On suction box dewatering mechanisms

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Abstract
In previous studies on suction box dewatering, three mechanisms were identified that determine the dry content of a web, viz. web compression, displacement of water by air and rewetting. In the present work, the relative importance of the three mechanisms was investigated through direct measurement of the web deformation, the dry content changes during and after the suction pulse, the air flow through the fibre network and the saturation of the web after the suction pulse. Suction pressure, suction time and rewetting time were varied. The experiments were done with chemical and mechanical pulp webs of various grammages.

It was found that a large web deformation took place during the suction pulse, particularly at its beginning. Compression dewatering was found to be the most dominant dewatering mechanism. Displacement dewatering started after most of the web compression had occurred. Its contribution to the increase in dry content was most pronounced for higher suction pressures, longer suction times and for chemical pulp webs.

A surprisingly large expansion of the web was observed immediately after the suction pulse. This expansion was the effect of rewetting. This rewetting strongly reduced the dry content of the web if the web had not been immediately separated from the forming fabric at the end of the suction pulse. Under the conditions studied, the decrease in dry content amounted to the order of 3 to 6 %. Rewetting was smaller for longer suction times and higher suction pressures. A considerable air flow through the web occurred under these conditions. This air flow apparently moved water from the forming fabric into the suction box, thus making less water available for rewetting. Rewetting for mechanical pulp webs was more pronounced and took place faster than for chemical pulps.

The use of a membrane on top of the web during suction box dewatering proved to be advantageous for reducing the air flow through the web. However, under the conditions investigated, the dry content could not be improved. Although the web compression was increased when using a membrane, especially at a higher suction pressure, rewetting after the suction pulse had an even larger negative impact on the dry content, which, as a result, was lower.

Keywords: Suction box, vacuum, water removal, compressibility, displacement, rewetting, laboratory equipment.
List of Papers

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III. *The deformation of chemical and mechanical pulp webs during suction box dewatering.*
     Åslund, P., Vomhoff, H. and Waljanson, A.
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IV. *External rewetting after suction box dewatering.*
    Åslund, P., Vomhoff, H. and Waljanson, A.
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V. *Evaluation of membrane-assisted dewatering on a pilot paper machine.*
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VI. *Web deformation during membrane-assisted dewatering.*
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My contribution to the Papers

Paper I  I wrote the paper together with Hannes Vomhoff.

Paper II I developed the method and wrote the paper together with Hannes Vomhoff.

Paper III The experimental work was carried out by Alexander Waljanson. I analyzed the results and wrote the paper together with Hannes Vomhoff.

Paper IV The experimental work was done by me, in close collaboration with Alexander Waljanson. I wrote the paper together with Hannes Vomhoff.

Paper V The experiments were carried out by staff at the STFI-Packforsk EuroFEX Pilot Paper Machine. I analyzed the results and wrote the paper together with Hannes Vomhoff.

Paper VI I performed the experiments, analyzed the results and wrote the paper together with Hannes Vomhoff.

Paper VII I participated in the discussions leading to the central ideas described in the patent.
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1 Background

In papermaking, the sheet is formed from a highly diluted fibre suspension, i.e. a pulp slurry. This fibre suspension, with a concentration of about 5 g of fibres per litre of water is fed from the headbox to the wire section of the paper machine. After 10 to 100 seconds, depending on the paper grade, there is a paper web with a dry content of approximately 95 % at the end of the paper machine. This implies that 200 litres of water have to be removed in a short period to produce 1 kg of paper, see Figure 1 (Krook, 1996).

During paper making, effective dewatering is very important for cost-effective paper production and good runnability on the paper machine. It occurs in all three sections of a paper machine, i.e. the forming, press and drying sections. In the forming section, water is removed by gravity or the application of suction pressure. In the press section, water is pressed out of the web by mechanical pressing and, in the drying section, the majority of the remaining water is evaporated by heat.

The cost of removing water increases considerably throughout the production process. The most cost-effective dewatering is that in the forming section, which means that it is advantageous to remove as large a quantity of water as possible there.

The water removal in the forming section can be divided into two zones. The first zone begins at the headbox and ends just before the suction boxes. Here, the water is removed by gravity and by moderate suction or pressure pulses from stationary dewatering elements, or foils, as they are called. The second zone starts at the first suction boxes and ends after the couch roll. The driving force for water removal in this zone is suction pulses, which are stronger than those in the first dewatering zone.
1.1 **Suction box dewatering on a paper machine**

One or several suction boxes are located underneath the forming wire. *Figure 2* shows the location of the suction boxes on a Fourdriner paper machine. In this context, it should be mentioned that the couch roll could also be considered a rotating suction box.

![Figure 2. Suction boxes on a Fourdriner paper machine.](image)

When the fabric moves over a suction box, a suction pulse is applied to the web. The water removal is caused by the pressure difference between the vacuum in the suction box and the ambient air pressure. The vacuum in the suction box is maintained by a vacuum pump. The surface of the suction box opening is covered with low-friction material, e.g. ceramics, in order to reduce wear on the forming fabric. The surface of a suction box has holes or slits in it, where the vacuum is applied to the lower part of the forming fabric. An example of a suction box is shown in *Figure 3*. 
The suction pressure in a suction box is usually in the range of 15 to 40 kPa, but suction pressures as low as 65 kPa may occur, especially on fast running paper machines. Generally, higher suction pressures result in improved dewatering. An effective suction time varies from 20 ms to 450 ms, with individual suction pulses of 0.35 to 13 milliseconds in duration (Räisänen, 2000). Suction boxes increase the dry content of the web from values of around 4 to 10% to values in the order of 20% (Hansen, 1991).

Dewatering using a suction pressure is very energy intensive. In a Finnish study, vacuum pumping accounted for about 17% of the total electrical energy consumption on a paper machine (7 TWh/a). About one third of this energy was used in the wire section, with the couch roll and suction boxes as the main consumers of energy, see Figure 4.

Apart from causing an increase in energy consumption for vacuum generation, a greater suction pressure also increases the friction force between the suction box and the forming fabric and, consequently, the wear on the fabric. The
increased friction force also results in a higher energy requirement for operating the wire.

1.2 Previous experimental studies of suction box dewatering

Most of the previous research work has been done on laboratory equipment or pilot paper machines. Nordman (1954), Attwood (1960), Räisänen et al. (1993), Mitchell and Johnston (2002), and Granevald (2005) used laboratory suction boxes with various designs. Brauns and Oskarsson (1953), Eames and Ray-Moore (1976), Neun (1995), and Shands and Hardwick (2000) used pilot paper machines. Common to their work is that they studied how process parameters and web properties affect the dry content of the web after suction box dewatering. Suction pressure proved to be the most important process parameter for attaining high dry contents.

Lindberg (1970) and Neun (1993) concluded that dwell time, i.e. the suction time, is the second most important process parameter, especially in the initial stages of dewatering. The dry content increased with a long suction time, but was expected to reach a plateau value for longer suction times, see Figure 5. The pulsating effect caused by each suction element was assumed to be of minor importance.

The effect of the pulse frequency was studied by Räisänen et al. (1994). They observed that lower frequencies were preferable at a lower suction pressure (20 kPa), while the opposite was observed at a higher suction pressure (40 kPa). Their findings suggest that pulse frequency has to be adapted to the suction pressure in order to obtain the best dewatering. They concluded that the exact influence of the pulse frequency was not known.
The influence of web grammage was investigated by Müller and Rausch (1958) and Attwood (1962). They observed that higher web grammages made water removal more difficult, requiring longer suction times to obtain a higher dry content. Attwood states that the relationship between a dewatering result and grammage was far from linear and not completely understood.

Neun and Fielding (1994), Räisänen (2000), and Mitchell and Johnston (2000) made dewatering studies using webs made of chemical and mechanical pulp. Figure 6 shows that the dry content was higher for chemical pulp webs under the same process conditions. A higher compressibility of the chemical pulp webs was given as the explanation.

![Figure 6](image)

**Figure 6.** Dry content as a function of the total suction time (the sum of all individual suction pulses) for chemical ("Fine") and mechanical pulp ("TMP"); the experiments were carried out at two web temperatures, the web grammage was not given in the publication (Räisänen, 2000).

The effect of fines was discussed by Britt and Unbehend (1980, 1985), who found that the dewatering can be improved for increasing fines content levels up to a certain level. A decrease in the dewatering result was observed above this level. Britt and Unbehend proposed that the increased fines content made the web denser and less permeable to water.

It has been reported that filler decreases the dewatering efficiency. Springer and Kuchibhotla (1992) showed that the addition of filler increased the specific filtration resistance of the web. This was explained by a sealing of the pores. Räisänen et al. (1994) increased the filler content in a web and measured both the air flow through the web and the dry content after a suction pulse. In contrast to the previous results, the air flow through the web increased for the higher filler content but the dry content decreased. Räisänen explained this
result by saying that the filler led to a looser fibre network with a higher permeability while, at the same time, the network was less compressible.

In conclusion, it can be said that, common to all previous investigations, their focus was on the dry content attained, when evaluating suction box dewatering. When the results were interpreted, three possible mechanisms were more or less frequently mentioned: Compression dewatering, displacement dewatering and rewetting. At an early stage, evaporation caused by the air flow through the web was also considered. Its relevance was, however, ruled out by Brundrett and Baines (1966), who concluded from their results that moisture removal by evaporation during suction box dewatering was negligible. The suction time was far too short for a significant evaporation to occur.

1.3 Dewatering mechanisms

The water that is removed by the suction boxes is primarily located in the pores of the fibre network between the fibres. Water removal is done by web compression and the displacement of water out of the pores of the web, when air flows through the web. After the passage over the suction box, rewetting, i.e. the absorption of water by the web from the forming fabric, can occur. Figure 7 illustrates the occurrence of these three mechanisms during and after suction box dewatering.

![Figure 7. Mechanisms occurring during suction box dewatering: the illustration is simplified since only one long suction pulse is assumed.](image)

In general, little is known about the relative importance of these mechanisms. Furthermore, it has not been clarified whether web compression and displacement dewatering occur simultaneously or subsequently. In this context, Räisänen et al. (1994) suggest that water removal is mainly a result of the web compression, that the air flow through the web is more of a side effect of the applied pressure drop. On the other hand, Tarnopolskaya et al. (1998) formulated a model for suction box dewatering, assuming there was no web compression. Here, water removal was only assumed to be a function of the air flow through the web.
The model of Mitchell and Johnston (2003) is the only occasion when all three mechanisms were explicitly considered. Figure 8 shows an example from their calculations.

![Figure 8](image)

Figure 8. Simulated ratio of water volume to solid volume. Simulation parameters: grammage 1000 g/m², suction pressure 15 kPa (Mitchell and Johnston, 2003).

Their model predicted that water removal was initially carried out by compression dewatering, and air displacement dewatering started near the end. Rewetting occurred after every suction pulse. However, no experimental data were presented that confirmed the time scale and their quantitative results.

### 1.3.1 Web compression

When the web passes over a suction box, the pressure drop compresses the fibre web and water flows out. The dewatering result is therefore dependent on the compressibility of the fibre web, which describes the web deformation as a result of the applied stress (Campbell, 1947).

The compressibility is mainly dependent on the properties of the fibres in the network. Some researchers have studied the steady-state compression behaviour of saturated webs under low mechanical stress. Jones (1963) identified both the fibre length to diameter ratio and the fibre flexibility as important properties. Vomhoff and Schmidt (1997) measured a thickness reduction of more than 70% in the stress range of 30 Pa to 46 kPa for a saturated web. When the stress was decreased, the web expanded considerably but to a level below the original thickness.

To understand and describe the interaction between fluid flow through the fibre web and the compression of the fibre web during a suction pulse, Terzaghi’s principle is useful (Campbell, 1947).
It states that the sum of structural stress $\sigma$ in the fibre network and hydraulic pressure $p_h$ in the fluid is equal to the total applied pressure $p_{tot}$:

$$p_{tot} = \sigma + p_h \quad [1]$$

Assuming a constant, steady-state flow through the web, the structural stress increases in the flow direction, see the example in Figure 9. This results in an uneven compaction of the web. The layer closest to the surface, where the water leaves the porous material, is the most compressed layer, due to the highest structural stress. In the field of wet pressing, this phenomenon was investigated on several occasions and was termed “stratification” (MacGregor, 1983).

![Figure 9. Qualitative profile of the structural stress ($\sigma$) and hydraulic pressure ($p_h$) as a function of the web thickness ($z$) for the flow of a liquid through a compressible fibre network, assuming Terzaghi’s principle.](image)

According to Terzaghi’s principle, the sum of the structural stress and the hydraulic pressure is constant at every point in the fibre web. However, strictly speaking, this is only valid for a force balance. It can only be transferred into a stress balance, i.e. Terzaghi’s principle, if the reference areas for both structural stress and hydraulic pressure are identical. Terzaghi’s principle must therefore be applied carefully, especially for compressible porous media. This limitation was clarified in work done by Kataja et al. (1995).

The dynamic compressibility at structural stress values, relevant for suction box dewatering, has not yet been investigated. Previous dynamic experimental studies of suction box dewatering focused only on the final dry content of the web after the suction pulse, e.g. Attwood (1962), Neun (1995) and Räisänen et al. (1996).

In summary, it can be said that little information is available on the extent of web deformation in suction box dewatering. No direct measurements of the web deformation during a suction pulse have been performed.
1.3.2 Water displacement by air flow

When the air starts to flow through the web, the air displaces water out of the pores in the fibre network. However, for the air to break through an initially saturated web, the applied pressure difference must exceed the capillary pressure. This pressure difference for air penetration through a porous medium was termed “threshold pressure”. Brundrett and Baines (1966) and Eames and Ray-Moore (1976) measured the threshold pressure. According to their results, the pressure should be in the range of 7 to 14 kPa for newsprint sheets. It was also observed that a pressure lower than the threshold pressure would sustain air flow through the web, once the air had completely penetrated the web. The air flow prevented a re-filling, i.e. a closing of the pores.

During suction box dewatering, a certain time is required to establish an air flow through the fibre network. The time between application of the suction pulse and the air penetration through the wet web, termed “time to air penetration”, was experimentally determined by Granevald (2005). The webs were made from chemical pulp in the grammage ranges of 17 to 51 g/m². The time to air penetration was in the range of 0.2 to 1.9 ms. As expected, an increased suction pressure led to a shorter time to air penetration, see the examples in Figure 10.

![Figure 10. Examples of the time to air penetration, i.e. the intersections of the curves with the x-axis, for different suction pressures; grammage 17 g/m² (Granevald, 2005).](image)

The commonly used equation to describe the fluid flow in porous media is the empirical Darcy’s law. Darcy’s law is defined as:

\[
v = \frac{K \Delta p}{\mu L}
\]

[2]

where \(v\) is the superficial velocity of the fluid, \(K\) the permeability of the porous material, \(\Delta p\) the pressure drop, \(\mu\) the dynamic viscosity of the fluid, and \(L\) the thickness of the porous material. Darcy’s law is valid for Reynold numbers of less than one.
In suction box dewatering, the web is not necessarily saturated. The pores can be filled with both water and air. The measurement of the permeability in a system of two fluids is both complex and difficult. Deviations from Darcy’s law have been reported, see Polat et al. (1989). The laminar approximation of Darcy’s law for determining the permeability led to an error of 600%. This example shows that the validity of Darcy’s law cannot be taken for granted, when investigating the flow of air through a wet web.

When a fluid is displaced in a porous medium by another immiscible fluid of lower viscosity, the interface between the two fluids can become unstable, (Chuoke et al., 1959; Lenormand et al., 1988). The interface does not move smoothly but rather breaks up because of inherent instability. This results in a viscous fingering, where the displacing liquid penetrates into the displaced fluid. Consequently, the air tends to blow through certain parts in the saturated web and leaves much of the water undisplaced. A possible improvement to stabilize the interface by using hot gas was proposed by Miller (1973). However, Lindsay (1991) assumed that the effect of an unstable interface in a thin structure, such as paper, was of minor importance. He stated that the irregular pore structure in the web was the main reason for the less efficient displacement dewatering.

Another effect that influences the efficiency of displacement dewatering is the lateral flow of water in the paper. If the lateral permeability is larger than the transverse permeability, viscous fingering could tend to spread out in the plane of the paper. Lindsay (1993) measured the in-plane permeability and found that it could be 2 to 40 times higher than the transverse permeability. This difference in permeability could lead to an increase in water transport in the plane of the web. Consequently, the effective suction length during the passage over a suction slot would increase. This was also pointed out by Granevald (2005), who discussed an edge effect at the trailing edge of the suction box slot, when the moving fabric passed over it, see Figure 11.

**Figure 11.** The edge effect at the rear of the suction box slot. Zone 1 is the air flow through the zone associated with the slot. Zone 2 is the air flow through the zone behind the area associated with the slot (Granevald, 2005).

Granevald pointed out that, due to this edge effect, the effective suction time can be expected to be longer than the theoretical calculated suction time, based on the slot width. In accordance with Granevald’s reasoning, a similar effect should be present at the leading edge of a suction box as well.
Dewatering improvements can also be achieved with an increase in web temperature, see the results in Figure 6, for example. They are usually linked to an easier flow of water out of the fibre network. In the experiments done by Nordman (1954) and Attwood (1960), the dry content was raised as the temperature of the web was increased. This increase was explained by the decrease in water viscosity, allowing a more rapid removal of the water. In addition to the viscosity reduction effect, Ramaswamy (2003) also pointed out that a temperature increase leads to a reduction in surface tension of the water, which implies a reduced capillary pressure, enabling the emptying of more pores. No information was found as to whether the temperature also affects the dynamic compressibility of the fibre network.

Steam boxes, in combination with suction boxes, are a popular approach for increasing web temperature and, thus, improving dewatering. Patterson (2002) measured the heat transfer from the steam to the web. He found the permeance of the web to be the main controlling parameter for heat transfer. This implies that the heat transfer is limited in several practical application scenarios and that, consequently, its potential for improving dewatering is also limited.

1.3.3 Rewetting

When the web passes over the suction boxes, the web is compressed by the suction pressure. After the suction pulse, the web starts to expand and water flows from the forming fabric back into the web. This phenomenon is termed “rewetting”. For simplicity, rewetting is designated in the following text to be a dewatering mechanism, together with compression and displacement, although it actually has an adverse effect.

Rewetting, in connection with wet pressing, has been discussed frequently and was classified into internal, external and separation rewetting by Norman (1987), see Figure 12.

![Figure 12. Rewetting in wet pressing.](image-url)
Transferring this concept to suction box dewatering, separation rewetting is that part of the free water present at the interface between the web and the forming fabric, which follows the web at the separation of the web from the fabric. External rewetting corresponds to the water flow from the fabric into the web after the passage over suction box.

The fact that large amounts of water can remain in a fabric and be available for rewetting was shown by Luotonen and Sämpi (1995). They studied dewatering in a wire press on a pilot scale and found that rewetting strongly reduced the dry content of the web. In their experiments with pulp sheets, the effect of rewetting was as high as 1000 g/m². Vomhoff (1998) measured the dynamic expansion of a fibre network after wet pressing, i.e. at much higher levels of applied stress. The web expansion was significant and commenced immediately after the applied stress had been removed. The majority of the expansion occurred within the first second. This expansion can either cause or be the result of a significant external rewetting.

When suction box dewatering was investigated, rewetting was often neglected. Several indirect observations concerning rewetting in suction box dewatering were reported however. Brauns and Oskarsson (1953) and Attwood (1962) observed rewetting during their dewatering experiments without giving any quantitative data.

Granevald et al. (2004) drew conclusions with respect to rewetting, when studying the influence of the forming fabric design on the final dry content after suction box dewatering. In their experiments, the web was in contact with the forming fabric for a few seconds after the suction pulse. This implies that both external and separation rewetting most likely occurred. They found that the most important parameters, with respect to the dewatering result, were void volume and fabric thickness. Both parameters reflect the amount of water available in the forming fabric after dewatering. They thus suggested that rewetting could have a considerable influence on the result, but did not have the means to verify this.

In a long-term paper mill study, the dewatering behaviour of different forming fabrics was evaluated on a paper machine (Anon, 2004). For some fabric designs, the dry content of the web increased throughout the fabric life, see Figure 13. No analysis of the forming fabrics was made to clarify why the dry content increased in certain cases. However, a reduction in the thickness of the fabric, due to wear, could confirm the suggestions made by Granevald et al. (2004).
To this author’s knowledge, only one previous study has focused on the role of rewetting in suction box dewatering. McDonald (1999) studied separation rewetting during the web separation from the forming fabric on the couch roll. He found that a considerable amount of water was transferred from the wire to the web at the separation. McDonald concluded that a fine surface of the forming fabric was a good way of reducing the amount of water at the wire/surface interface, resulting in a reduction in separation rewetting.

1.4 Membrane-assisted dewatering

It has been suggested that placing a membrane on top of the web above a suction box to improve suction box dewatering might be a possibility. Due to the pressure drop over the membrane, the structural stress on the web increases, leading to a higher web compression. The membrane would also reduce the air flow through the web, most likely affecting the displacement dewatering mechanism and also leading to a reduced air flow through the web.

Trasente (1991) tested the use of a permeable membrane in her Master’s thesis. Using a membrane increased the dry content of the web after the suction pulse when compared with experiments not using a membrane. She found that the use of a membrane had a “positive response on vacuum dewatering” i.e. the dry content of the web was strongly increased. However, a shortcoming in her study should be mentioned. The vacuum level was higher when she used a membrane, due to the reduced pressure loss in her experimental set-up. Consequently, the exact effect of the membrane on dewatering could not be properly determined.

Moosavifar (2002) used a permeable membrane in his laboratory experiments. His main result was that the air consumption could be reduced by a factor 6 to
10 when using a membrane, while still achieving the same dry content. His results indicate the potential of using a membrane for reducing energy consumption.

To further reduce energy costs and increase the pressure drop, there was a suggestion to place a pressure box above the membrane. Several such ideas regarding possible industrial processes were proposed, see, for example, Grabscheid et al. (2000a; 2000b). In one of those designs, the use of several consecutive pressure chambers/suction box combinations was proposed, see Figure 14.

Figure 14. A means of increasing the pressure difference over the web, using several pressure chambers above and suction boxes underneath the web (Grabscheid et al., 2000b).

Beck (2005) presented a complete layout of a paper machine, where a single pressure chamber, in combination with a membrane, is implemented on a tissue machine, see Figure 15.
Unfortunately, there is no publication on practical experiences with such a process. The reduction of air leakage and dealing with the friction between the membrane and the pressure chamber has to be considered key issues when it comes to an industrial implementation.

### 1.5 Summary

Previous suction box dewatering studies focused on the influence of web properties and process parameters. Three mechanisms that determine the dry content of the web after suction box dewatering were mentioned: Web compression, displacement of water by air, and rewetting. As the evaluation of the experiments was based on the dry content achieved after the suction box dewatering, this work did not provide information concerning the relative importance of the three mechanisms.

Neither web compression nor water displacement has been measured directly. Only a few researchers have considered rewetting in suction box dewatering. Assuming that rewetting considerably influences the dewatering result, many earlier results might have been overshadowed by a large rewetting.

Using a membrane on top of the web during suction box dewatering is believed to have the potential for an increase in content dry and energy savings. The increased dry content is supposed to be a result of an increased web compression. There are, however, just a few publications on the use of a membrane during suction box dewatering, but they have inconclusive results.
2 Objectives

The main aim of this thesis is to investigate the possibilities for improving suction box dewatering. Current knowledge of the suction box dewatering process is limited. A deeper understanding of the dewatering mechanisms should provide valuable information for further optimization of suction box dewatering. Furthermore, membrane-assisted dewatering appears to have the potential for improving dewatering, both in terms of energy savings for vacuum generation and increased dry content.

The objectives of this thesis are, therefore, two-fold:

I. To determine the relative importance of the three dewatering mechanisms.

The relative importance of the different dewatering mechanisms can be determined through direct measurement of the web deformation, the dry content changes during and after the suction pulse, the air flow through the fibre network, the amount of rewetting and the web saturation.

II. To evaluate the membrane-assisted dewatering process.

The potential of membrane-assisted dewatering, both in terms of energy savings and the potential increase in dry content, should be determined
The work in this thesis was organized as follows:

**Dewatering mechanisms and their influence on suction box dewatering process – A literature review (Paper I)**

**Objective**
- Overview on previous work in the field of suction box dewatering

**Conclusions**
- More knowledge on mechanisms during suction box dewatering is required
- Membrane-assisted dewatering has potential to make suction box dewatering more efficient

**Method for studying the deformation of a fibre web during suction box dewatering (Paper II)**

**Objective**
- Develop a method to study the web deformation during and after a suction pulse

**Result**
- Method works

**Evaluation of membrane-assisted dewatering on a pilot paper machine (Paper V)**

**Objective**
- Study the air consumption in relation to dewatering result during membrane-assisted dewatering

**Result**
- The use of membrane can significantly reduce the air consumption during the dewatering

**The deformation of chemical and mechanical pulp webs during suction box dewatering (Paper III)**

**Objective**
- Investigate the deformation behaviour of webs during a suction pulse

**Results**
- Compression dewatering is important as dewatering mechanism
- A considerable web expansion takes place after the suction pulse

**Web deformation during membrane-assisted dewatering (Paper VI)**

**Objective**
- Investigate the web deformation during membrane-assisted dewatering

**Results**
- The use of membrane can increase the web compression
- A larger rewetting after the suction pulse results in a much lower dry content when using a membrane

**External rewetting after suction box dewatering (Paper IV)**

**Objective**
- Develop a method to study the external rewetting after a suction pulse

**Results**
- The external rewetting can strongly reduce the dry content after the suction pulse
- Web compression and rewetting are the most important mechanisms in suction box dewatering

**Vorrichtung zur Entwässerung einer Faserstoffbahn (Paper VII)**

This patent application is a result of the evaluation of membrane-assisted dewatering trials on the EuroFEX pilot paper machine

*Figure 16. Structure of the work.*
3 Investigation of the dewatering mechanisms
This section summarizes the work in Paper II to Paper IV. Two laboratory methods were developed and used. The first method measured the deformation of the web during and after the suction pulse. The second method measured the dry content of the web at defined times during and after a suction pulse.

The results obtained were grouped and presented according to the three dewatering mechanism, viz. compression, rewetting and displacement.

3.1 Experimental methods
A laboratory suction box was used to study the deformation of a fibre web during and after a suction pulse. A diagram of the suction box is depicted in Figure 17.

![Figure 17. Laboratory suction box.](image)

A circular forming fabric with a newly-formed web was placed on top of the perforated plate of the suction box. The diameter of the forming fabric was 78 mm and it was surrounded by a plastic sheet. The suction pulse was exerted by moving the slit plate. The slit plate, placed between two slotted plates, acted as a valve and, when located in its left position, connected the suction box to a vacuum tank that was located below the suction box. Vacuum was then applied to the lower side of the forming fabric. The movement of the slit plate was driven through an excenter by an electrical drive. The length of the suction pulse was adjusted by setting the time that the slot plate was in its left position.
A laser displacement meter was used to measure the deformation of the web during the suction pulse. A steel net with a small plastic plate on top was placed on top of the web. It served as a target for the measurement of deformation. The target was placed on to the web, using a thin nylon wire to raise the target up and down.

The lower part of the suction box was connected to a vacuum tank with a volume of 250 l. A pressure sensor was used to control the pressure inside the vacuum tank. The pressure drop over the web during a suction pulse, i.e. the suction pressure, was measured directly below the forming fabric, using a micro-pressure transducer.

The dry content at different stages during and after a suction pulse was determined by removing the web from the forming fabric at defined times. A separation device was arranged on top of the suction box, see Figure 18.

![Figure 18. Separation device arranged on top of the laboratory suction box.](image)

A nylon net (1) was located between the web (2) and forming fabric (3). The net was mounted onto an aluminium frame (4), see Figure 19. At a defined time during the experiment, the frame, together with the web, was rapidly separated from the forming fabric using a pressurized cylinder (5). In its end position, the web was approximately 100 mm above the forming fabric.
Webs were produced by placing the plastic sheet with the forming fabric on the forming wire of a Finnish sheet former. For the experiments with the separation device, the aluminium frame was placed onto the forming fabric. A web of the target grammage was formed on the forming fabric.

In order to avoid a non-uniform sheet formation, a maximum web grammage of 75 g/m² proved to be practical. Webs with a higher grammage were produced by couching together several previously formed wet webs onto each other. Prior to a suction pulse, the web was sprayed with water until it appeared to be completely saturated (chemical pulp in the range of 7 to 8 % dry content, mechanical pulp in the range of 6 to 7 %).

To measure the web deformation during a suction pulse, the web together with the forming fabric and the plastic sheet, was placed onto the suction box. The target was carefully placed on top of the web. A suction pulse was applied by moving the slit plate. Web thickness and suction pressure sensors were recorded before, during, and after the suction pulse. In order to compensate for variations in grammage among the different samples, the thickness was converted into bulk when evaluating the results. About 5 seconds after the suction pulse, the web was removed for determining the dry content.

To measure the dry content at different stage during the suction pulse, the total arrangement, comprising the fabric, aluminium frame and web, was placed on the suction box. The aluminium frame was attached to the pressurized cylinder. The suction pulse was started and, after a specified time, the web was separated from the forming fabric by lifting the aluminium frame with the nylon net and the web. The web was then removed from the net and the dry content was determined.

In order to reduce the influence of an uneven moisture distribution in the web due to edge effects, a circular area (diameter 38 mm) of the sample was punched out in the centre of it. Only this area was used for determining the dry content. This area was weighed about 30 seconds after the suction pulse and then put in an oven to dry. After drying, the sample was weighed again to obtain both the dry content and the web grammage.
The most common parameter for evaluating suction box dewatering is dry content. In order to use the thickness measurements for estimating the effect of compression dewatering, the web was assumed to be a two-phase system, consisting only of water and fibres and a “two-phase dry content” was calculated.

It should be pointed out, that the “two-phase dry content” assumed a completely saturated web, without any air in it. In reality, however, the web might have contained a significant amount of air. This implies that such a web has a higher dry content than that calculated. Nevertheless, the “two-phase dry content” gives a good estimate of the effect of the web compression on the changes in dry content, due to web compression.

Figure 20 shows an example of a web deformation and a suction pressure measurement and the corresponding “two-phase dry content”.

In the experiments, chemical (100-200 g/m²) and mechanical (50-100 g/m²) pulps were used, the lower grammage of the mechanical pulp was chosen, according to commercial paper production. The pressure was in the range of 10 to 40 kPa, as the normal suction pressure in a suction box. The suction time was in the range of 50 to 2000 ms. This was a bit of a longer time, when compared to commercial paper machines, but it was necessary in order to get a better understanding of the process.

3.2 Compression dewatering

It is commonly known that a higher dry content can be obtained with chemical pulp webs, when compared with mechanical pulp under the same process conditions. A higher compressibility of the chemical pulp webs has been given as an explanation, but no qualitative measurements exist to verify this. To investigate the reason for the difference in dry content, the web deformation of chemical and mechanical pulps was studied under the same process conditions, see Figure 21.
The deformation rate in the web made from chemical pulp was much faster, compared to that of the mechanical pulp web. In addition, the minimum bulk was lower for the chemical pulp. The expansion of the web after the suction pulse was greater for the mechanical pulp. This difference in expansion explains most of the differences in the final bulk levels. In order to obtain an impression as to what this deformation might imply in terms of dry content, the bulk was converted into a “two-phase dry content”, see Figure 22.

The web made from chemical pulp was compressed maximally to a “two-phase dry content” of 19 %, while the corresponding value for the mechanical pulp...
web was only 17%. After reaching the maximal dry content, the considerable expansion further lowered the value of the “two-phase dry content”.

In this comparison, the increased dry content from the air displacement was not included, but the large effect on the dry content indicated that the compression was the main mechanism that controls the dry content of the web. However, no information was available about the dry content during the pulse and no conclusions about the actual importance could be derived from this result.

The deformation measurements showed that the webs made from chemical pulp could become more compressed, when compared with the mechanical pulp webs. The mechanical pulp web also expanded much more after the suction pulse.

Figure 23. Bulk as a function of time, (a) chemical pulp, SR: 24.6, 100 g/m², (b) chemical pulp, SR: 24.6, 200 g/m², (c) mechanical pulp, CSF: 87 ml, 50 g/m², (d) mechanical pulp, CSF: 87 ml, 100 g/m².

*Figure 23* shows the web deformation as a function of time for different suction pressures and suction times. Webs made from chemical pulp with a grammage of 100 g/m² showed an initial fast compression rate. At the highest suction pressure, the main deformation took about 10 ms. For a grammage of 200 g/m², the deformation was significantly slower. At the higher suction pressure, the main deformation took about 70 ms, while it lasted basically throughout the entire suction pulse of 400 ms at the lower suction pressure. For mechanical pulp webs with a grammage of 50 g/m², the main deformation took about
20 ms. Again, for the higher grammage of 100 g/m², a slower compression rate was observed.

A marked expansion of the web occurred after the suction pulse in all the experiments. This expansion was most likely caused by rewetting. The expansion was slower at an increased web grammage, most likely due to the larger amount of water that had to be transported back into the web. The expansion, i.e. the rewetting, seemed to be reduced with increased suction pressures and suction times. Longer suction times and a higher pressure drop usually led to an increase in air flow through the web. This increase in air flow most likely reduced the amount of water that was available for rewetting in the forming fabric.

### 3.3 Rewetting

The expansion of the web after the suction pulse (Figure 23) suggested that a large rewetting took place after the suction pulse. In order to verify this, the difference in dry content was determined, with and without external rewetting. In the experiments without external rewetting, the web was removed from the fabric after a predetermined time, while the vacuum was still being applied. In the experiments with external rewetting, the samples were in contact with the forming fabric for about 6 seconds after the suction pulse, before they were separated from the forming fabric.

![Figure 24](image)

**Figure 24.** External rewetting of mechanical pulp webs (CSF: 81 ml); 40 kPa suction pressure, 50 g/m² grammage. "Time" designates length of suction pulse, "with rewetting" implies that the web was in contact with the forming fabric after the suction pulse for approx. 6 seconds.

*Figure 24 depicts the rewetting effect obtained with mechanical pulp webs. The difference between the black and the grey line corresponds to the amount of external rewetting, under the assumption that separation rewetting remained*
unchanged. The external rewetting was significant, with a dry content difference of about 6% being observed. The maximum dry content without rewetting was about 20%, while the corresponding values were about 14% when rewetting occurred.

Figure 25. External rewetting of chemical pulp webs (CSF: 81 ml); 40 kPa suction pressure, 100 g/m² grammage, “Time” designates length of suction pulse, “with rewetting” implies that the web was in contact with the forming fabric after the suction pulse for approx. 6 seconds.

Figure 25 shows the results obtained for the chemical pulp webs. The rewetting caused a decrease in dry content of 4 to 5%. As previously observed, higher absolute dry contents were obtained with the chemical pulp webs, when compared to the results from mechanical pulp webs.

3.4 Displacement dewatering

This section not only reviews the experimental results related to displacement dewatering. The relative importance of all three mechanisms is also illustrated. This was achieved by comparing the calculated “two-phase dry content” with the actual dry content measured throughout the length of the suction pulse. Both the onset and the extent of the displacement dewatering could be determined. An example of this is shown in Figure 26.
The shapes of the curves were very similar, both in the compression and expansion phases. This implied that compression dewatering was more dominant as a dewatering mechanism and that the web expansion after the suction pulse coincided with the water transport from the forming fabric into the web, i.e. rewetting.

At a low suction pressure of 10 kPa, web deformation and the dry content measured corresponded with each other. This meant that the web was basically saturated with water. Dewatering by web compression during the suction pulse and rewetting after the suction pulse explained most of the changes in dry content. No displacement of water by air occurred. The fact that the dry content measured was, in some cases, lower than the “two-phase dry content”, can be explained by the occurrence of separation rewetting. Here, some of the water that was in the surface of the forming fabric was pulled off, together with the web, during the separation. This led to the measured result of a lower dry content.

When the suction pressure was increased to 40 kPa, the measured dry content was greater than the calculated “two-phase dry content”. Here, displacement dewatering, i.e. the displacement of water by air, improved the dewatering during the suction pulse. The effect of displacement dewatering started to become visible after the initial compression phase. This was maintained even after rewetting, which meant that a certain amount of air was still present in the web.
When the grammage of the web was increased from 50 to 100 g/m², the same qualitative behaviour was observed, see Figure 27. However, the rate of increase in the dry content was slower, which can be clearly seen with the high suction pressure. External rewetting also appeared to occur more slowly. This might be expected, since twice the amount of water had to flow back into the web to produce the same effect in decrease of the dry content.

Figure 28 depicts the results for chemical pulp webs of 100 g/m². At the low suction pressure of 10 kPa, the dry content measured and the “two-phase dry content” was basically identical. Clearly, displacement of water by air had not
occurred. Increasing the suction pressure to 40 kPa led to a much more pronounced compression. Furthermore, displacement dewatering became much more visible as a dewatering mechanism. Displacement dewatering roughly started when the compression reached its plateau value. Based on these results, it can be concluded that compression and displacement dewatering are more subsequent than parallel processes. The effect of displacement dewatering led to an increase in dry content of approx. 4 %.

When the grammage was increased from 100 to 200 g/m², the effect of displacement dewatering was only visible in the case of the longer suction pulse and the higher suction pressure, see Figure 29. Under these conditions, the displacement process did not appear to be completed at the end of the 400 ms suction pulse.

When the results for mechanical pulp webs were compared with those for chemical pulp webs, the effect of displacement dewatering was much more apparent for the chemical pulp. Furthermore, higher absolute dry contents were obtained for the chemical pulp webs and the absolute amount of rewetting, i.e. the drop in dry content after the suction pulse, was smaller.

Based on the results in Figure 26 to Figure 29, the water saturation of the webs was calculated to evaluate the effect of displacement dewatering, see Figure 30. The saturation was calculated at the end of the suction pulse (“without rewetting”) and 600 ms after the end of the suction pulse (“rewetting”).

![Figure 29. Dry content development for chemical pulp webs in terms of "two-phase dry content" (SR: 24.6) and measured dry content (SR: 21.4) as a function of time and suction pressure; 200 g/m² grammage, 400 ms suction pulse.](image-url)
Figure 30. Water saturation of the chemical and mechanical pulp webs immediately at the end of the suction pulse (without rewetting) and 600 ms after the end of the suction pulse (rewetting); 40 kPa suction pressure, 400 ms suction time.

With values in the range of 75 % and 95 %, the absolute water saturation levels were surprisingly high. It might have been expected that the webs contained a much higher proportion of air. Furthermore, the saturation after rewetting was about the same as that at the end of the suction pulse. Imagining rewetting as a pure filling of the pores between the fibres due to capillary-like mechanisms, it might have been expected that the degree of saturation increased considerably after rewetting. The webs made from mechanical pulp had a higher saturation level. Air displacement dewatering was more important for the chemical pulp webs.
4 Evaluation of membrane-assisted dewatering

This section summarizes the work in Paper V and Paper VI. The experiments were carried out on a pilot paper machine and a laboratory suction box. The laboratory suction box was described in the previous chapter (see Figure 17). The evaluation of the membrane-assisted dewatering comprised two parts. In the first part, the potential for saving energy, in terms of reduced air consumption, was investigated. In the second part, the effect on dewatering results was studied.

4.1 Experimental methods

The pilot paper machine trials were carried out on the EuroFEX Pilot Paper Machine at STFI-Packforsk AB. A membrane loop was arranged over the suction boxes at the end of the Fourdriner forming section. A diagram of the membrane loop is depicted in Figure 31.

![Diagram of the membrane loop and the arrangement of the suction boxes in the trials; four suction boxes, denoted 1 to 4, were used in the trials.](image)

The membrane loop could be lifted up and down onto the web. The membrane was pressed against the web by the pressure difference between the pressure in the suction boxes and the ambient air. This pressure was enough to drive the loop, which consequently did not need a separate drive.

The air flow into the suction boxes was measured. The dewatering trials were carried out using suction boxes 2 and 3. They were connected to the vacuum system through the same pipe and had the same suction pressures. At the end of the membrane loop, suction box 4, with a low suction pressure, was used to separate the web from the membrane. The ingoing and outgoing dry contents were measured by taking samples just before suction box 1 and after suction box 4. Samples were taken using a spoon that was pressed against the wire. The dry content was determined in the laboratory. Air consumption and suction pressure were measured at each trial point. Reference trials, without using a membrane, were done by lifting the membrane loop 50 cm above the web.
The effect of a membrane-assisted dewatering on the web deformation was studied on the laboratory suction box, see Figure 17. Different types of membranes, one impermeable and two different permeable membranes were evaluated by placing them on top of the web. Figure 32 illustrates the configuration during these measurements.

Figure 32. Configurations for the experiments without a membrane (left) and with a membrane (right).

The deformation of the web and the dry content after a defined suction pulse were measured.

4.2 Effect of membrane-assisted dewatering on air consumption

Figure 33. Dry content as a function of the air velocity and suction pressure; the suction pressure is given in the graph (in kPa); machine speed of 200 m/min, Chemical pulp (SR: 15.5), 100 g/m² grammage, membrane: Tyvek® with 55 g/m² grammage.

Figure 33 depicts the dry content as a function of the air flow into the suction box at different suction pressures. To attain the same dry content, the air flow was reduced by a factor of approximately two when the membrane was used.
The use of a membrane proved to be advantageous for reducing the air flow through the web during suction box dewatering. It therefore has the potential for saving large amounts of energy when generating a vacuum.

### 4.3 Dewatering result of membrane-assisted dewatering

To further investigate the potential of membrane-assisted dewatering, both the dry content and deformation of the web were studied on the laboratory suction box.

![Figure 34. Dry content as a function of the suction time, suction pressure and membrane configuration; suction pressures and suction times are given in the graph, 100 g/m² web grammage, chemical pulp (SR: 22), the web remained in contact with the forming fabric for approx. 5 seconds after the suction pulse.](image)

Figure 34 shows the dry content obtained with a 100 g/m² chemical pulp web with different membrane configurations (“High permeance”: one sheet of a FLUOROPORE™ filter, “Low permeance”: two sheets of a FLUOROPORE™ filter). In the experiments, the web was in contact with the forming fabric for approx. 5 seconds after the experiments, implying that substantial rewetting occurred. For a suction pressure of 10 kPa, the difference in dry content was very small among the configurations; a longer suction time and no membrane resulted in a slightly higher dry content. When the suction pressure was increased to 40 kPa, the highest dry content was obtained without a membrane. For the other configurations, the dry content decreased with a decrease in membrane permeance.

The dry content results were surprising, since lower dry content values were obtained when using the membrane. The deformation in the webs during the suction pulse was therefore analyzed.
Figure 35. "Two-phase dry content" as a function of time and the dewatering configuration; chemical pulp (SR: 22), 100 g/m² grammage, 40 kPa suction pressure and 400 ms suction time.

Figure 35 shows the "two-phase dry content" for a 100 g/m² web and a suction pressure of 40 kPa. As expected, the use of a membrane generated a higher maximal "two-phase dry content", i.e. a higher compression, when compared to the configuration without the use of a membrane. The increase in web compression using a membrane corresponded to an increase of 3 to 4 % in the dry content. However, an increase in rewetting after the suction pulse greatly reduced the dry content of the web to a value below that of the configuration not using a membrane.

The permeance of the membrane did not affect the maximal compression level so much. However, when using a membrane with a higher permeance, the extent of rewetting seemed to be reduced. A higher air flow through the web may result in less water being available for rewetting in the forming fabric. This hypothesis explained the differences observed in final dry content for the different configurations, see Figure 34. For the given process conditions, the use of a membrane did not improve the final dry content.
Figure 36. “Two-phase dry content” as a function of time and the dewatering configuration; chemical pulp (SR: 22), 200 g/m² grammage, 40 kPa suction pressure and 400 ms suction time.

Figure 36 shows the results obtained for 200 g/m² webs and a suction pressure of 40 kPa. There was a small difference in the maximal “two-phase dry content” among the different configurations. However, the compression rate was much slower, when using membranes; the less permeable the membrane, the lower the compression rate. Apparently, the additional compression of the web, when using a membrane, made the flow of water out of the web slower. When extrapolating the compression results to longer suction pulses, it is reasonable to believe that the web compression would increase with configurations using a membrane.
5 Summary and conclusions

In previous studies of suction box dewatering, three mechanisms that determine the dry content of the web were identified, viz. web compression, displacement of water by air, and rewetting. However, the evaluations focused on the web dry content that was achievable. Since the dry content is the result of all those mechanisms, it is difficult to derive information on the importance of a single mechanism.

In the present work, the relative importance of the three mechanisms was investigated. It was found that a large web compression took place during the suction pulse, particularly at its beginning. Displacement dewatering started after most of the compression had occurred. Its contribution to the increase in dry content was most pronounced for higher suction pressures and longer suction times. Nevertheless, compression dewatering was found to be the most important dewatering mechanism.

A surprisingly large expansion of the web was observed immediately after the suction pulse. This expansion was a result of rewetting and, if the web was not separated from the forming fabric immediately at the end of the suction pulse, it greatly reduced the dry content of the web. Under the conditions studied, this rewetting amounted to a decrease in dry content to the order of 3 to 6%. The rewetting effect was reduced with longer suction times and higher suction pressures. A considerable air flow through the web and the forming fabric was generated under these conditions. Apparently, the air flow moved water from the forming fabric into the suction box, with less water being available for rewetting as a result.

The results obtained explained the reason why a higher dry content can be obtained for chemical pulp webs, when compared with mechanical pulp webs under the same process conditions. The deformation rate of chemical pulp webs was much greater and they were also more compressible. At higher suction pressures and longer suction times, the displacement dewatering was more pronounced for chemical pulp webs. Furthermore, rewetting was lesser for chemical pulp webs. The combination of these effects resulted in a higher dry content for chemical pulp webs.

The use of a membrane on top of the web, during suction box dewatering, proved to be valuable for reducing the air flow through the web. It therefore has the potential to save large amounts of energy for vacuum generation. However, the dry content could not be improved. An explanation for this was found when looking at the web deformation. Here, it was observed that the web compression was increased when using a membrane, especially at a higher suction pressure. But rewetting after the suction pulse was also much more pronounced when the membrane was used. The final dry content after suction box dewatering with a membrane was therefore lower. This result can most likely be ascribed to the fact that there was much more water still left in the forming fabric that had not been removed by the air flow. This water rewetted the web, leading to the lower dry content.
When these laboratory dewatering results are compared quantitatively with those obtained on a paper machine, it is important to remember that paper machine dewatering is carried out by several short suction pulses instead of one long suction pulse. Furthermore, water is scraped off the back of the forming fabric when it passes over the top cover of the suction box. In addition, both the ingoing dry content and the suspension temperature on a paper machine can be higher. All these effects, combined, should explain the difference that, in order to achieve the same absolute values in dry content in the laboratory experiments, significantly longer suction times were required.
6 Recommendations for future work

The results of this study provide a deeper understanding of the relative importance of the mechanisms controlling the dry content of the web in suction box dewatering. To further investigate suction box dewatering, the influence of additional process parameters should be studied. Generally, the total suction time is obtained by dividing the total slot width by the machine speed. Due to edge effects, it can however be expected that the effective total suction time will be longer than the calculated total suction time for different suction box cover designs. Information on the influence of the suction pulse frequency could therefore be valuable for understanding the influence of the design of a suction box cover.

Rewetting has been found to be very important for the dry content after suction box dewatering. The prime aim should be to avoid this. The extent of rewetting is dependent on the interaction between the web and the forming fabric. Further investigation should therefore focus on the possibilities of avoiding rewetting by means of improvements in the design of forming fabrics, since this most likely affects both separation and external rewetting. Forming fabric designs or post-treatments that reduce the amount of water available for rewetting should be considered. A question to ask is why not incorporate a barrier layer in the forming fabric to permit a unidirectional water flow, only?

Furthermore, based on the above findings, there discussions should be held about the running of the web through the paper machine with the aim of reducing rewetting. On existing paper machines, decreasing the distance between the individual suction boxes but also between the last suction box and the pick-up position are obvious measures that could be taken to reduce rewetting.
The evaluation of the membrane-assisted dewatering showed that it is possible to achieve a higher compression dewatering by using a membrane, at the same time as less air flows into the suction boxes. However, rewetting after the suction pulse strongly reduced the dry content. Membrane-assisted dewatering could thus be effective if rewetting could be avoided. This could be realized by separating the web from the forming fabric immediately after the last suction slit of the suction box. The membrane could then be used as a transfer belt into the press section. An example of such a layout is illustrated in Figure 37.
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Peter Åslund
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