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Influence of Shrinkage and Stretch During Drying on Paper Properties

Torbjörn Wahlström

ABSTRACT

A drying paper strives to shrink due to the shrinkage of the individual paper fibres. Laboratory results show that a reduction of the shrinkage or an imposed stretch leads to a large increase in tensile stiffness and a large decrease in strain at break.

In a cylinder drying section the water in the web is repeatedly heated on the drying cylinder and evaporated in the free draw. To evaluate the drying process regarding influence on paper properties these sub-processes, or drying phases, have to be studied separately.

The effect of the conditions on the drying cylinder and on the VacRoll is investigated in pilot trials. Both the fabric tension and the vacuum in the VacRoll reduces the shrinkage of the paper. The laboratory results are used as input to a numerical simulation of the conditions in the free draw. If the web width is increased or the length of the free draw is reduced the mean shrinkage of the paper web is reduced. However, the difference in shrinkage between the middle and the edge of the web is increased.

1. Introduction

During the paper-drying process, it is possible to make large changes in the paper properties by straining the paper web. As an example, laboratory studies have shown that an 8% strain increase, from -4% (shrinkage) to +4% (stretch), can give a relative increase in tensile stiffness of as much as 500%! The strain at break is reduced to the same extent and the tensile strength can be doubled.[1] The strain during drying is also known to affect compression properties,[2] dimensional stability[3] and surface properties.[4]

In conventional paper machines, the paper web can be stretched to different extents in the machine direction (MD) by varying the speed, for example between different dryer groups. Over the dryer cylinders, the pressure from the dryer fabric prevents the paper from shrinking in the cross machine direction (CD). Between each pair of dryer cylinders, the paper web passes a free draw where there are no forces acting on the edges of the web, and this allows the paper to shrink in the cross machine direction. The conditions in the free draw lead to a greater cross directional shrinkage at the edges than in the middle of the paper web.[5] Consequently, a profile in paper properties in the cross machine direction is unavoidable.[6]

The shrinkage difference between the

• Manager, Drying R&D, Board Machines, Valmet-Karlstad AB, Box 1014, SE-651 15, Karlstad, Sweden.

edge and middle of the web is often referred to as the shrinkage profile and is a well-known problem for papermakers. Producers of, for example, liner board or other grades that require high stiffness want to reduce the shrinkage at the edges to increase the stiffness. On the other hand, producers of sack paper wish to increase the shrinkage in the middle of the web in order to increase the strain at break. A common disire of all producers is to flatten out the shrinkage profile. If the paper could be prevented from shrinkage or even stretched in the cross direction, the CD stiffness could be substantially increased and it would be possible to eliminate the undesired cross machine variation in paper properties.

The development of the dryer section has been driven by a need for increased runnability and reliability, together with higher speeds for increased production. This paper deals with how the industrial scale paper-drying process influences the mechanical properties of the paper. The first part deals with shrinkage and stretch during drying on a laboratory scale. Based on pioneering work by Brecht *et al.*[7] and by Lindem,[8] a new apparatus has been developed. The knowledge gained is used in the second part for a simulation of the shrinkage profile created in cylinder drying. In the last part some commercial drying processes are evaluated with regard to their influence on paper properties.

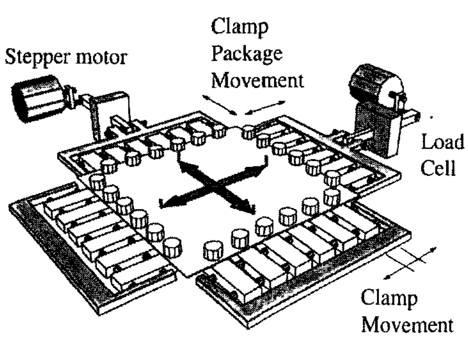

Figure 1. Biaxial Dryer. Laboratory apparatus for simultaneous straining in MD and CD.

2. Laboratory Drying Expeiments

2. 1 Drying strategies

In order to obtain fundamental knowledge of how different combinations of strains in MD and CD influence the final paper, a new apparatus, called the Biaxial Dryer and shown in Figure 1, has been developed. With the Biaxial Dryer, it is possible to evaluate the effects of strain (shrinkage and stretch) during drying in both directions of the paper simultaneously. Load cells make it possible also to measure the stresses occurring during drying. When different amounts of shrinkage or stretch are imposed on the paper during drying in different ways, they are often referred to as dif-

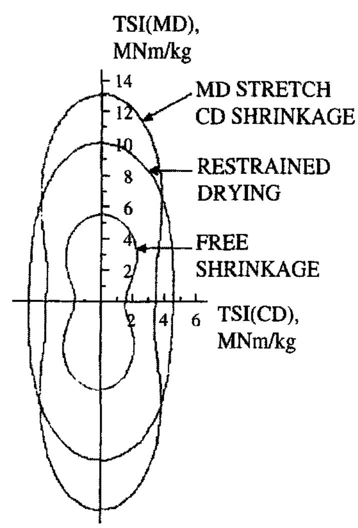

Figure 2. Polar plot of the tensile stiffness index for papers dried with the drying strategies in Figures 3-5.

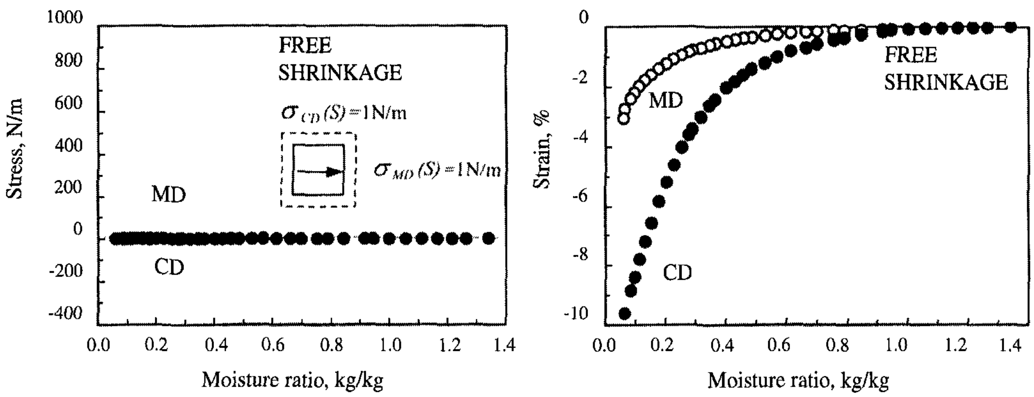

Figure 3. Drying strategy: free shrinkage. The paper is allowed to shrink without restriction.

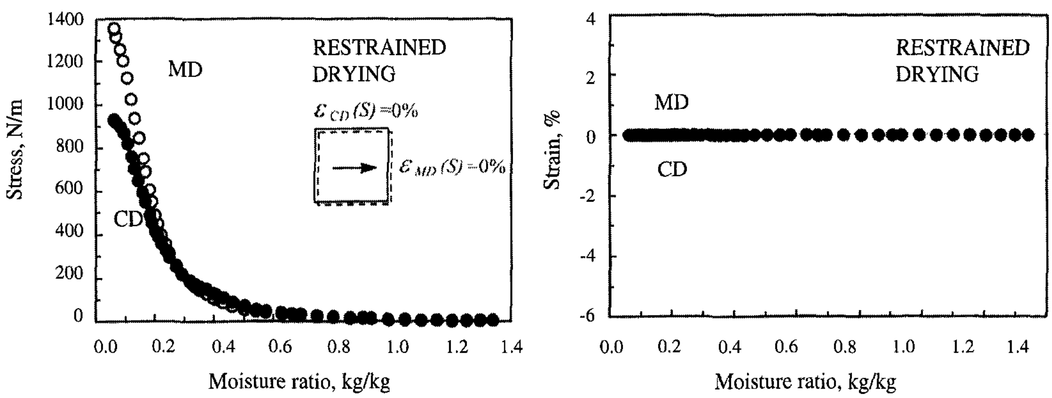

Figure 4. Drying strategy: restrained drying. No shrinkage or stretch is allowed.

ferent drying strategies. Three different strategies and their effects on stiffness are here dealt with to exemplify how the influence of strain on paper properties can be studied.[9]

Free shrinkage, Figure 3. When a paper dries, it strives to shrink and, if no forces are acting on the paper, the shrinkage can continue unrestricted and is often referred to as free shrinkage. The shrinkage is higher in CD than in MD since more fibres are oriented in MD and the fibres can shrink more in their transverse direction. This also makes the stiffness higher in MD than in CD, which is shown in Figure 2.

Restrained drying, Figure 4. Neither shrinkage or stretch are allowed during the drying process. When the natural occurring shrinkage is restrained, a stress builds up in the paper. Due to the higher stiffness of the fibres in their axial direction, the stress reaches a higher level in MD. Figure 2 shows a remarkably higher stiffness in both MD and CD compared to free shrinkage.

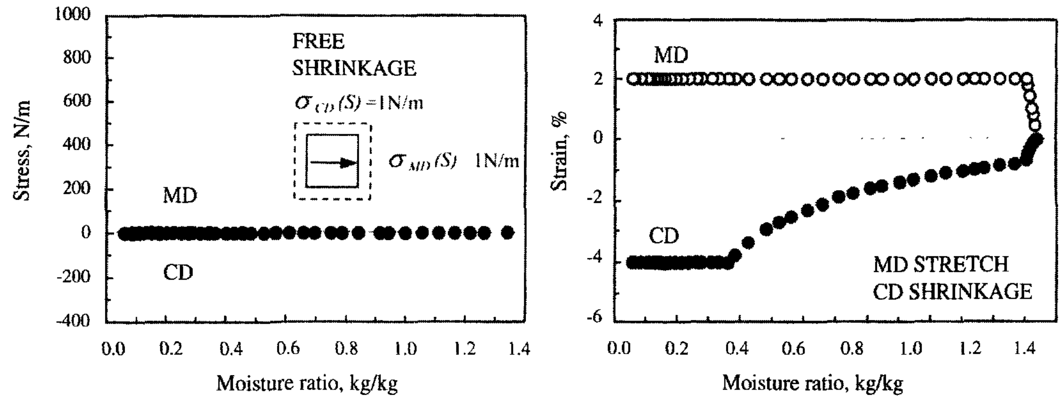

Figure 5. Drying strategy: MD stretch and CD shrinkage. Simulates the straining conditions in a dryer section.

MD stretch and CD shrinkage, Figure 5. This drying strategy simulates a conventional dryer section. In MD, 2% stretch is imposed in the beginning of the drying process and in CD -4% strain (4% shrinkage) is allowed. Note that, as a result of the stretch in MD, the paper contracts about 0.8% in CD. Figure 2 shows that the MD stiffness is increased compared to restrained drying and CD stiffness reduced.

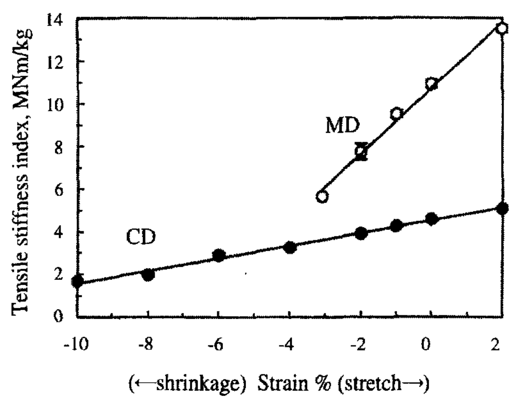

Figure 6. Stiffness increases remarkably in both MD and CD with increasing strain.

2. 2 Tensile stiffness

Either the stresses or the strains (shrinkage and stretch) can be used as control parameter when performing experiments with different drying strategies. It has been shown that strain imposed on the paper during drying shall be used if the influence on paper properties is to be evaluated. Strain is defined as elongation (positive or negative) divided by original length. A positive strain is referred to as stretch and negative strain as shrinkage.

Figure 6 shows how the tensile stiffness index changes if a paper is stretched and allowed to shrink to different degrees in both MD and CD. The lowest values of strain in MD and CD respectively represent the free shrinkage of the paper. At zero strain, the paper is restrained-dried. The tensile stiffness index increases with increasing strain, whether this is reduced shrinkage or increased stretch. Note that the slope of the relation is the same for both positive and negative strains. This result is not self-evident, since two different mechanisms are involved; imposed wet stretching and shrinkage as a result of the natural behaviour of paper during drying. In MD, the absolute increase is very large, 6 units of tensile stiffness index, when going from a situation with free drying to two per cent stretch. In CD it is about 3 units, but the relative increase in CD is 200% compared to 100% in MD.[9]

2. 3 Interaction between MD and CD

To investigate the interaction between MD and CD, trials was carried out with a number of different combinations of strain in the two directions of a paper. The results show that it is possible to change the strain in one direction without affecting the in-plane properties in the perpendicular direction. An example is given in Figure 7 where the strain in CD has been varied from 10% shrinkage to 2% stretch while the strain in MD has been kept constant at 0% (restrained drying) in all cases. The results show that the strain in CD does not affect the properties in MD.[9]

If these results could be transferred to the papermaking process, it would be possible to improve the cross direction paper properties by preventing shrinkage or even stretching the paper in CD without any negative influence on the properties in MD. This requires however that the strain can be controlled in both directions independently of each other, and this is not possible in a conventional dryer section.

2. 4 Delamination resistance

Paper and board are sheet materials that are made in one or several layers. As a result of the manufacturing conditions, the

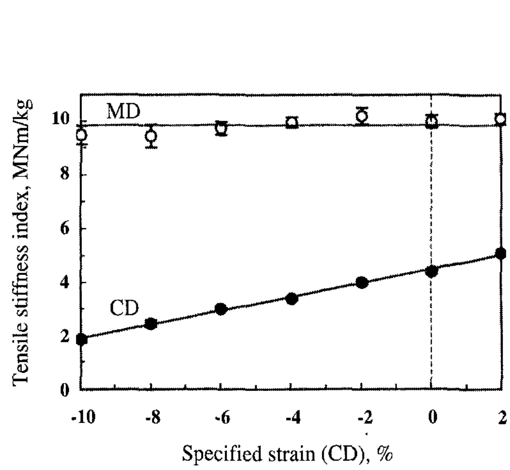

Figure 7. A change of strain in CD does not influence the paper properties in MD.

fibres are oriented mainly in the plane of the paper. A consequence of this is that the delamination resistance in the Z direction is of the order of 1/100 of the strength of the paper in the plane. There is a limit which the delamination resistance must exceed in order to avoid problems. In converting, delamination may occur during printing and plastic coating. In the end-use of corrugated boxes, the material is joined by gluing in one of the corners. Due to the spring-back moment in the material, delamination can occur after some time at the edge of the glued part of the material. A particular aspect of delamination is evident in the creasing and folding of carton board. In these operations, the material is required to delaminate locally into several thin layers, and this requires uniformity in delamination resistance through the thickness.

To evaluate the influence of drying conditions on the delamination resistance, different combinations of shrinkage and stretch were applied in two perpendicular directions of the paper. Figure 8 shows that, regardless of how the shrinkage or stretch is performed during drying, the total change

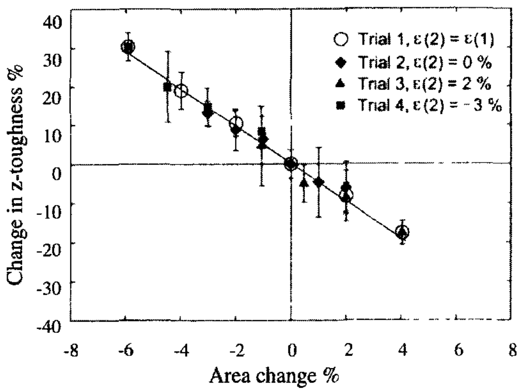

Figure 8. Delamination resistance is reduced by a decrease in shrinkage or by an increase in stretch.

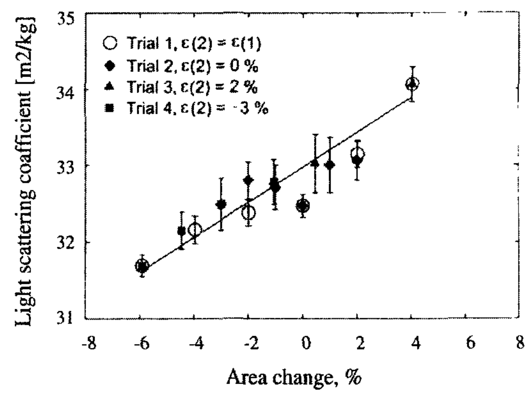

Figure 9. A reduction in fibre to fibre bonding indicated by an increase in scattering explains the reduction in delamination resistance.

in area is the controlling factor for the delamination resistance. The area change is equal to the sum of the strain in MD and CD. An area increase, a stretch or reduced shrinkage, led to a loss of delamination resistance. This decrease in delamination resistance was attributed to a reduction in the bonded area between fibres in the sheet, characterised by an increase in the light scattering coefficient, Figure 9.[10]

2. 5 Development of stiffness during drying

To increase the understanding of the drying process, more detailed knowledge is needed about the development of the properties during drying. The way in which the MD and CD stiffness developed during the drying process was investigated for three different drying strategies. Drying in the biaxial dryer was interrupted after different drying times, the moisture ratio was determined and a tensile test was performed.

Figure 10 shows the development of tensile stiffness index in MD and CD during restrained drying. The stiffness increased exponentially with decreasing moisture ratio. Most of the increase took place during the final stage of the drying. The stiffness reached a higher value in MD than in CD due to the anisotropy of the fibre orientation.

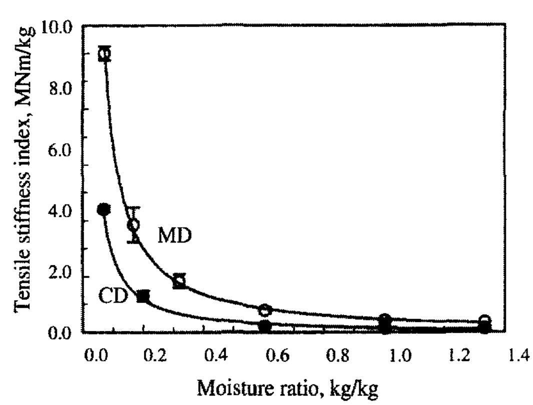

Figure 10. The stiffness develops in the final stage of the drying process.

Figure 11 shows the development of the stiffness in MD during drying. Three different drying strategies were used, restrained

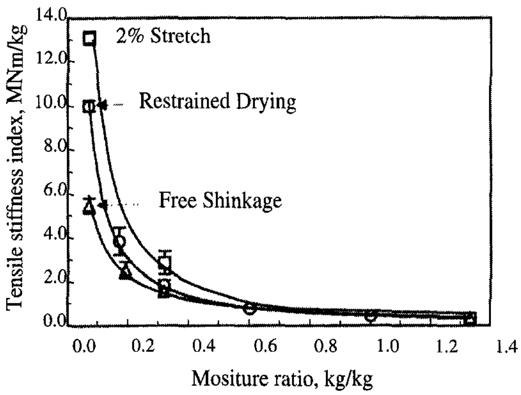

Figure 11. Development of stiffness in MD for the different drying strategies in Figures 3-5.

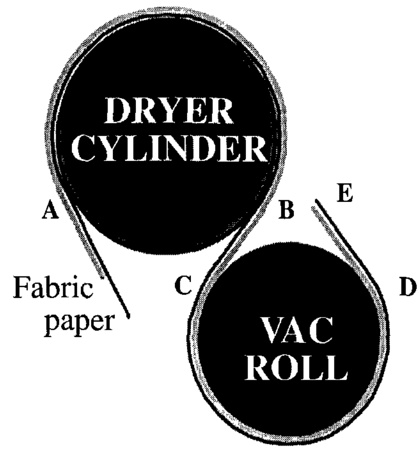

Figure 12. One cycle of a single felted dryer section divided into its different drying phases.

drying, free shrinkage and 2% stretch imposed in the beginning of the drying process. When free drying was permitted a lower final value of tensile stiffness index was reached than in restrained drying, but the exponential type of relation still remained. The stiffness does not increase directly when the web is subjected to wet stretching at the beginning of the drying process. At lower moisture ratios, however, the stiffness increased compared to that of the restrained dried sample. Obviously the stiffness was dependent on the strain history during drying.[9)]

3. Cylinder Drying

3. 1 The drying phases

The drying of paper is a dynamic process. Repeatedly and with very short time cycles, heat is transferred from the drying cylinder and water is evaporated in the free draw. The dynamic nature and its importance for the paper properties explains the difficulties in making use of data from static laboratory trials. The key to advancing the knowledge about drying, the last unexploited unit process in papermaking, is to study separately the sub-processes, the different drying phases.

A single felted, or single tier, dryer section with vacuum rolls, Valmet VacRolls, is here used as an example, to investigate the influence of the separate drying phases on paper properties. Figure 12 shows one cycle of the dryer section divided into the different drying phases. From A to B, the paper is located On the Dryer Cylinder under the dryer fabric. The evaporation has been simulated with a physical model for heat and mass transfer developed by Wilhelmsson.[11)]

Figure 13 shows a simulation of how the temperature develops over the drying phases in one cycle. **On the dryer cylinder,** the temperature increases, particularly on the side of the paper towards the dryer cylinder. The temperature becomes high enough for evaporation to start, but the evaporation is reduced by the dryer fabric. Figure 14 shows a simulation of the local evaporation rate, based on paper area, in one cycle. Evaporation is low but not negligible; about

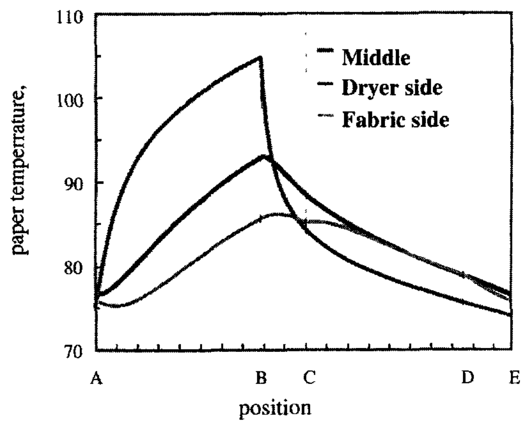

Figure 13. Simulated temperature in a paper passing through a drying cycle as in Figure 12.

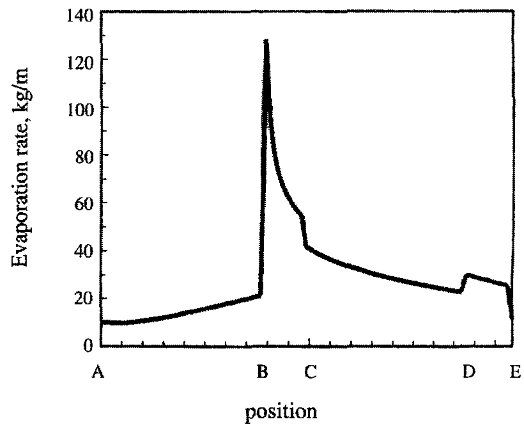

Figure 14. Simulated evaporation for paper passing through a drying cycle as in Figure 12.

20% of the total evaporation occurs on the dryer cylinder. From B to C and from D to E the paper runs between the cylinders **In the Free Draw.** When the paper reaches the free draw the energy built up over the dryer cylinder leaves the paper as vapour. Initially the evaporation rate is very high but it decreases rapidly as the paper temperature decreases. About 40% of the evaporation can take place in this phase. The remaining part of the evaporation takes place from C to D **On the VacRoll.** The dryer fabric is located between the paper and the VacRoll and does not therefore reduce the evaporation as it does on the dryer cylinder.

3. 2 On the dryer cylinder

The first drying phase considered is when the paper is on the dryer cylinder and under the dryer fabric. If the paper is exposed only to this phase during drying, the relevance of this phase for the paper properties can be investigated. Figures 15 and 16 show the result from a trial where 100 and 300 g/m^2 testliners were dried over a 1.83 m dryer cylinder in a single pass. The results for 0 kN/m were measured separately with the drying strategy free shrinkage. The pressure produced on the paper by the dryer fabric increases the heat transfer from cylinder to paper, but it also restrains the shrinkage of the paper. When the fabric tension is increased, the shrinkage is reduced and the final stiffness of the liner increases. Compared to free shrinkage, the impact on shrinkage and stiffness is high, but in the region of fabric tensions used on a production machine, 2-3 kN/m, the changes in shrinkage and stiffness were small. For grades that require high bulk, it is not possible to use a high fabric tension because of the densifying effect. Too low a fabric tension leads to a deterioration in surface properties and reduces the heat transfer.

3. 3 In the free draw

Hitherto, no attempts have been made to increase the understanding of the physics behind the shrinkage profile. With the finite element method, it has been possible to sim-

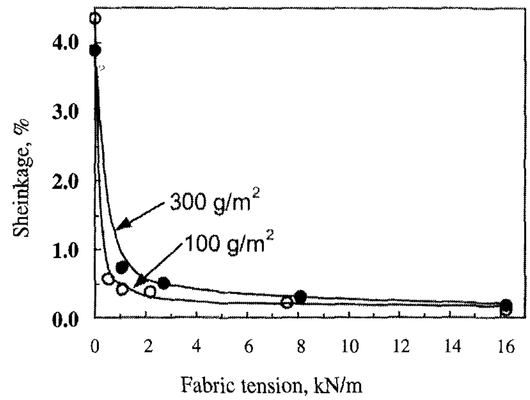

Figure 15. The shrinkage decreases with increasing fabric tension.

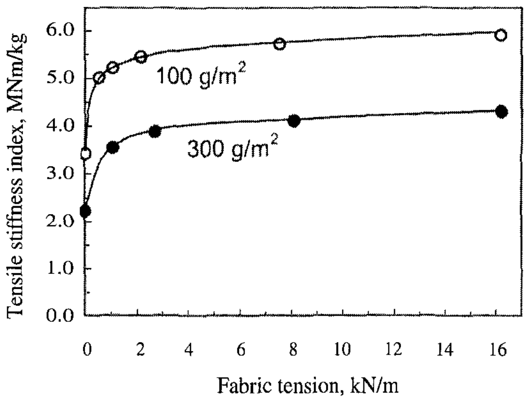

Figure 16. The stiffness increases with increasing fabric tension.

ulate stresses and strains in a paper web passing through a dryer section. The simulations have been aimed at investigating how the conditions in the free draw influence the shrinkage profile. The model was developed for a general orthotropic behavior of the paper and the kind of relations presented in Figures 3, 6 and 10 were used as input. The total strain in the paper was assumed to be the sum of a mechanical strain and a hygroscopic strain due to water evaporation. A mechanical strain can for example be due to a speed increase in MD between two dryer groups and the resulting contraction in CD. The hygroscopic strain is identical to the free shrinkage. It was assumed that when the paper web is on the cylinders it is restrained from shrinkage by the pressure from the dryer fabric. In the free draw between the dryer cylinders there are no forces acting on the edges of the web.[12]

To validate the model, the shrinkage profile was measured on two paper machines and their respective free draw geometries simulated. Figure 17 shows the measured shrinkage profiles. The dryer section with the double-felted configuration was 6.5 m wide and had a free draw length of 2.3 m. The free draw in double felting was defined as the length where the web is not in contact with the dryer fabric. In the single-felted case, the free draw was 0.9 m and the web width 9.5 m. Figure 18 shows the results of the simulations of these dryer sections. There are some deviations in the absolute level of shrinkage and too low a prediction in the middle of the web. The model was, however, able to capture the general behaviour of the shrinkage and it gives a qualitative understanding of the influence of the studied variables.

Figure 19 shows the results of a series of simulations where the length of the free draw was varied. When the length of the free draw was reduced, the shrinkage in the middle of the paper web decreased significantly. At the edges, the shrinkage also decreased but to a smaller extent. The region in the middle of the web with low shrinkage also became wider when the free draw was shortened, which means that the shrinkage gradient at the edges of the web became steeper. A shorter free draw reduced the total web width shrinkage, but

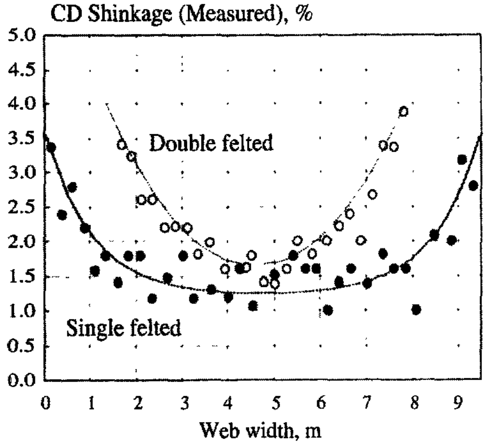

Figure 17. Measured shrinkage profiles for a single felted and a double felted dryer section.

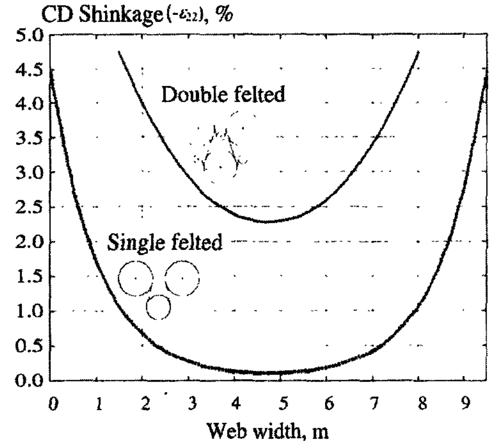

Figure 18. Simulated shrinkage profiles for a single felted and a double felted dryer section.

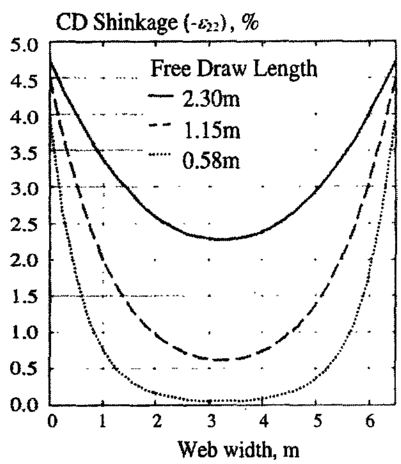

Figure 19. Simulated shrinkage profiles for three different lengths of the free draw.

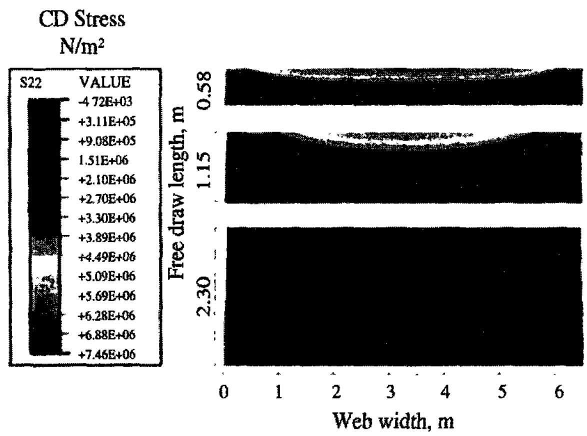

Figure 20. Simulated CD stresses in the final free draw for three different free draw lengths.

the difference in shrinkage between the edge and the middle increased. This also means that the difference in most paper properties between the edge and the middle would have increased with a reduction in the length of the free draw.

The origin of the shrinkage profile can be explained by a difference in stresses. In CD, the stress became much higher in the middle of the web than at the edge where it was close to zero. The explanation of the higher stress was the boundary conditions, free edges in the free draw and a fixed situation when the web was under the fabric or on the VacRoll. The high stress in the middle of the web restrains the shrinkage more in the

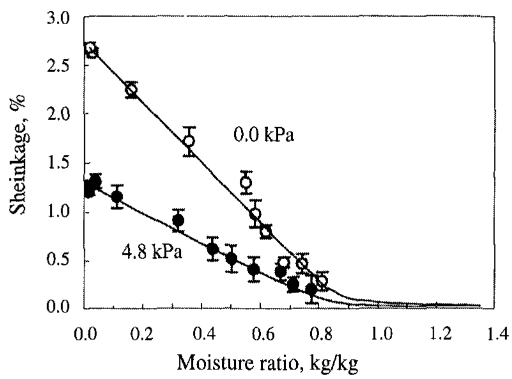

Figure 21. Development of shrinkage during drying with and without vacuum.

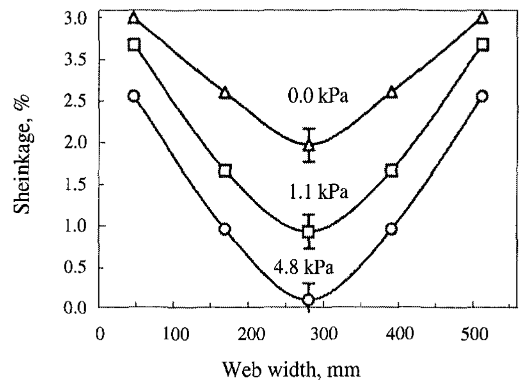

Figure 22. Shrinkage profiles for different levels of vacuum in the VacRoll.

middle than at the edge. Figure 20 shows the calculated CD stress fields in the final free draw for the simulated cases in Figure 19. The shortest free draw had the highest CD stresses and consequently also the lowest shrinkage.

3. 4 On the VacRoll

On the VacRoll, the web is pressed against the fabric by the vacuum inside the roll. This restrains the shrinkage but, as will be shown, not as effectively as the restraining effect of the dryer fabric over the dryer cylinder. To increase the understanding of this drying phase, a pilot trial was carried out. A pilot-machine-made 200 g/m^2 testliner was dried over a VacRoll in a single pass by blowing hot air onto the paper.

Figure 21 shows how the vacuum influences the development of the shrinkage during drying. The total web width shrinkage is highest without any vacuum in the VacRoll. The shrinkage starts at the same moisture ratio, around 0.9 kg/kg, in both cases. In the trial with vacuum, the paper was dried in a more restrained state and the final level of shrinkage was lower. The free shrinkage for this grade was 3.8%. Since the shrinkage was about 2.6% when the vacuum was zero, some restraint was obviously imposed on the paper even in this case.

If the restraint is caused by stress gradients, it can be suspected that this drying phase also gives rise to a shrinkage profile. Figure 22 shows the shrinkage profiles measured on the dry 200 g/m^2 liner for three different levels of vacuum, 0, 1.1 and 4.8 kPa. With the highest vacuum, the shrinkage in the middle of the web is close to zero but it is as high as 2.6% at the edge. The profile for the paper dried without vacuum shows a more even profile than the high vacuum case but the total web width shrinkage in higher. The difference in shrinkage between the middle and edge of the web is greatest for the trial with the highest vacuum. As is indicated by laboratory data in this paper, this also means that the difference in paper properties between edge and middle was largest in this case.

Figure 23. Conventional double-felted dryer section.

4. Evaluation of Commercial Drying Processes

4. 1 Conventional double-felted cylinder drying section

The effect of cylinder drying on the mechanical properties of paper is very dependent on the shrinkage or stretch during the drying process. Figure 23 shows a conventional double felted dryer section from Valmet. Figures 17- 18 show the results from both a measurement and a simulation of the shrinkage in the cross machine direction of another double-felted dryer section. The free draw length in this case was 2.3 m and the web width 6.5 m. This and many other double-felted dryer sections in use have relatively long free draws, compared to new installations and in relation to the width of the machine.

The shrinkage in the cross direction of the paper machine is greater at the edges than at the middle of the web. This difference also creates a great difference in mechanical properties, as shown in the laboratory data presented in this paper. The simulations shows that the shrinkage profile is created by the situation with free edges of the web in the free draw and the restrained conditions under the dryer fabric.

4. 2 Single-felted dryer section

In a single-felted dryer section (Valmet SymRun), all the rolls at the top are steam-heated cylinders and all the rolls at the bottom are vacuum rolls (VacRolls), Figure 24. The sheet run is totally closed and supported through the entire dryer section for improved runnability. The total web width shrinkage is less than that in a conventional dryer section.

Historically, the speed and the width of the paper machine has increased to increase production, and the free draws have become shorter to improve runnability. Figures 17 and 18 show how the shrinkage profile changes when the web width increases and the length of the free draw decreases. In the middle of the web, the shrinkage decreases significantly. At the edges the shrinkage also decreases but to a smaller extent. Consequently a wider machine and shorter free draws reduce the total web width shrinkage and thereby increases the mean stiffness. The difference in shrinkage between the edges and the middle of the web increases however, which means that

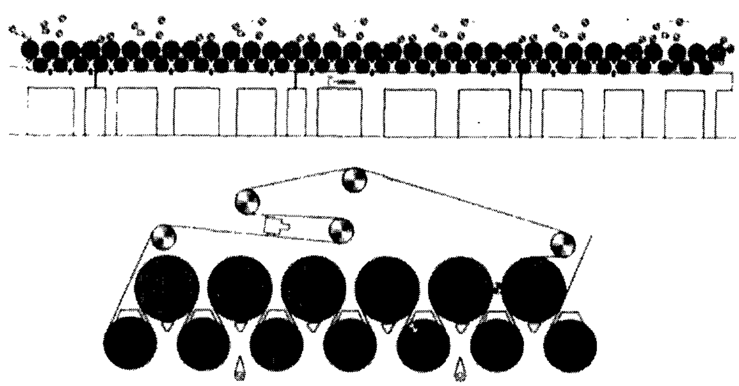

Figure 24. Single-felted dryer section,Valmet SymRun.

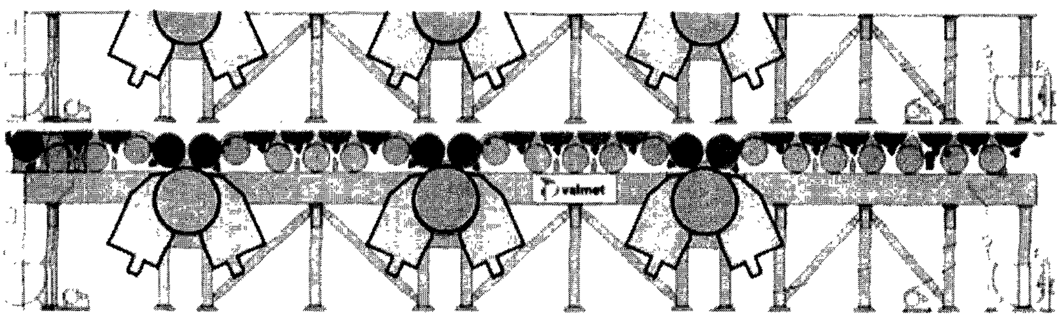

Figure 25. OptiDry concept.

the differences in most paper properties between the edges and the middle also increase. The results presented in Figure 22 show that a part of the shrinkage profile is also an effect of the conditions on the VacRolls.

4. 3 OptiDry concept

The most recently developed and commercialised drying process from Valmet is the OptiDry concept shown in Figure 25. The special features of the concept are the totally closed sheet transfer beginning in the press section, the use of two different forms of energy for heating, and a new high efficiency paper drying unit. The benefits are improved runnability, fast grade changes and a shorter dryer section. The concept consists typically of three air impingement modules added to a SymRun-type dryer section. On the impingement modules or OptiDry units the web is on top of the dryer fabric and is vacuum-supported by a large diameter VacRoll. The effect on paper properties does not differ significantly from that of the SymRun dryer section.

4. 4 Condebelt

There are currently two board mills utilising the Condebelt process, the Pankakoski

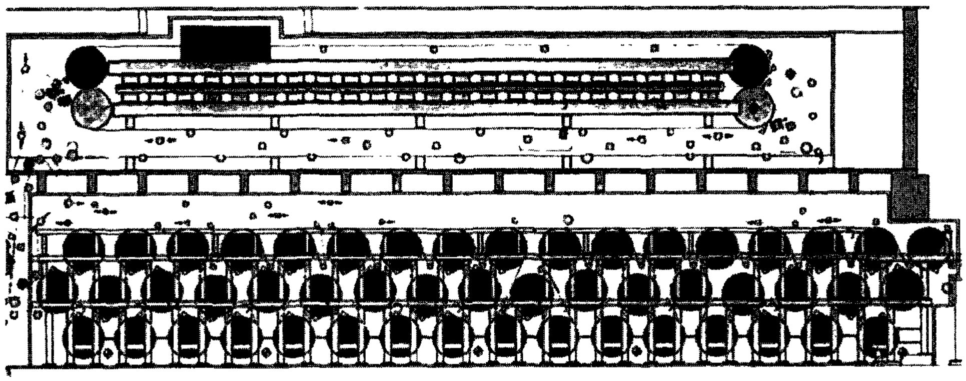

Figure 26. Condebelt.

mill of Stora Enso in Finland, shown in Figure 26, and the Ansan Mill of Dong Il in South-Korea. In the Condebelt process, the wet web is carried on two permeable wires and fed between two long smooth steel belts. The web is dried by being under pressure (0.5 to 5 bar) and in contact with the upper steam-heated (111- 159°ΔC) belt. As the moisture in the web evaporates, the vapour gene-rated passes through the wires and condenses on the lower cooler steel belt. [13]

The z-directional pressure and the contact with the glossy, hot metal belt has two major consequences with regard to sheet properties. First, the pressure applied to the hot and moist web acts to plasticize fibres, improve bonding, increase density and create a smooth surface. Second, the pressure prevents all shrinkage during drying, which has earlier been shown to have a large effect on the paper properties in CD. The totally prevented shrinkage in the Condebelt unit, of course, also eliminates the shrinkage profile. Figure 8 showed that a reduction in the shrinkage leads to a reduction in delamination resistance. In the Condebelt process, this drawback is more than compensated for by the increase in density of the sheet.

4. 5 Airborne dryer

In an Airborne dryer, the paper is dried by hot air blown towards the paper web by nozzles. Figure 27 shows an Airborne dryer from Valmet. The very long free draws extend from the left-hand to the right-hand side of the dryer. On each side, the web is turned on turning rolls. In the free draws, the air blown by the nozzles creates an air cushion that carries the web.

Figure 19 shows how the length of the free draw influenced the shrinkage profile in the paper. These results can be extrapolated towards very long free draws, which give a higher total shrinkage and a more even shrinkage profile. Only a small force is needed to pull the web through the dryer, and this gives minimum web tension. The very low web tension also allows for shrinkage in the machine direction. In a conventional cylinder dryer section, a small stretch is always necessary between the dryer groups to give sufficient web tension for good runnability.

Figure 6 showed that the tensile stiffness decreases when the shrinkage increases. This means that the strain at break, that is the extent to which it is possible to stretch the paper before it breaks, increases. This makes the airborne dryer suitable for the production of sack paper that requires a high strain at break. Most installations of this type of dryer section are however made for pulp drying.

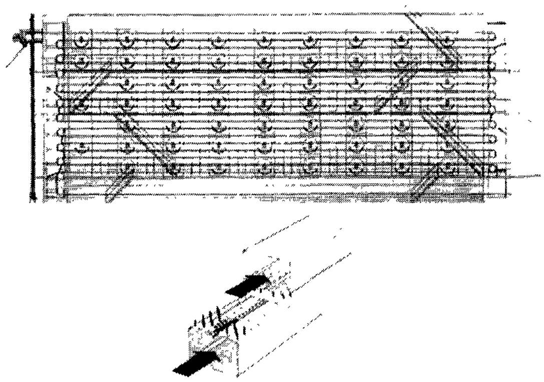

Figure 27. Airborne dryer.

4. 6 Air impingement drying for sack paper

The increasing restraint in the dryer section due to shorter free draws and wider machines makes it harder to produce sack paper of good quality in a modern conventional dryer section. Sack paper requires high shrinkage, which is beneficial for producing a stretchable material. There are ways to increase the shrinkage in a conventional cylinder dryers section. Figure 28 shows an installation of impingement drying hoods in a conventional dryer.

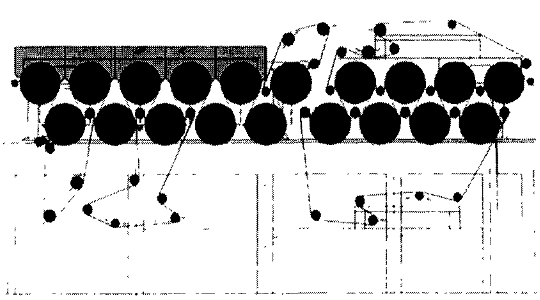

Figure 28. Air impingement drying for sack paper.

Hot air is blown onto the web when it passes over a dryer cylinder. The web is not restrained from shrinkage by the fabric on these particular dryer cylinders, and this explains the increased shrinkage. The length of the free draw can then be considered as the length where the web is not restrained by a dryer fabric. Since the evaporation capacity is high in impingement drying, a large part of the drying takes place in this long "free draw."

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