* (2008). This implies that the causality of the re-expansion depends on both rewetting and sheet network stability.

After the sheet's passage through the nip or after vacuum application, though there is a lot of potential for re-expansion due to elastic recovery, such expansion is expected to be relatively slow. To the extent that significant expansion takes place before the next unit operation, a likely consequence would be the pulling of water from adjacent layers in the sheet. Räisänen *et al.* (1995a) proposed that in such cases the densified layer might function as a kind of pump, repeatedly being compressed and then expanding, thus contributing to dewatering of the adjacent areas in the paper.

Capillary pressures

One of the distinctive features of the results reported by Sjöstrand *et al.* (2015) for rewetting after vacuum flatbox dewatering was that the determined amounts of rewetting were highly variable. An explanation for this can be attempted based on Fig. 12, which was shown earlier in the context of a discussion of the Lucas-Washburn equation and its likely relevance to dewatering analysis. As a hypothesis, it is suggested that the largest amounts of rewetting might be associated with conditions that happen to be favorable simultaneously for the three criteria listed in Fig. 12: the total pressure just below the breakthrough point for a typical meniscus at the side of the paper sheet opposite to that of the forming fabric, a contiguous column of water present within the paper, and favorable amounts of compression of the mat, allowing for substantial expansion. As mentioned in the cited work (Sjöstrand *et al.* 2015), re-expansion of the sheet can draw air as well as water. The tendency to draw air will tend to be resisted by the same forces already considered, namely meniscus forces at air-water interfaces and viscous forces that depend on the size of the capillaries as well as the velocity and wetted length.

The subject of whether the water column within a pressed damp sheet of paper within the press nip and immediately thereafter and is completely saturated with water remains uncertain, in many cases. Bergström and Kolseth (1989) found that sheets formed from chemithermomechanical pulp (CTMP) had about 40% air volume after pressing, whereas sheets formed from refined bleached kraft fibers contained about 1 to 4% air by volume.

Evidence of a filtering effect of densified layers

Some unique evidence reported by MacGregor (2002) supports the idea that there is substantial flow from the felt back into the web of paper as it re-expands after the midpoint of a press nip. The evidence consists of the previously mentioned membrane that was discovered loosely attached to that side of the sheet during careful experimentation. As noted earlier, the membrane was found to be about 1 to 2 µm in thickness, indicating that it would have been composed of colloidal-size matter, including fibrillar cellulosic fines. A reasonable explanation is that such material could have been forced out of the wet web and into the felt during the course of pressing, but during re-expansion of the sheet some of the water was drawn back up into the paper. The densified surface layer of the paper web, however, would be expected to act as a filter. One can envision the re-expanding paper web itself thus acting as a kind of forming fabric for formation of a sheet from the colloidal material. The fact that the membrane was only intermittently attached to the main structure of the paper (MacGregor 2002) will be familiar to anyone who has attempted to form another sheet of paper on top of one that already has been densified; in such cases the adjacent paper layers can easily be pulled apart, even after drying. This relative lack of ply bonding can be attributed to a lack of inter-leaving between fibrillar elements in the adjacent layers.

Film splitting

Film splitting can be defined as a process by which water that remains between paper and a forming fabric or felt at the moment when the two become separated will tend to be about evenly divided between the two surfaces. To complete the process, one assumes that the transferred water then may have sufficient time to be drawn into the paper web as a result of the action of the two mechanisms already considered. These are capillary suction due to meniscuses (including the Lucas-Washburn wetting mechanism) and suction induced by re-expansion of the web when it is no longer being compressed by vacuum or applied pressure. The occurrence of film splitting, and its significant contribution to rewetting, have been suggested by several researchers (Wrist 1962; Wahlström 1969; MacGregor 1989; McDonald 1999; Paulapuro 2001; McDonald and Kerekes 2018).

Evidence of the probable importance of film splitting as a major factor in rewetting comes from studies involving different basis weights. Wahlström (1969) noted that time does not appear to affect the extent of rewetting after a press nip to a significant extent. This observation is consistent with a mechanism in which the amount of water is determined by a simple splitting of a film of water existing between the paper and a felt, followed by redistribution of at least a substantial part of that water into the paper. Sjöstrand *et al.* (2015) observed that basis weight did not appear to play a significant role regarding how much water was taken up by the web as a result of rewetting. In other words, low basis weight sheets gained proportionately more weight as a result of rewetting. In the case of rewetting after the flatbox, such results reasonably could be attributed to either film splitting or to capillary pressures drawing ever more water from the void spaces of the forming fabric into the narrower capillary channels within the paper. McDonald and Kerekes (1995) determined that the rewet water was best described as a linear combination of water that had just been squeezed out of a press nip and film-split water. Later work by McDonald and Kerekes (2018) demonstrated that the water in the paper-felt interface is drawn to the paper by greater surface tension forces when the paper separates from the felt.

Remedies to rewetting

To the extent that rewetting is governed by time-dependent processes, such as re-expansion of the web and capillary flow after a vacuum flatbox or wet-press compaction, it makes sense to consider possible remedies. Sweet (1961) discussed a strategy that had been considered by Albany Felt Co. that involve rapid separation of the paper web immediately after the press nip, which avoids post-nip rewet but has no effect of separation rewet (McDonald and Kerekes 2018).

DRAINAGE-ENHANCEMENT STRATEGIES

Overview

This next to last main section before the Conclusions will consider some practical strategies that could benefit those who have responsibility in some way for the effectiveness of papermaking operations. As may be clear already from earlier parts of this article, many of the most promising strategies are already well known and substantially implemented in paper mill systems. Some others of them already have been incorporated into the foregoing discussion in this article pertaining to paper machine operations and rate-limiting mechanisms. The purpose of this section is to highlight certain aspects of the papermaking process that tend to stand out as potential areas of focus in the continuing efforts to remove water with greater cost-effectiveness and speed without hurting paper product quality. Because it shares a similar focus, readers who are especially interested in this topic of practical strategies are recommended to read an article by Kiviranta (1993).

Minimizing Early Drainage

Starting at the very beginning of the dewatering process, it has been recommended to avoid excessive early dewatering (Giles 1990; Eames 1993). The concern has been that too high a rate of forming a mat of fibers on a forming fabric may be associated with conditions of high resistance to flow, *i.e.* fabric sealing (Giles 1990). Also, as shown vividly by Britt and Unbehend (1980, 1985), flocculating the stock, as a result of polymer treatments, though it can greatly promote early dewatering, can have a very bad effect on the dryness of paper at the couch, since a flocky sheet will respond poorly to vacuum dewatering.

Velocity forming

The first possible location where an excessive rate of dewatering would be possible would be when there is a steep angle of impingement of the jet of furnish onto a forming fabric (Miller 1998; Herzig and Johnson 1999). This situation can be called pressure forming. The contrasting situation, in which the jet is directed nearly parallel to the forming fabric, is called velocity forming (Kallmes 1986; Wahren 1987). The latter strategy can be justified as follows: By placing the furnish gently on the surface of a Fourdrinier fabric, the initial fibers can be expected to lie down mainly in a horizontal format, as they do during formation of a TAPPI handsheet. They would be less likely to have their ends or middles shoved down forcibly into a void area between adjacent filaments of the forming fabric. Whether or not any of this really matters probably depends on the extent of refining and many other factors.

An especially aggressive form of pressure forming sometimes occurs when the jet of stock is directed downwards steeply and early enough that at least some of the filtrate coming through the forming fabric continues its path while in contact with the breast roll (see Fig. 5), around which part of the forming fabric is wrapped. Such a condition is called breast roll discharge, and it is generally to be avoided (Miller 1998). It occurs when the jet impinges so close to the breast roll that the breast roll acts like a big table roll, creating a suction that draws the jet down into the wire. Harsh jet impingement also has been understood by papermakers as being a contributor to wire-mark problems (Pye 1971). Decreased efficiency of retaining fine particles in the paper is another likely consequence.

Fine weave of fabric surface layer

Strategies related to the design of the forming fabric can benefit by focusing on the image presented by Kufereth (see Fig. 11), in which representative fibers are encountering a funnel, which is representing the surface of a forming fabric. As mentioned earlier, situations analogous to having fibers in the throat area of the funnel are to be avoided, since they would be expected to adversely affect drainage. A counter-intuitive conclusion of this kind of thinking is that a forming fabric with a finer weave as its surface layer might be more resistant to fabric sealing in comparison to a fabric with a more open surface. Indeed, there sometimes can be a negative correlation between the permeability of a forming fabric and the observed rates of dewatering (Giles 1990; Sjöstrand *et al.* 2017). Giles (1990) also suggested that a potential benefit of using a multilayer forming fabric with a suitably fine pattern of weave on its sheet-facing surface might be related to an avoidance of excessively fast initial drainage, as just discussed. A finer pattern on the side facing the paper web also can be beneficial for paper smoothness, which is important for many grades of paper.

Forming board considerations

Another way to minimize early dewatering on a Fourdrinier forming section is to physically block it. That may have been one of the initial ideas behind the placement of a so-called "forming board" under the forming fabric at the location of impingement of the jet (Giles 1990; Miller 1998). A modified version of this approach was described by Eames (1993); the article describes a type of hydrofoil with a designed-in pressure pulse, tending to force water back up into the sheet. Though this can be viewed as a way to moderate the net rate of early dewatering, it also can be viewed as a way to overcome a buildup of density and resistance to flow of the bottom layer paper web adjacent to the forming fabric, which happens to be the next topic to be discussed.

Thickening/refluidizing

Moderation is perhaps the best word to focus on when considering strategies that involve incorporation of thickening and refluidization features into paper dewatering processes. As mentioned near the start of this article, the paper dewatering process as a whole can be regarded as essentially a filtration process. As such, it is natural to expect that stratification will tend to occur with each unit operation of dewatering. Due to the densified layers, it is reasonable to expect that the related effects of sealing and the plugging of drainage channels by fines will be more pronounced. Especially during early dewatering, a tendency for flow to be obstructed by denser layers of fibers adjacent to the forming fabric can be mitigated by action of hydrofoils and dewatering blades. But if the design or set-up of such dewatering elements is too aggressive, then one can expect a decrease in the paper's strength attributes. As already noted, this has been shown in the case of roll-blade twin-wire forming (Nordström and Norman 1996; Nordström 2006). Bearing that cautionary statement in mind, there are some specific ways that papermakers can approach the issues of judiciously refluidizing the paper in an effort to achieve faster or more completed dewatering in the forming fabric section of the operation.

Leading edges of hydrofoils

As has been reported, much can be accomplished with respect to optimally refluidizing the wet web by adjusting details of the hydrofoils. Cadieux (1983) described a "step blade," in which a small initial land area contacts the forming fabric, and then the remainder of the hydrofoil surface is at a lower plane that would not be contacted, except by means of some bending of the forming fabric from its neutral plane. By making those specific changes, Cadieux was able to produce a unique kind of pressure signature, which was found to have useful effects. Likewise, a variant hydrofoil described by Eames (1993) had a short initial angular portion tending to direct an upward spurt of pressure, depending on the angle of the machining. Similarly, a bit later in the dewatering process, there is likely more to be gained by making adjustments of the planing action (Attwood 1962) that can take place at the leading edge of a vacuum flatbox, depending on the details of its shape.

Microturbulence

A Fourdrinier paper machine can be "tuned" by use of stroboscopic illumination of the early forming section, as the stock proceeds out of the slice and down the first part of the table. In principle, the type, angular position, and spacing of the hydrofoils can be adjusted in order to achieve different patterns of intensity and coarseness of the volcano-like micro-turbulence or "activity" of the fiber suspension, which is often called spouting (Kiviranta 1992; Kiviranta and Paulapuro 1992; Miller 1998). The movement of the surface of the wet web can resemble an assembly of seemingly random intermittent spouting. Though it would be tempting to think that the spouting events could be somehow due to such factors as upward flow of water at the leading edge of hydrofoils (Eames 1993; Miller 1998), it seems more likely that a bigger contribution comes from subtle changes in the path of the forming fabric resulting from the vacuum that is applied at each successive hydrofoil. The up and down movements of the forming fabric accelerate the wet web up and down (Sodergren and Neun 2000). When the forming fabric changes its direction from an upward path, the wet web tends to continue in the upward direction. This produces instabilities in the form of spouting, which are visible as surface "activity". A spout is a localized vertical flow of water. The law of continuity requires that each spout draw water laterally from the adjacent zone. This lateral motion is the cause of formation improvement. The intensity can be judged relative to a pictorial scale, in which the highest intensity values lead to separation of water droplets from the peaks of the spouts. Such high intensity is generally to be avoided, since the material that drops back onto the web sometimes will not become well incorporated into the sheet, leading to a dusty sheet of paper.

Because papermakers need to optimize a large number of production goals and paper properties simultaneously, often it is not possible to predict what conditions of microturbulence, along with many other input variables, will achieve the most favorable results. Ahonen (1992) observed that a moderate level of activity, applied early on the forming table, gave them the best results. Excessive microturbulence had a strong negative effect on fine particle retention. In the work described, the lower retention caused the automated system to increase the level of retention aid. The result was a flockier sheet, which was undesirable. Automated detection of table activity has been described (Kiviranta and Paulapuro 1992; Farnood *et al.* 1998). Such systems purportedly can make the adjustment of microturbulence less subjective. Kiviranta (1992) noted their findings that the optimum conditions can involve a recognizable profile of microturbulence.

The frequency of pulsation events can be adjusted. Thus, Giles (1990) suggested that the frequency of pulsation generated by hydrofoils ought to exceed the rate of formation of a mat. Such adjustments in frequency are typically dictated by machine speed and the spacing of hydrofoils. A closer spacing is expected to give a finer scale of microturbulence (Miller 1998). Studies with controllable pulses of flow during dewatering have shown, in principle, that there could be an advantage in being able to independently tune the frequency and intensity of pulsation as a means to optimize the results (Persson and Österberg 1969; Lindberg 1970).

Mitigation of the plugging of drainage channels

In a broad sense, papermakers generally aim to retain fine particles in the wet web during formation of the sheet. However, fine materials tend to be washed out from the layers adjacent to the forming fabric during commercial-scale production on a Fourdrinier forming section (Zeilinger and Klein 1995). Such an effect might actually be viewed as part of a two-step sequence. In the first step, there is some loss of fines from a densified layer adjacent to the forming fabric. But as a consequence, resistance to dewatering is reduced as the sheet passes over subsequent hydrofoils. The cellulosic fines trapped within a densified layer may be acting as a key contribution to resistance to flow through such a layer. Fines that are not retained during a given pass through the forming section mostly are recirculated with the white water back to the fan pump and then they pass again through the forming section, where they could be retained on the second pass, *etc.* Tests by Eames and Moore (1976) suggested that significant washing took place when the average solids content of a wet web was 3%, but no significant washing took place from a web having 9.2% solids.

Deaeration of the Stock

Though the practice of removing dissolved and entrained air from papermaking furnish is well established, the importance of such an operation is often overlooked. Brecht and Kirchner (1959) showed that addition of about 0.75% air, by volume, to papermaking furnish was sufficient to increase the dewatering time during handsheet formation by a factor of more than two. Rauch and Sangle (2000) reported a two-fold increase in dewatering time in pilot papermaking experiments when 0.4% air content was added. Lamminen (2004) likewise found a decrease in drainage rates in the presence of entrained air, but the effect was small. Helle (2000) carried out some highly revealing experiments with different levels of air present in the furnish of a pilot paper machine. The addition of 0.8% air by volume approximately doubled the needed time of application of vacuum to reach the same solids content as an air-free suspension. It has been estimated that the amount of air present in typical paper machine headboxes, usually as a combination of dissolved and entrained air, can be up to 4% on a volume basis, once the pressure is released at the headbox slice (Lorz 1987). Much of the air that comes out of solution as a result of the drop in pressure will then be present as tiny bubbles, which can plug up drainage channels in a manner resembling that of cellulosic fines. A new perspective on the findings just described is provided by recent studies of foam-forming technology (Lehmonen *et al.* 2020). Notably, even with air contents in the range of 50 to 70% it was possible to achieve dewatering rates in the same range as in air-free system.

Mechanical equipment for the removal of air from papermaking furnish can take different forms. The older type of such equipment involved application of vacuum to remove air from stock, often as it emerged as accepted pulp from a primary set of hydrocyclones, which are used mainly to remove sand from the furnish (Lorz 1987; Matula and Kukkamäki 1997). An alternative type of equipment, involving centrifugal action as white water flows through a rotating cylindrical assembly, has been developed more recently (Helle *et al.* 1999). Whether or not either of these mechanical approaches to air removal is employed, most paper machine systems employ a defoamer formulation, which is typically an emulsion of a water-insoluble surface-active compound or mixture (May and Buckman 1975). Such defoamer formulations work by allowing small bubbles to coalesce into progressively larger bubbles, which tend to separate themselves quickly from the water phase and pop. However, in the absence of mechanical deaeration, drainage rates typically will be suppressed by entrained air within the stock coming out of the headbox.

Formation Uniformity Improvement

Papermakers appear to have the good fortune that a more uniform sheet of paper also tends to be a sheet that has higher solids content after vacuum dewatering, as discussed earlier in this article. The main principle is that a flocky sheet will allow the energy of vacuum pumping to be wasted as air passes unproductively though thin areas or pinholes in the flocky paper, and water will tend to be left behind in the floc areas. Though it would likely be difficult to prove the point, it seems likely that the same trend will hold true during wet-pressing. An unusually thick and wet spot within the paper may be prone to crushing in the nip, meaning that material within the core of the web retreats from the closing nip, which can adversely affect the uniformity of the paper (Wahlström 1969). Papermakers often need to balance quality *vs.* production rates and costs; so it is pleasant to have certain situations in which a quality attribute such as uniform formation tends to be aligned with rapid and efficient production.

Vacuum Box Operation

Vacuum progression

Coming after the forming board, hydrofoils, and low-vacuum flatboxes of a typical Fourdrinier paper machine, the high-vacuum boxes conform to the overall pattern of gradually more aggressive forces being employed to remove progressively smaller proportions of water remaining in the web (Eames and Moore 1976; Skalicky *et al.* 1991a,b; Gagnon and Neun 1996; Baldwin 1997). The graduated progression of increasing vacuum levels is also recommended for successive high-vacuum boxes. Eames and Moore (1976) observed better overall performance, in terms of dryness and energy consumption, when using a sharply graduated arrangement of vacuum levels. Koponen *et al.* (2016) reported a strong linear correlation between maximum achievable solids and how the material responded to the applied pressure difference.

Relatively little has been published regarding the principles and optimization of low-vacuum dewatering. An exception is the work of Hansen (1985), who recommended to begin flat-box dewatering with a pressure low enough to minimize sealing phenomena. This seems a sensible approach in light of the absence of mechanical integrity of the wet web near the start of vacuum dewatering. Presumably as progressively more water is removed from the web, its mechanical strength would become strong enough to bear the next applied level of vacuum. It is important that all the fibers, especially those facing the forming fabric, continue to remain entwined with each other in the mat rather than to act separately, leading to wire mark, fuzziness, and fabric sealing.

Optimization of the number of boxes

At each level of vacuum, the time of application, as determined by the sum of the slot widths at that level and the machine speed, needs to be kept suitably short (Neun 1995; Baldwin 1997). One way to achieve such a goal is to reduce the number of boxes (Eames and Moore 1976; Attwood 1960), if in fact there are too many. Miller (1998) suggested that there was a tendency to have too many slots on a single box; a maximum of eight slots per box was recommended. Such a strategy of minimizing suction time at a given level will tend to avoid a plateau region, where little additional water is being drawn from the sheet. In particular, prolonged application of the highest levels of vacuum are wasteful in three ways. They waste vacuum pumping energy, they increase the amount of wear on the forming fabric, and they increase the electrical power needed to overcome the friction between the forming fabric and the covers of the vacuum flatboxes. Gagnon and Neun (1996) noted that the plateau level, where little more water can be removed, is reached more quickly at higher levels of vacuum application.

The potential trade-off between energy and dryness, as it is affected by vacuum levels and durations, is illustrated in Fig. 14, which is redrawn based on inspiration from Baldwin (1997). Part A depicts the commonly reported finding that flow tends to be rapid at first but reaches a plateau with continued vacuum at a given level. The red line represents energy consumption; it is linear, since the vacuum pumps and paper machine drive motors are assumed to keep working at the same levels. Part B depicts what is expected to happen if the vacuum level of a second box is adjusted so that it now has a higher vacuum setting. The transition between boxes is shown as being near to the point where the first box has stopped being effective. The line representing energy consumption is steeper due to the higher vacuum applied, which requires more pumping energy, and the greater friction between the forming fabric and the cover of the flatbox. Part C represents what is expected if a third box in the series is then adjusted to a yet higher level of vacuum. The same points just mentioned in the previous cycle are expected to continue to be true. The two red boxes in part C compare the solids contents for running just at the lowest vacuum level *vs.* running in a graduated system with three levels of vacuum. It is clear that higher solids could be achieved when using the graduated system. The red circles compare the corresponding expenditures of energy, which happen to be equal, based on how the situation was depicted. Though this hypothetical example is clearly oversimplified, it suggests a need for optimization of vacuum levels and durations of vacuum application.

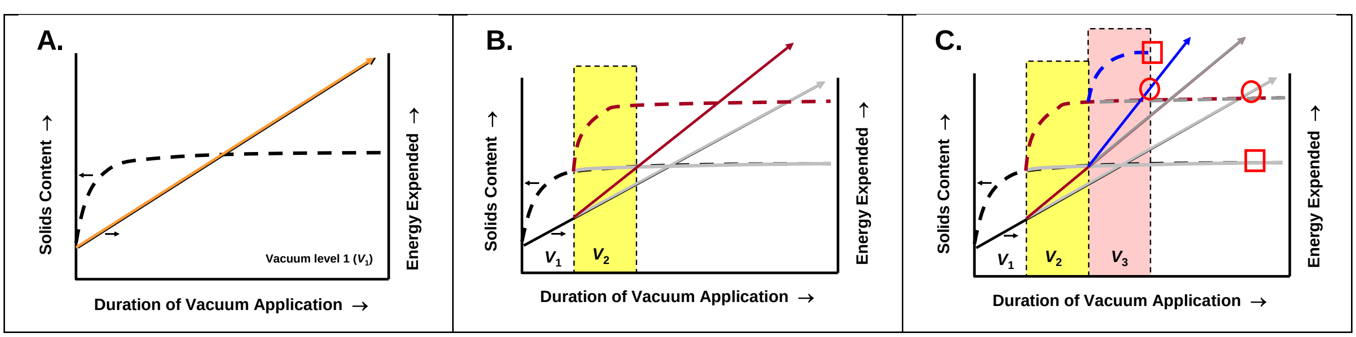

Fig. 14. Idealized plots illustrating an expected favorable impact on energy costs when using a suitably graduated progression of vacuum levels in three successive flatboxes

Forming fabric considerations

As noted by Granevald *et al.* (2004), forming fabrics can differ with respect to thickness, void volume, and air permeability. Fabric design clearly can affect dewatering rates (Helmer *et al.* 2006). As was the case in the cited work, however, it is often hard to figure out what aspect of a forming fabric made the difference. In particular, the air permeability of a forming fabric is not a good predictor of dewatering rates (Kufereth 1982c), except possibly in the case of the lightest tissue grades. In general terms, however, it appears that a consensus solution has emerged as a result of efforts by both felt manufacturers and papermakers. That is, a successful forming fabric ought to have a relatively coarse structure facing potentially abrasive surfaces such as the covers of vacuum flatboxes. Not only will the sturdy coarse weave tend to extend the useful life of the fabric, but it also will help it to stay dimensionally stable. The upper surface ought to involve a finer structure, composed of narrower filaments. The optimum, which is often determined by a series of trials, needs to be well matched to the type of fiber furnish and the demands of the paper grade, especially regarding smoothness. Based on points discussed earlier in this article, a relatively fine weave pattern will typically make the fabric less prone to fabric sealing. This can be understood based on Kufereth's concepts of fibers either lying across the wide part of a funnel or bent down into its throat (Kufereth 1983). A finer weave adjacent to the paper web makes it less likely that the fibers will droop into the recessed areas of the forming fabric surface.

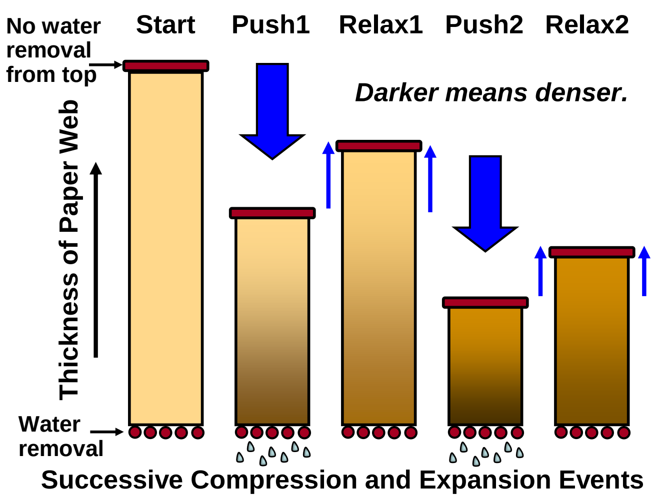

Fig. 15. Conceptual diagram of a pumping action resulting from successive densification, re-expansion, and redensification, *etc.* during the dewatering of paper. In the figure, a darker coloration means a higher density of cellulosic material. As the wet web enters a vacuum application or press nip (indicated by the word "push"), water is forced from the side of the sheet from which water is able to pass into a forming fabric or felt. Some air can enter the web, and some rewetting can occur, when the vacuum or mechanical pressure is removed ("relax").

Rewetting as a necessary aspect

When the topic of rewetting comes up among papermakers, a logical next step in the conversation is to discover strategies to avoid or eliminate it. For instance, this might be achieved after a vacuum flatbox by immediately separating the wet web from the fabric by means of a strategically placed pickup felt (Leinonen 2001). Or in a wet-pressing operation, a strong vacuum can be applied to the felt side of the outgoing nip, according to a Tamfelt system (Paulapuro 2000). As a more conventional approach, one might employ finer-scale filaments in the surface layer of the press-felt to reduce the amount of water at the paper-felt interface and thereby to reduce separation rewetting (McDonald *et al.* 2013; McDonald and Kerekes 2018). Another way to view the situation, is that maybe the tendency for moderate amounts of rewetting following successive vacuum applications and successive wet-press nips might actually be producing benefits. It is speculated that flow back into the just-dewatered web of paper may decrease the density of a densified surface layer. This would tend to restore some of the symmetry to the paper's structure and set the stage for effective pressing in a subsequent nip. The scenario just envisioned is depicted in Fig. 15. Additional study would be required to determine whether such a mechanism is realistic or necessary in practical operations.

Wet-press Nip Issues

Many practical strategies have been developed with respect to design and operation of wet press systems. For example, it has been common wisdom that a paper web ought not to be sent into a press nip, especially at high loading, if its moisture content is too high. But even such a well-established rule needs to be put to the test with suitable experiments. Pikulik *et al.* (1992) showed, surprisingly, that a wet web with an incoming web solids content as low as 9.6% could be successfully pressed to form a newsprint paper sheet. Because newsprint paper is relatively thin, and felt conditions vary widely, the cited results cannot be taken as strong evidence that such low incoming solids contents can be tolerated for other grades of paper and other paper machine circumstances. This only works for lightweight sheets where the water volumes are low and can be handled by the felts.

As was noted earlier, single-felted wet-press nips tend to produce a stratified sheet in which there is a densified layer on the side that had been facing the felt. In some press layouts such stratification can be mitigated by alternating the side of the sheet facing the felt in successive nips. If the basis weight is relatively high, one can employ double-felted nips (Kawka 1977; DeCrosta and Paisted 1978; Bergström and Kolseth 1989). Another strategy to reduce the degree of density stratification, especially when using popular three-nip press configurations, is to follow the last felted nip with a smoothing press, *i.e.* a nip without any felt and no dewatering (Paulapuro and Nordman 1991). However, pilot machine trials suggest otherwise (McDonald 2020).

Consideration needs to be paid to the capacity of the press felts to hold water, in comparison to the amount of removable water contained in the paper web. Thus, for high basis weight and an initial wet-press nip it can make sense to employ a double-felted nip (Kawka 1977). The cited author suggests that this can be followed up by one or two single-felted nips, which offer the potential to achieve higher maximum pressures due to the shorter zone of compression in a single-nip press.

Long nips

There has been a trend, in the building of new paper machines and in retrofitting press sections, to favor extended-nip presses, especially in the case of paperboard-weight sheets (Wicks 1983; Paulapuro and Nordman 1991; Schlegel *et al.* 1997; Cedra 1999; Pikulik 1999; Lang and Meitner 2006; Kawka and Reczulski 2008). The performance of such systems can be optimized by engineering the systems to apply ramps of increasing pressure within the nip, while at the same time applying a lower peak pressure in comparison to ordinary wet-press systems (Cedra 1999). Such practices are consistent with a general theme that has pervaded this whole article, that of progressively increasing the applied forces or pressures.

Recently ultra-long pulses (up to one second) have been studied (Järvinen *et al.* 2018; Järvinen *et al.* 2019) with a wet press simulator. The motivation for these studies has been the re-emerging of foam forming and its ability to give higher bulk and solid contents after wet press when compared to water forming. Although such long pulses are not practical for traditional paper machines, they could be used in making new types of fibrous materials enabled by foam forming. When comparing 20 ms and 1000 ms pulses, the cited authors obtained 3 to 4% higher solids content in water forming, while the increase in solids content was even higher in foam forming. Currently there is no theoretical explanation for the obtained results, and more work is needed.

Allowing water to flow out from the felt

Though press felts are generally expected to have a high amount of void space in comparison to the amount of water present in the entering wet web of paper, that void space will shrink greatly during compression in the nip. Most press rolls, backing a felt, are designed with holes or grooves to accommodate the filtered water (Rempel 1972; DeCrosta and Paisted 1978; Micheletta 1984; Szikla 1991b). There is also a long history of applying vacuum to the felt by means of a backing roll with drilled holes and baffles (Micheletta 1984). Such systems become less effective with increasing speeds, since the acceleration of water outwards from the roll works in opposition to any applied vacuum from the inside of the roll. Vacuum rolls are also subject to problems related to their strength and susceptibility to corrosion (Vadas and Thompson 1971).

Wet-Press Fabric Issues

Permeability

Wet press felts are designed to be highly permeable. For instance, Chang (1978) detected very little hydraulic pressure when a wet-press simulator was run with only a press felt in the absence of a wet paper sheet. But during use, felts are repeatedly compressed with very high loads. In addition, their void space can easily become filled with wood pitch components, mineral particles, and various chemical additives used during the manufacturing process (Tewksbury and Heiland 1970). Programs to continually and also periodically clean the felts are used by papermakers to overcome such problems (Wilson and Kopec 1985; Dickens 1990). A further dimension of optimization concerns when to replace an old felt with a fresh one; Drummond *et al.* (2009) showed that such replacement can be optimized using mathematical models.

Earlier it was mentioned that within the entering side of a press nip there can be transverse flow within the paper web, which in its most extreme form becomes known as sheet crushing. A parallel phenomenon appears to take place within the felt (Back 1979), and such transverse flow within the felt can relieve the buildup of hydraulic pressure (Wahlström 1969; Best and Velten 1999). Because the felt is strong and highly permeable, such flow appears to merely facilitate smooth operations.

Pore size of felt on the side facing the paper

The relatively high permeability of typical press felts can be generally understood based on the relatively high filament sizes and their relatively incompressible nature, leading to capillary spaces that are much larger than those associated with the damp paper. Thus, the capillary force equation (Eq. 8) predicts that capillary forces will tend to draw water back from the felt into the paper, especially after the maximum compression in the nip (Sweet 1961; McDonald and Kerekes 2018). However, the rate by which water is drawn back into paper during rewetting is also governed by the effects of viscous forces, which can be approximated by the Poiseuille equation, Eq. 9. According to that equation, the viscous resistance to flow increases with the inverse square of the effective capillary radius. As discussed earlier, when the forces represented by Eq. 8 (meniscus forces) and Eq. 9 (viscous forces) are set equal to each other, one obtains the Lucas-Washburn equation (Eq. 11), which predicts the overall dependency of the rate of meniscus-induced rewetting on the effective capillary radius. The Lucas-Washburn equation predicts slower progress of water back into a layer of paper web that has become densified as a result of pressing. This is a favorable circumstance from the papermaker's perspective, since it tends to limit the impact of this potential contribution to rewetting.

Heating

Temperature of the process water

Because the viscosity of water decreases with increasing temperature, it can make strategic sense to increase the temperature before the wet web enters various stages of dewatering (Nordman 1954; Opherden and Rudolph 1980; Carlsson *et al.* 1983a; Novikov *et al.* 1988; McDonald and Kerekes 1991; Neun and Fielding 1994; Räisänen *et al.* 1996; Räisänen 2000a; McDonald and Kerekes 2017a). Consideration also needs to be paid to the cost of heating, as well as safety and some physical constraints. Process water in the wet end of a paper machine is often heated to about 30 to 50 °C for this reason. A yet higher temperature will tend to make the environment around the machine unpleasant, due to a fog of condensing vapor that can form above a Fourdrinier table. Also, excessively high temperatures of the wet web theoretically can lead to boiling of the stock when it is subjected to the highest levels of vacuum as it passes over the flat-boxes.

Steam box usage

Because heating requires energy, there can be a higher potential advantage when the heating of the wet web is applied later on in the dewatering process. That way there is less water that needs to be heated. Such considerations help to justify the use of steam-boxes, which are sometimes used before vacuum flat-boxes (Gagnon and Neun 1996; Patterson 2002), but are more common just before wet-press nips (Back 1979; Powell and Cutshall 1985; Paulapuro 2000). Francik and Busker (1986) reported an increase of about 1% dryness for each 6 °C of temperature elevation in the wet press. However, the likelihood of sheet crushing also was found to increase with increasing temperature.

Fiber-related Strategies

Because cellulosic fibers make up the major portion of most paper products, and because such fibers become swollen with water in the course of conventional processing, their selection and preparation for papermaking clearly can be important with respect to dewatering of paper. To give an example of this, Stenström and Nilsson (2015) showed that, to some degree, the dewatering of pulp by vacuum application can be predicted based on such information as fiber length, width, and elliptical cross-section. Kullander *et al.* 2012) likewise showed that water removal by vacuum is affected by the choice of pulp and how it is refined. Britt (1981) reported that more rapid drainage is favored by relatively stiff fibers, providing a relatively bulky fiber mat with ample paths for water to flow. The same explanation also may account for an increase in dewatering rates of kraft pulp is dried, reslurried, and then evaluated again for its dewatering rate (Lindsay and Brady 1993b; Hubbe and Panczyk 2007a,b). Such drying and reslurrying, if not combined with additional refining, can be expected to render the fibers stiffer, leading to a bulkier and more drainable fiber mat.

Refining optimization

As an over-riding trend, it is understood that mechanical refining of pulp generally slows down dewatering (Nordman 1954; Carlsson *et al.* 1983a,b; Kullander *et al.* 2012; Lindqvist *et al.* 2012). However, it is important to consider studies that have sometimes indicated favorable effects of intermediate refining levels. Britt and Unbehend (1980) noted that beaten pulp sheets tend to respond better to vacuum dewatering. Räisänen *et al.* (1995b) noted that an optimal degree of refining will achieve the highest drying in response to vacuum. Such effects are consistent with effects discussed earlier in this article. First, an optimum degree of refining might favor more uniform formation, which can help to avoid ineffective drawing of air through thin regions of the mat. Second, some refining may help delay the breakthrough of air into the wet web during vacuum application; thus the sheet will become compressed more effectively by the applied vacuum as a means to squeeze water out (Han and Ingmanson 1967). And third, an optimum degree of internal delamination of fibers might help in the compressibility of the mat as a means to force out water by squeezing the sheet. All of these contributions need to be viewed with caution, since refining also tends to produce cellulosic fines, which have a highly negative effects on dewatering, especially in the earlier parts of the process.

Fines management

Cellulosic fines, especially the highly fibrillar and smallest material removed from fiber surfaces in the course of refining, have a major negative effect on the rates of gravity drainage during standard freeness tests, and also when forming paper sheets at relatively high basis weights and fines contents. As suggested by Doshi (1998), papermakers are tempted sometimes to just dump the fines as a means to achieve higher rates of dewatering. But cellulosic fines also can play an essential role in the preparation of many grades of paper, for which the smaller material tends to fill in the voids of the structure, yielding a denser sheet. It has been shown that primary fines (present in the pulp before refining) and secondary fines (generated during refining) both can increase the strength of paper made from kraft pulp, but the secondary fines are more effective (Hawes and Doshi 1993). Also, a moderate amount of fines sometimes can improve the effectiveness of vacuum dewatering (Nordman 1954; Räisänen 2000a).

Enzyme treatments

Cellulase and xylanase enzymes are large protein assemblies of specific types that work together to catalyze the breakdown of cellulosic into smaller pieces and ultimately into glucose. Studies have shown that judicious enzymatic treatment of pulp, after it has been refined, is able to increase rates of dewatering, while at the same time also achieving the desired strength properties of the paper (Eriksson *et al.* 1997; Gruber and Gelbrich 1997; Blomstedt *et al.* 2010; Oksanen *et al.* 2000). In principle, what happens is that the enzymes, which adsorb onto and start to degrade cellulose on all of the exposed surfaces, have an especially large effect on the thinnest of the fibrillar fines, sometimes dissolving them entirely. In particular, the amorphous regions of cellulose and hemicellulose are susceptible to enzymatic hydrolysis (Szijarto *et al.* 2008; Li *et al.* 2013). These are the same regions that tend to interact strongly with water. This so-called "hard-to-remove water" (Park *et al.* 2006; Kerekes and McDonald 2020) is resistant to removal by wet-pressing. Care must be exercised with respect to such variables as dosage, time of exposure, and temperature, since too aggressive treatment will excessively degrade the fibers too.

Hydrophobic fibers

Ordinary pulp fibers for papermaking are hydrophilic, as is evident from their low contact angles with water and tendency to swell when wetted. Hakovirta *et al.* (2014) showed that important increases in dewatering rates could be achieved by addition of relatively small amounts of cellulosic fibers that had been treated to make them hydrophobic. In the case of hardwood pulp, the presence of as little as 5% of hydrophobized fibers to ordinary hardwood or softwood kraft fibers markedly increased the values of Canadian standard freeness. Adding 5% of the hydrophobized fibers markedly decreased the water retention value of the mixture. In fact, the pulp mixtures tended to more resemble 100% hydrophobized fibers in terms of their water retention ability. The mixtures composed of 100% hydrophobized fibers exhibited very high sediment volumes, which remained high even after long-term settling.

Wet-end Chemical Additives

Strategies related to chemical additives have been left until the end of this article because that the topic was covered in more detail in a previous review article (Hubbe and Heitmann 2009). Some overview comments will be provided here. In a broad sense, chemical additives can be effective for promoting the dewatering of paper when they promote the formation of a relatively bulky wet web structure that has relatively open channels for the flow of water. Numerous articles have reported the drainage-promoting effects of chemical additives to the papermaking system (Britt and Unbehend 1980, 1985; Stratton 1982; Davis *et al.* 1983; Wegner *et al.* 1984; Allen and Yaraskavitch 1991; Räisänen *et al.* 1995a; Hubbe *et al.* 2008; Svedberg and Lindström 2012).

Frictional effects

Positive correlations have been found between the bulkiness of wet web structure and rates of dewatering (Gruber *et al.* 1997; Kugge *et al.* 2005; Hakovirta *et al.* 2014). An effective way to study such issues in the laboratory is the sediment volume test (Kline 1967; Alince and Robertson 1974; Gruber *et al.* 1997; Hubbe and Heitmann 2007). For example, Kugge *et al.* (2005) reported increases in dewatering rates, as well as increased sediment volume upon addition of debonding agents to papermaking furnish. A similar combination of effects was reported by Hakovirta *et al.* (2014) when adding different portions of hydrophobized fibers to suspensions of ordinary hardwood and softwood kraft fiber suspension. The great effectiveness of microparticle-based systems for drainage and retention might be attributed, at least in part, to the bulky nature of the initial wet web before it is pressed. Lindström (1989) proposed that such systems were effective due to their ability to form reversible attachments.

In the examples just cited, the reason that the chemical treatment tended to increase the sediment volume appears to have been related to an increase in the effective friction coefficient between fiber surfaces. In principle, if adjacent fibers in a suspension do not slide after they come into contact with each other during sedimentation, then a bulky sediment will be expected. The result, in the case of paper formation, can be a bulky web structure in which there are relatively large channels, allowing flow (Kugge *et al.* 2005). By contrast, if the surfaces exhibit short-range repulsion, for instance from having the same sign of charge at a sufficiently high level, then they will tend to mutually slide into a position of relatively high density. These concepts are consistent with earlier proposals that the ability of fibers to bend and slip relative to each other tend to contribute to ease of densification of fiber mats (Gurnham and Masson 1946; Jones 1963; Han 1969).

Fines retention

To the extent that dewatering is being inhibited by the plugging of drainage channels by cellulosic fines, part of the answer may lie in the use and optimization of an effective retention aid system. Such a strategy has been confirmed in several studies (Britt 1981; Ramarao *et al.* 1994; Balea *et al.* 2019). A secondary goal of effective retention aid usage, also contributing to dewatering, is to decrease the rate of filling of the void space of wet-press fabrics. In principle, when fine materials such as wood pitch are held tightly onto fiber surfaces by retention aids, they are less likely to become driven into the structure of the press felt.

There are several mechanisms by which chemical additives can contribute to holding fine particles onto the surface of full-length (1 to 3 mm) pulp fibers. Starting from the weakest of these, various publications have shown that fines retention tends to increase when charge-charge repulsions are reduced or eliminated by addition chemicals sufficient to achieve near-zero zeta potential or by adding salts to repress the electrostatic repulsion effects (Horn and Melzer 1975; Carlsson *et al.* 1983a; Hubbe and Panczyk 2007a). Due to the high levels of hydrodynamic shear present during key parts of the papermaking process, mere suppression or neutralization of charge repulsion forces is usually not sufficient to meet the goals of papermakers in terms of retention and drainage. So under realistic conditions of papermaking, success has been achieved most often by systems involving the addition of very-high-mass copolymers of acrylamide. These additives area able to bring about bridging flocculation (Hubbe 2007), which can be effective in holding fine particles onto longer fibers even with a low level of chemical addition and a moderately high level of hydrodynamic shear. Various studies have shown contributions to dewatering, especially in the early phases of the process, when adding such retention aids (Maunier and Ramarao 1996; Hubbe and Panczyk 2007b; Hubbe *et al.* 2008; Sjöstrand *et al.* 2019).

A very effective, but often overlooked mechanism by which chemical additives can promote the release of water during papermaking is the charged-patch mechanism (La Mer and Healy 1963; Gregory 1976; Hubbe *et al.* 2007). Such systems have been shown to be effective for promoting drainage in the early part of the dewatering process (Goossens and Luner 1976; Akari *et al.* 1996; Gruber *et al.* 1997; Pfau *et al.* 1999). The principle of operation of such systems is that a high-charge, moderately high-mass cationic polymer, often having a branched structure, is allowed to adsorb onto the surfaces of solids in a suspension. Because of the large size of the polyelectrolyte, the coverage, at an optimized dosage, will resemble patches, whereby some regions of the surface are covered and some are not. Random collisions among the particles and fibers then can be expected to bring about agglomeration that is much stronger than would be expected for mere neutralization or suppression of charge repulsion. Also, depending on how strongly the initial adsorption becomes established, systems agglomerated by a charged patch mechanism are expected to exhibit reversibility, *i.e.* coming back together if sufficient hydrodynamic shear was been applied to break the attachments apart (Hedborg and Lindström 1996; Hubbe 2001; Tripattharanan *et al.* 2004).

Highly fibrillated cellulose products, *i.e.* nanofibrillated cellulose (NFC), which is also called cellulose nanofibril, has a lot of potential. But from the perspective of removing water during paper manufacture, it also can be regarded as a particularly harmful variety of cellulosic fines. Studies have reported decreases in dewatering rates upon addition of various types of nanocellulose or microfibrillated cellulose to papermaking furnish (Balea *et al.* 2019; Salas *et al.* 2019; Sjöstrand *et al.* 2019). Such deteriorated dewatering is consistent with the plugging of drainage channels by the fibrillated fine material (Rantanen and Maloney 2013). Balea *et al.* (2019) showed that the deterioration in drainage resulting from NFC addition could be reduced by addition of retention aid. Dimic-Misic *et al.* (2013) and Koponen *et al.* (2015) showed that addition of highly fibrillated cellulose to papermaking furnish has potential to improve vacuum dewatering under certain conditions. Presumably, this favorable effect is attributable to preventing air from penetrating easily through any large channels in the mat. Dimic-Misic *et al.* (2013) and Rantanen *et al.* (2015) showed that shear-thinning behavior can be important when forming paper form suspensions that include substantial content of microfibrillated cellulose. Recently it has been shown that NFC, after pretreatment with high levels of cationic starch, can achieve high levels of paper strength, even when the extent of refining of the main pulp has been greatly decreased (Rice *et al.* 2018; Hubbe 2019). This approach made it possible to prepare low-density sheets having high stiffness. In addition, relatively high freeness values could be achieved when colloidal silica was added after then cationic starch treatment. By such a combined treatment, it was possible to achieve both a strength improvement and low product density, while avoiding unfavorable effects of the NFC on dewatering.

Floc redispersion

An unfavorable aspect of some of the most cost-effective additives to promote retention of fine particles during the formation of paper is increased flocculation of the fibers, which can lead to reduced paper strength and less effective vacuum dewatering. This tendency has been observed especially in the case of very-high-mass acrylamide copolymers, *i.e.* retention aids (Linhart *et al.* 1987). A practical strategy to overcome a tendency for over-flocculation in a typical paper machine system involves selection of the addition point for the retention aid (Hubbe and Wang 2002; Hubbe *et al.* 2008). By adding the retention aid before the pressure screen, polymer bridges become established both between adjacent fibers and between fibers and fine particles. However, the connections that hold fiber flocs together all become broken by hydrodynamic shear of the rotors in the screen systems before the stock passes to the next stage. Though one can expect some loss in initial dewatering when stock is strongly agitated after application of a retention aid, there still will be a strong increase in drainage relative to parallel tests without retention aid (Hubbe *et al.* 2008). Selectivity in the breakage of bonds between the fibers, in preference to the breaking of similar attachment between fibers and fine particles was established theoretically and experimentally in earlier work (Hubbe 1985).

Micro- and nanoparticle systems

In comparison to other strategies based on addition of non-enzymatic chemicals, the most impressive increases in dewatering rates have been achieved by use of so-called microparticle or nanoparticle additive programs (Hubbe 2005; Svedberg and Lindström 2012). Briefly stated, such programs depend on a strong interaction between a cationic polymer (usually cationic starch or a cationic copolymer of acrylamide) and very small negatively charged particles such as colloidal silica or sodium montmorillonite (bentonite). It appears that when the tiny negatively charged particles diffuse into the coils of cationic polymers that bridge solids within the wet web of paper, they cause a localized contraction; this tends to squeeze out water and result in more open channels for water to flow within the wet web (Hubbe and Heitmann 2007). The mechanism recently has been confirmed by use of model nanoparticles consisting of cellulose nanocrystals (Lenze *et al.* 2016; Brockman and Hubbe 2017). Because the paper that has been treated in this way subsequently passes through wet-press nips, the paper ends up with suitable density and porosity, while at the same time having been able to release its water more rapidly during formation of the sheet. Such additive programs are widely implemented in paper machine systems making printing paper grades, which present challenging requirements for paper strength, uniformity, and retention of fine particles.

CLOSING STATEMENTS

A series of hypotheses was posed near the beginning of this article, and these now can be considered in light of the evidence and discussion that has been presented. As listed in Table 2, it had been proposed that rates of release of water from paper during the manufactural process would be dependent on general effects of changes in the relative positions of solids within the wet web of paper in response to hydrodynamic and mechanical forces. Within this general hypothesis, it was proposed that dewatering would be affected by densification of surface layers, plugging of drainage channels, sealing effects, flocculation, healing mechanisms, and rewetting. As has been shown in this article, each of these proposed mechanisms can be supported by various evidence that has appeared in published works. However, it is important to emphasize that not every mechanism will be important in every situation. That is because there are major differences in the types of fibers, the degrees of refining, basis weights, and the types of equipment used in different paper machines systems.

A significant bottleneck in understanding water removal is the lack of realistic material laws for the behavior of wet pulp fiber networks under stress with different solids fractions and different time scales. In the future, standard rheological models should be used more rigorously for the analysis of wet fiber networks. Especially, *model-based measuring* is called for, *i.e.*, the experiments should be designed based on the used rheological models. This approach is rather tedious and is further complicated by the fact that simple linear models are not sufficient, in general. Instead, finite deformation models including *e.g.* plasticity are needed thereby increasing the number of material parameters to be measured. A recent example towards this direction can be found in Paterson *et al.* (2019), where flow-induced compaction of a fibrous porous medium over increasingly rapid rates of compaction is studied.

Another fundamental problem in the modelling of water removal during vacuum dewatering and pressing is the universal, still largely unresolved, challenge to solve two-phase flow (water and air) in a complex heterogeneous porous structure. Here the complexity of the problem is increased by the non-negligible capillary forces between water and fibers, leading to water holdup in the fiber network. There are various ways, involving varying degree of complexity, to build up the multi-phase models from the microphysical equations characterizing the different phases, such as using simple generalized models of Darcy's law or volume averaging (Lasseux *et al.* 2008; Pasquier

2017). Once the model is formulated, the values of the material parameters of the model need to be found. While this problem can in some cases be addressed theoretically and/or by numerical simulation, it usually requires highly sophisticated model-based measurement. The complexity of such measurements is illustrated in Kataja and Hirsilä (2001), where the parameters of continuum and momentum equations are determined for slow filtration of liquid-fiber suspension in a gravity driven laboratory filtration device. There are currently various numerical methods that can, in principle, be used in simulating two-phase systems without major simplifications. An example of such a technique is the lattice-Boltzmann method (including several variants), which has been used for similar purposes, *e.g.* in geological sciences (Ramstad *et al.* 2019).

A general lesson that emerges not only from this article, but also from many years of optimization work by companies involved with paper production is that it can be advantageous to employ a gradual, stepwise approach to dewatering, in which the pressures and forces are gradually increased. At the start of the process, the wet web has almost zero mechanical strength, but water will flow from it quite easily. Applying severe forces of pressing at that point would make no sense, since the web would not have enough integrity to pass through a press nip at that point. Another part of the lesson is that sometimes one has to be ready to take half a step back after advancing a step. It is likely that rewetting phenomena at the leading edges of hydrofoils, after vacuum flatboxes, and after wet-press nips can help to relieve some of the densification of surface layers of the sheet. Rewetting may help the sheet to recover enough bulk so that it can benefit more from the next unit operation of dewatering. In addition, the tendency of refluidization and recovery of void spaces in the sheet will be favorable in terms of final paper performance, since a sheet with near-equal properties in each side is usually preferred.

Nevertheless, more research needs to be done. Hopefully this review article has been able to highlight some questions that have not yet become well settled. There is a need to be able to predict the effects of many factors not only with respect to their effects on dewatering, but also with respect to how they affect paper properties. For this, there will be a need for further developments of mathematical models. Up to this point, there has not been much effort to incorporate such issues as stratified density, plugging, sealing, flocculation, and healing into models to predict dewatering rates. However, with ongoing advances in computing power, new developments in numerical methods, and an ongoing need to achieve higher production speeds and paper quality, there will be plenty of opportunity for research in the coming years.

ACKNOWLEDGEMENTS

The authors wish to express their great appreciation for the following people who volunteered their time to study an earlier version of the article and to provide corrections, clarifications, and suggestions: Richard Kerekes, Pulp and Paper Centre, University of British Columbia; Paul Krochak, Innventia AB, Stockholm, Sweden; Thaddeus Maloney, Aalto University, Department of Bioproducts and Biosystems, Espoo, Finland; Gyeongyun Kim, Moorim Paper Co., Ltd., South Korea; and Bouchaib El Idrissi, Institut d'innovations en Écomatériaux, Écoproduits et Écoénergies à Base de Biomasse (I2E3), Trois-Rivières (QC) Canada. In addition, Antti Koponen gives special thanks to Professor Markku Kataja for consultation.

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