Improved Vacuum Dewatering of Grease-proof Paper Utilizing a Multi-slit Vacuum Suction Box in Laboratory Scale

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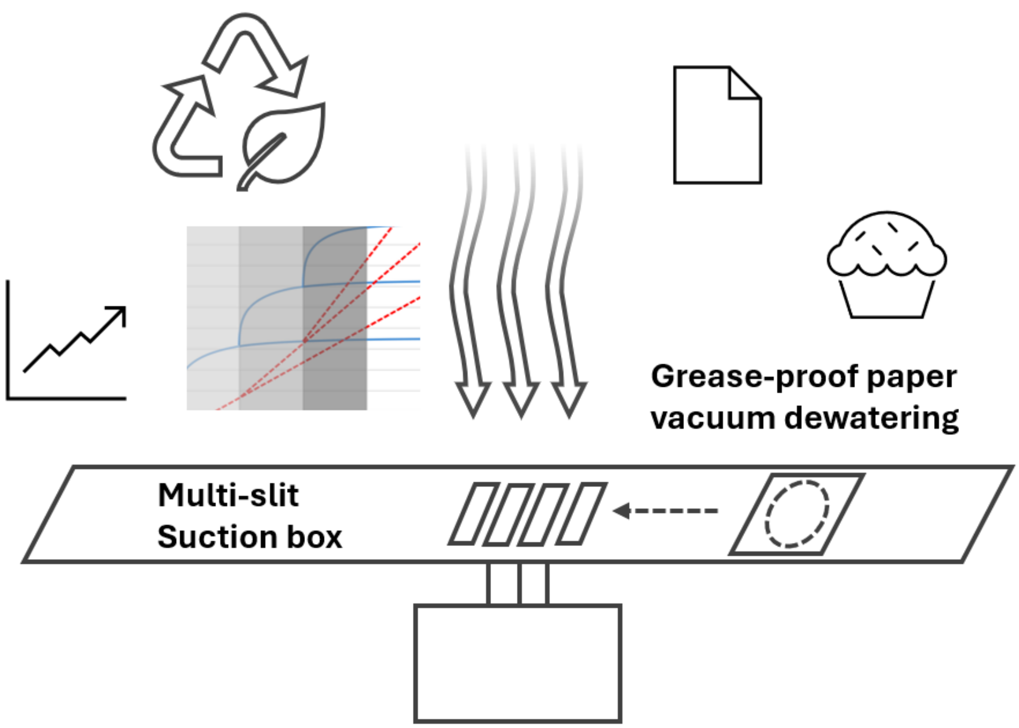
GRAPHICAL ABSTRACT



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Grease-proof paper is an energy-demanding paper product to manufacture, especially during refining and dewatering. Increases in energy efficiency in either stage could result in major savings. This article investigates the potential gains with addition of a stepwise progression vacuum suction box to the forming section during production. For both a lighter, 50 g/m^2, and a heavier paper grade, 100 g/m^2, with a pulp-drainability of 86 °SR, a stepwise progression vacuum suction box in four steps would result in increased dryness, simultaneously with decreased energy expenditure. The observed effects were higher for the lower basis weight paper (50 g/m^2). Both basis weights experienced clogging of the forming fabric due to the high degree of refining. This adversely affected the dewatering rate, decreasing the amount of air pulled through the paper even when increasing the vacuum pressure. When a stepwise progression suction box in four steps was compared to a single vacuum suction box, there was a 14% increase in dryness for lighter paper, over an equal energy consumption, measured as amount of air pulled through the paper. For the 100 g/m^2 paper, the increase in dryness was 3% compared to the 50 g/m^2 paper run over a single vacuum suction box. The results show great promise for energy savings when utilizing stepwise progression suction box dewatering for grease-proof paper production.

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Keywords: Grease-proof paper; Vacuum dewatering; Papermaking; Triple vacuum suction box; Basis weight, Energy efficiency

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INTRODUCTION

The purpose of incorporating wood into all types of possible applications is because the forest is a cyclic system. Wood is an attractive option for the environmentally conscious because of its perks of being non-toxic, renewable, as well as readily available and biodegradable. Therefore, one of the biggest aims currently is exchanging current oil-based products, such as fossil-based plastics, with wood-based alternatives for environmental benefits (Gellerstedt 2006a; Leskinen *et al.* 2018). One main application of wood is paper products, with approximately 13 to 15% of all wood-based products being paper products (FAO 2021). Along with the wide variety of uses for paper products comes a wide variety of subcategories of paper, one of these being *grease-proof paper*.

Grease-proof Paper

Grease-proof paper is a paper grade with grease-proof properties, *i.e.*, resistance against fats and oils. Typically, the products are being used in contact with foods; therefore, they require specific properties, such as not releasing any type of smell or taste, being impenetrable by fluids, and not containing any kind of additives that would render harmful or toxic (Gellerstedt 2006b). This is not easily achieved. Efficient production of grease-proof paper grades is difficult because the fluid-impenetrable properties of these papers results in them being significantly harder to dewater, compared to regular paper grades. The dewatering of paper is a process required in all types of paper manufacturing and is one of the most energy expensive stages of the paper manufacturing process (Hubbe *et al.* 2020). Dewatering can be responsible for as much as one fifth of a mill's total energy expenditure (Håkansson 2010), including refining prior to the machine. For grease-proof paper, which is harder to dewater due to low drainability after substantial refining, correspondingly higher energy consumption occurs throughout the paper machine. The refining enables grease-proof properties by lowering the porosity (Stolpe 1996), which is the papers' void volume in relation to the total volume (Cengel and Ghajar 2020). It can also be expressed as permeability, which measures how easily the paper is penetrated by fluids (Kjellgren 2005; Fellers 2007).

To acquire the needed levels of porosity and permeability to meet the requirements of grease-proof grades, the fibers are extensively refined to yield a dense enough structure with a sufficiently low permeability to not let water or grease pass through the structure. This is obtained because the refining procedure leads to three main changes within the fibers, namely internal fibrillation, external fibrillation, as well as shortening of fibers (Mandlez *et al.* 2022). These result in an increase in fiber-to-fiber interactions, along with reductions in fiber size, together with an increase in fines, which leads to a more compact paper and the paper being more hard-penetrable by fluids (Kang and Paulapuro 2006; Motamedian *et al.* 2019; Hubbe *et al.* 2020). This extensive refining requires a much greater energy input than for a more commonly beat paper. Koponen *et al.* (2023) stated that for a given degree of dryness, a higher dwell time over vacuum is needed for the more refined pulp (Koponen *et al.* 2023). Additionally, according to Håkansson (2010), the refining of the less refined pulp used for newspapers can correspond to 35% of the total energy expenditure of a mill, meaning that the refining process is a very energy intensive process. Annergren and Hagen (2006) compared the energy expenditure of refining of sack paper to that of grease-proof paper and found that the refining of the latter can require two- to up to almost four times the energy input. Thus, the refining process for grease-proof paper is expected to stand for more than 35% of the total energy expenditure of the mill, or, an equal percentage, over a greater total energy expenditure. Therefore, the process of producing grease-proof paper is a very energy expensive process, giving great potential for savings.

The drainage of pulps defines the ease of early dewatering. The °SR-value of pulp heavily affects the time required to remove a set amount of moisture from a paper of a given basis weight (Koponen *et al.* 2023). The relationship between °SR-value and drainage time is nonlinear. Thus, if 1 s is required to remove a set amount of water from a paper of 43 °SR, the corresponding amounts of time for an 85 and 97 °SR paper would be 10 and 100 s, respectively, suggesting an exponential difficulty in dewatering. The study also found that the 97 °SR paper was more rapidly dewatered than the less refined pulp during the initiation of the forming, *i.e.*, the gravity dewatering (Koponen *et al.* 2023).

Tissue paper, which is thin and bulky compared to grease-proof, typically has a drainage value of approximately 20 to 40 °SR (Sjöstrand *et al.* 2023b), depending on the refining strategy and product. During the laboratory work by Sjöstrand (2023), testing a laboratory scale triple vacuum suction box, a 22 °SR tissue grade paper reached a dryness of 22% when run over a 20 kPa vacuum with a vacuum dwell time of 20 ms. In another study by Sjöstrand (2017), the water ratio of a 23.1 °SR tissue paper run over a 40 kPa vacuum pressure for the duration of 20 ms resulted in a moisture-dryness ratio of roughly 3:1, which converts to a 25% dryness level. These results were obtained for a seemingly easy-to-dewater paper grade. In comparison, a high °SR paper, such as grease-proof paper, is expected a much lesser dryness over equal vacuum dewatering. The 22 to 25% is a high dryness level compared to typical outgoing dryness after the full forming section for grease-proof paper, which commonly lies closer to 15% (Stolpe 1996).

Dewatering

Vacuum dewatering is an efficient process for dewatering paper initially, when there is a high water-content of the paper. Vacuum dewatering utilizes a pressure drop to remove water from the paper. It is in this section where the most part of the total water content of the stock is removed (Kuhasalo *et al.* 2000; Hubbe *et al.* 2020; Koponen *et al.* 2023). The optimization of the forming section is of great importance. When the water content of the stock is high, the water is the least reluctant to leave the wet web; *i.e.*, the water is the most easily removed. To utilize this, at the very beginning of the forming section, the paper is dewatered using only gravity (Ramaswamy 2003; Sjöstrand 2020). Not only is this efficient in terms of energy savings, but it is also beneficial because it puts less stress on the wire, causing less wear and tear. Then, after the gravity dewatering, *foils* are used (Hubbe *et al.* 2020). These foils have an upwards angle towards the wire, almost scraping the water from the wire from beneath, while also creating a component of vacuum as the sheet passes over these foils due to their angles. Thereafter, vacuum suction boxes are used with an increasing level of vacuum as the dryness, and therefore reluctance of the water, increases (Attwood 1962; Neun 1994; Räisänen 1996; Pujara *et al.* 2008; Sjöstrand 2020, 2023; Hubbe *et al.* 2020). Figure 1 below shows a typical forming section layout.

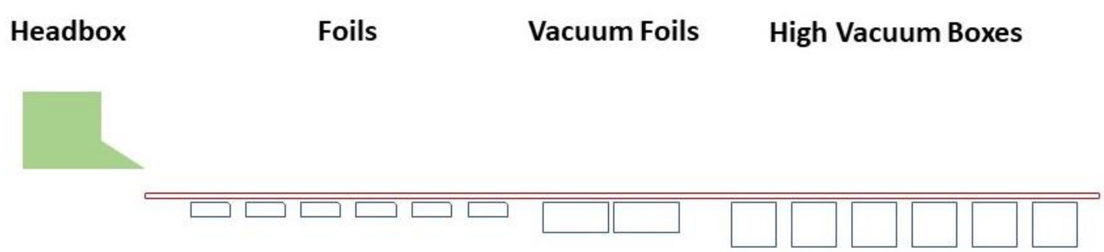

Fig. 1. Schematic of a typical forming section layout

According to Koponen *et al.* (2023), a low vacuum level is also needed initially to keep a good permeance and formation in the paper (Koponen *et al.* 2023). A good formation is crucial for grease-proof paper as a means to achieve the product-specific properties; as a paper with variations in thickness, *i.e.*, a paper with a less consistent basis weight, would yield a variation in grease proof abilities as well (Norman 2008). Additionally, to achieve a good coating of the paper, a good formation is required, along with a low porosity of the paper.

According to Kjellgren (2007) a low porosity leads to the coating layer being adsorbed, rather absorbed, *i.e.*, the coating is applied to the surface, and is not being absorbed into the structure of the paper, resulting in a more film-like coating on the surface, yielding a better and more uniform proofing against grease.

It is of huge importance in terms of energy efficiency to monitor the vacuum dewatering process. When paper is left on the same level of vacuum pressure too long, *i.e.*, after it has reached its point of diminishing returns, the vacuum will start pulling air through the paper, rather than water from the paper. From this point forth, all extra energy input goes to waste. Therefore, an arrangement where the paper reaches the succeeding vacuum suction box as soon as the air starts being pulled through the sheet is the most optimal (Hubbe *et al.* 2020). Theoretically, the air flow will initially be zero, until the largest interfibrillar pores are evacuated, and then it will increase linearly with dwell time; the slope of the line will increase with increased pressure drop (Sjöstrand *et al.* 2023). Therefore, the integral of the airflow over dwell time is a good representation of the rate of energy consumption.

To achieve a good formation of the paper and to prevent flocculation, extreme amounts of water are needed in the headbox of the paper machine, typically around 99.5 to 99.9% water. This is described as the “water paradox” by Sjöstrand (2020). A huge amount of water is required to be added to the stock, and then a great amount of energy is required to remove this newly added water during the formation of the paper (Kuhasalo *et al.* 2000; Norman 2000; Sjöstrand 2020). To give a better understanding of the amount of water added, which then needs to be removed, approximately 100 to 170 kg of water needs to be removed per kg finished paper (Heikkliä and Paltakari 2000). This is because the wanted, ingoing, stock dryness is 0.1 to 0.5% (Kuhasalo *et al.* 2000; Norman 2000; Sjöstrand 2020), hence creating the previous mentioned paradox. The common stock refining-dryness ranges from 2 to 35%, from low to high consistency refining, before needing dilution to fit the forming section criteria (Lumiainen 2000). Grease-proof paper also comes in a wide range of basis weights, *i.e.*, weight per area. According to Gülsoy and Şimşir (2017), a higher basis weight paper will be harder to dewater per weight unit due to not only a close to linear increase in water content, but also due to a thicker paper having a greater permeability; and as according to Åslund *et al*. (2008), who found that the dewatering rate increases with a decrease in basis weight (Åslund *et al.* 2008).

In 1997, Baldwin hypothesized that using a vacuum suction box with three setups of vacuum slits in succession, with increasing vacuum throughout with such a small gap in between slits that close to no rewetting could occur, would yield a more energy-efficient dewatering (Baldwin 1997). This is because the dryness of a single vacuum box acts asymptotically over time, meaning that an increased time over vacuum, *i.e.*, an increased dwell time, would only result in a marginally higher dryness, while the energy input remains constant as seen in Fig. 1(A) below.

These asymptotes would thereby be overcome by utilizing a higher degree of vacuum by the time these asymptotes have been reached in order to reach a higher degree of dryness, with a lesser energy expenditure (Attwood 1962; Neun 1994; Räisänen *et al.* 1996; Baldwin 1997; Räisänen 2000; Ramaswamy 2003; Granevald *et al.* 2004; Pujara *et al.* 2008; Rahman *et al.* 2018; Sjöstrand *et al.* 2019, 2023; Hubbe *et al.* 2020; Sjöstrand and Brolinson 2022). Common commercial paper machines utilize dwell times in terms of milliseconds (Ramaswamy 2003).

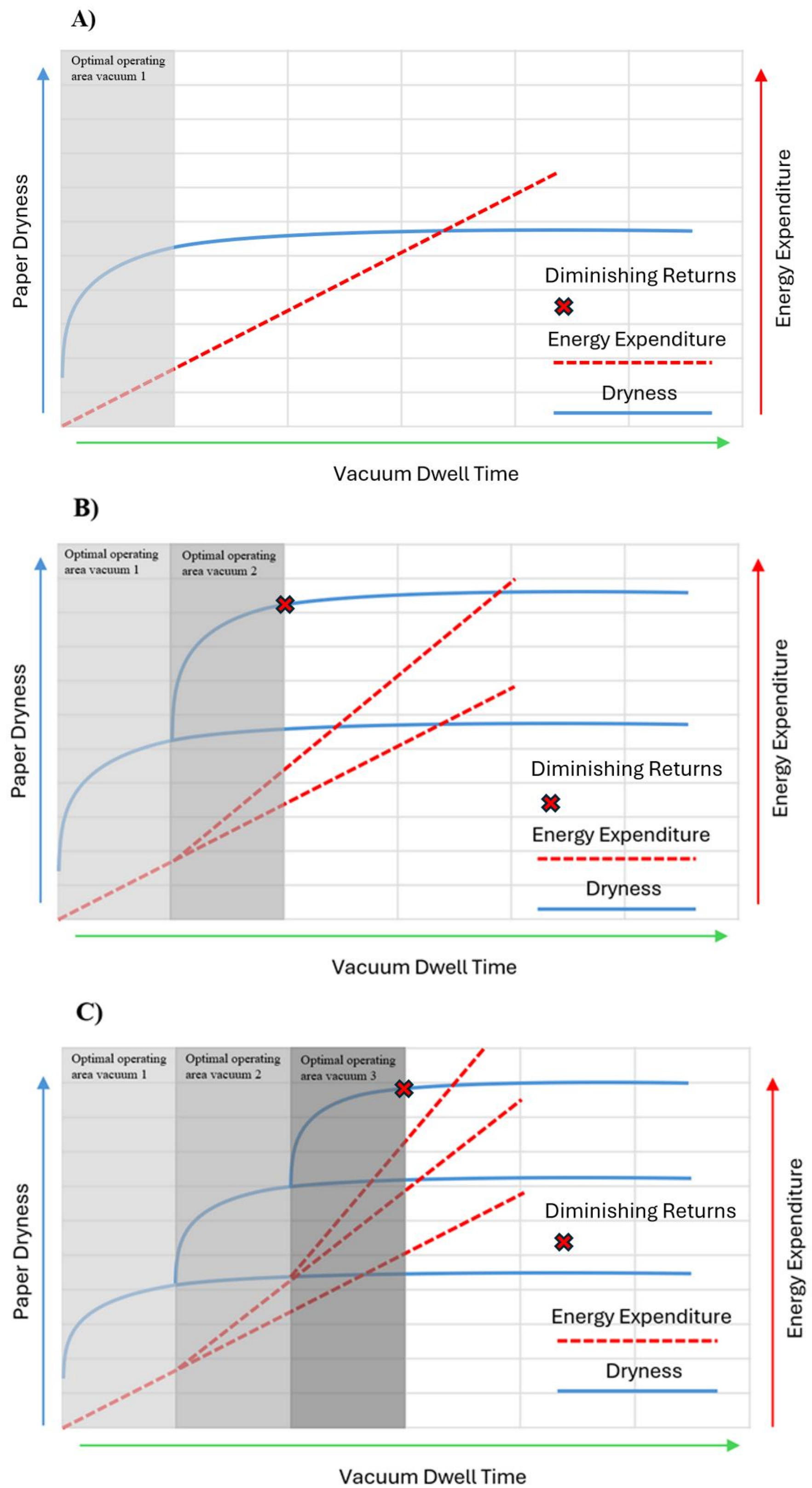

Fig. 2. Visualization of the expected point of diminishing returns in dryness and corresponding rate of energy expenditure over dwell time for vacuum boxes with 1, 2, and 3 vacuum slits with increasing pressure. Redrawn with inspiration from Hubbe *et al.* (2020).

The gain in dryness as compared to energy spent over dwell time for these successive multiple split vacuum boxes hypothesized by Baldwin is presented below in Fig. 1(B) and (C) for a dual and triple vacuum suction box, respectively, showing the decrease in gains in dryness, with the energy expenditure held constant (Hubbe *et al.* 2020; Sjöstrand 2023). Thus, it is shown that stopping the vacuum at the point of diminishing returns in (C), *i.e.*, operating within the optimal operation area, would yield a greater dryness, and at the same time a lesser amount of energy spent.

Not only is the grease-proof paper more energy demanding to dewater, but it is also harder to dewater in terms of reaching a high dryness in the forming section. Where a typical dryness after the forming section reaches 20%, the dryness after the forming section for grease-proof paper only reaches approximately 15% (Stolpe 1996). This is in accordance with Baldwins' (1997) findings of a paper with an increased drainage rate. An increase in *Canadian Standard Freeness*, CSF, led to not only a higher dryness after forming section, but also to a more rapid rate of dewatering.

Grease-proof paper not only faces challenges in dewatering due to their harder-to-dewater nature, but due to having a low porosity, grease-proof paper is expected to rewet more easily. This is because the low porosity of grease-proof paper means narrower pores of the paper structure, which will expose the paper to stronger capillary forces, the driving factor of rewetting (Hubbe *et al* 2020; Sjöstrand 2017). This is where and why grease-proof paper manufacturers could utilize a multiple stepwise increasing vacuum suction box such as the one theorized by Baldwin (1997). Due to the great ability of grease-proof paper to rewet, utilizing a multiple vacuum suction box, where there is close to no time between slits, the grease-proof papers' ability to rewet would be greatly reduced. According to Koponen *et al*. (2023), highly refined pulp is also more prone to clog the wire with its fine fibers, as they found that a 97 °SR paper clogged the wire efficiently. This resulted in a longer time over vacuum needed to achieve a high dryness because the wires' ability to let water diffuse through, *i.e.*, the wires' permeability drastically decreased (Koponen *et al.* 2023). Reducing the possibilities of rewetting is interesting for grease-proof paper. According to Åslund *et al*. (2008) and Sjöstrand *et al*. (2015), the rewetting of the paper after being exposed to vacuum pressure can account for a decrease of up to six percentage units in dryness (Åslund *et al.* 2008; Sjöstrand *et al.* 2015), which is a large part of the total change of 5 to 15% in a typical grease proof forming section (Kjellgren 2005). The pulp used in Sjöstrand *et al.* (2015) was unrefined, which suggests that the highly refined pulp used for grease-proof paper could, potentially, experience an even greater decrease in dryness due to rewetting caused by the strong capillary forces from its low porosity.

EXPERIMENTAL

Equipment

The experimental apparatus employed in the laboratory investigations comprised a Williams Apparatus CO hand sheet former (refer to Fig. 3), accompanied by a manually operated stomper plate (see Fig. 3). Additionally, a laboratory-scale vacuum suction machine (illustrated in Fig. 4) was utilized. The method was developed by Granevald *et al.* (2004) and described further in the cited article.

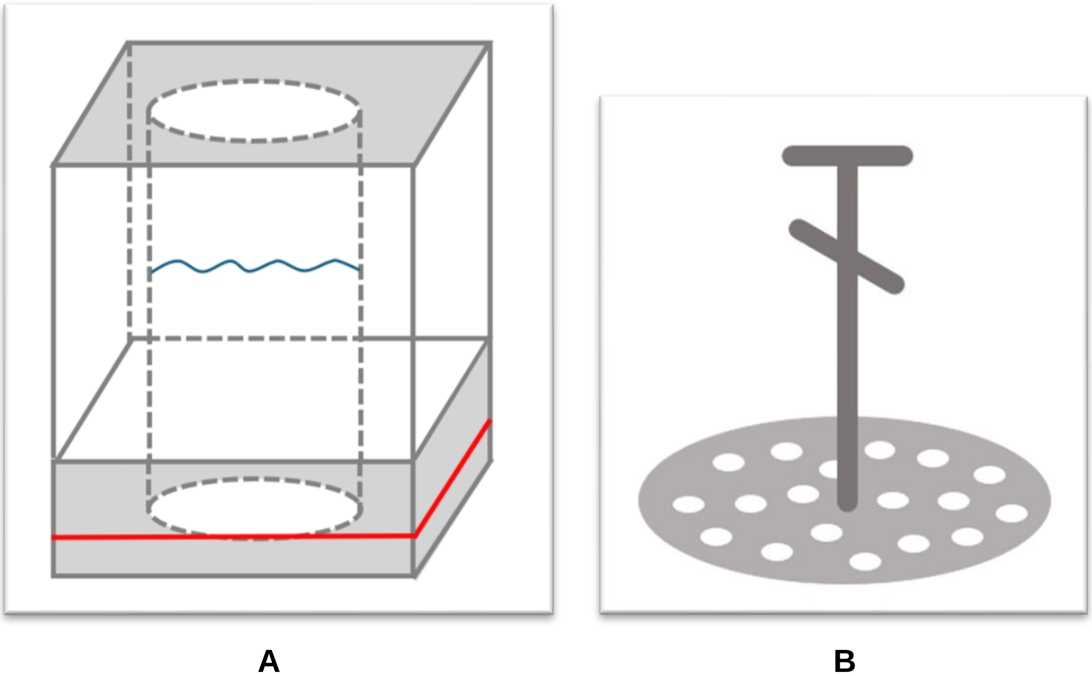

Fig. 3. A: schematic of the hand sheet former used. Red line denotes the opening from which the paper is removed after drainage of the water; B: stomper used to homogenize the pulp.

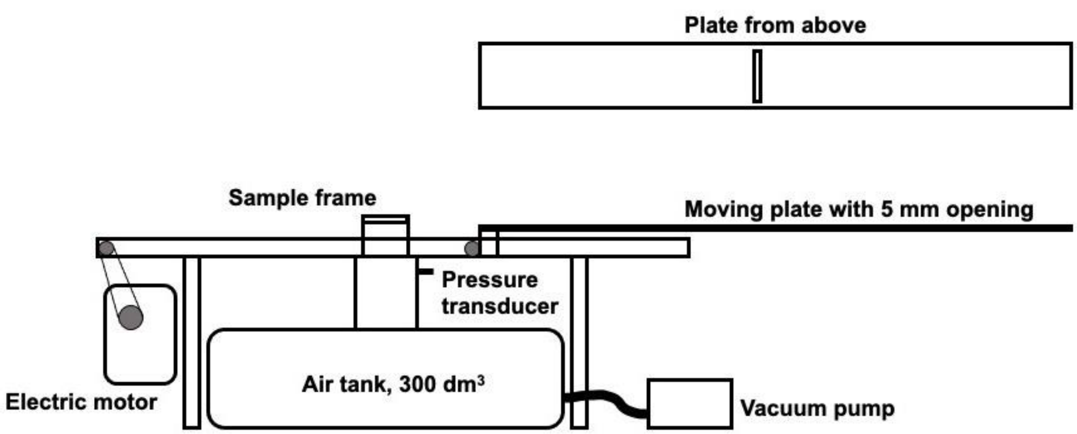

Fig. 4. Vacuum dewatering machine in laboratory scale. Vacuum pressurized tank with a moving bed on top passing over the vacuum slit (permission to use image granted by Björn Sjöstrand, original author (Sjöstrand 2023)).

Materials

Both the pulp and fabric used in this laboratory work were supplied by Nordic Paper Seffle AB. The provided fabric used was a commercially used Packline EL warp type fabric with a 2/10 shed 2:1 shute ratio, with a 425 CFM permeability. Drainage (°SR), according to ISO 5267/1 (1999), was used for describing pulp drainability in this article. A high °SR-value indicates a well-refined pulp, hence, a high °SR-value indicates a lower rate of drainage of the paper (Lumiainen 2000).

Softwood from a spruce and pine mix, 86 °SR, kraft pulp with a consistency of 3.2% dryness was used in all experiments.

Preparation and Execution

The pulp was diluted to a consistency of 0.2 w-%, with the assumption of the fiber density is equal to that of water.

The pulp was continuously stirred to prevent flocculation, and to homogenize the pulp. For the simulation of a successive multiple slit vacuum box, the method is in accordance with the method by Sjöstrand (2023). The paper, supported by its screen, was run over vacuum, then removed so the machine could reset. Then, the paper was returned to the machine to be run over the next vacuum; this was repeated for each vacuum slit. These removals and re-applications of the paper are expected to yield a greater rewetting (Sjöstrand 2023).

The multiple vacuum dewatering procedure is described below:

- To achieve the intended basis weight of 50 g/m^2, 664.8 ± 1 g was poured into the hand sheet former, and 1329.6 g ± 1 g for 100 g/m^2. The diameter of the circular sheet former was 18.4 cm.
- The stomper was pressed through the pulp to homogenize it once again immediately before draining the water, forming the paper.
- After drainage, the paper, still on the fabric, was moved to the laboratory scale vacuum dewatering machine. Vacuum dewatering was performed once or several times, in order to simulate a multi-slit vacuum suction box. For this simulative multi-slit suction box, the first slit was recorded, then for the later slits of higher vacuum, simulating a multi-slit vacuum box; the first slit was run as before, the machine was reset, before reapplying the paper to the machine for the second slits' run. Likewise, for slit three and four, as according to Table 1.
- Then, the middle area of the paper was gently scratched off, ensuring that no edge effects areas were used, as per Granevald *et al.* (2004), added to a pre-weighed container, and measuring its wet-weight, before being dried over the duration of 24 h at 105 °C, according to ISO 638-1 (2022), before its dry-weight is measured and the dryness calculated according to Eq. 1. Edge effects are considered inhomogeneous airflow close by the edges of the sheet due to the sheet holder, also causing extra rewetting due to sheet having slight overlapping against the holder, leading to a less uniform dewatering (Granevald *et al.* 2004).
- For every sample, the pressure drop was recorded, with the pressure being measured with a pressure transducer every millisecond.
- For single vacuum box reference measurements, 50 and 100 g/m^2 paper were prepared according to above method, run once over 20 kPa vacuum pressure and 33.3 ms dwell time to record air volume through the sheet. 50 g/m^2 paper over 20 kPa vacuum pressure and with a 33.3 ms dwell time was used as a reference for dryness. These were used as references, mimicking regular commercial vacuum box dewatering for grease proof paper.

The pressure drop curves were adjusted according to Granevald *et al.* (2004), who found that 15 to 50% of the achieved pressure drop was due to leakage. From this, a 0.2 kPa leakage was assumed, and all pressure drop data was corrected in accordance with this.

Table 1. Setup of Multiple Slit Vacuum Suction Box Dewatering

Slit Number	Vacuum Pressure (kPa)	Vacuum Dwell Time (ms)
1	10	0, 1, 2.5, 5 10
2	10, 20	10 + (1, 2.5, 5, 10)
3	10, 20, 30	10 + 10 + (1, 2.5, 5, 10)
4	10, 20, 30, 40	10 + 10 + 10 + (1, 2.5, 5, 10)
Single Slit Box	20	33.3

Equations

Paper dryness was calculated using Eq. 1,

$$Dryness = \frac{m_{wet} - m_{dry}}{m_{wet}} \quad (1)$$

where m_{wet} and m_{dry} are the wet and dry weight (g), respectively.

RESULTS AND DISCUSSION

In accordance with the previously mentioned expected dryness curves, the dryness of the grease-proof paper over dwell time reached a plateau (Attwood 1962; Neun 1994; Räisänen *et al.* 1996; Baldwin 1997; Räisänen 2000; Ramaswamy 2003; Granevald *et al.* 2004; Pujara *et al.* 2008; Rahman *et al.* 2018; Sjöstrand *et al.* 2019; Hubbe *et al.* 2020; Sjöstrand and Brolinson 2022; Sjöstrand 2023). Each of the four series, for both paper basis weights, representing a new set of slits with increased vacuum throughout, is plotted in Figs. 5 and 6 below, showing dryness, in percentage, as a function of dwell time.

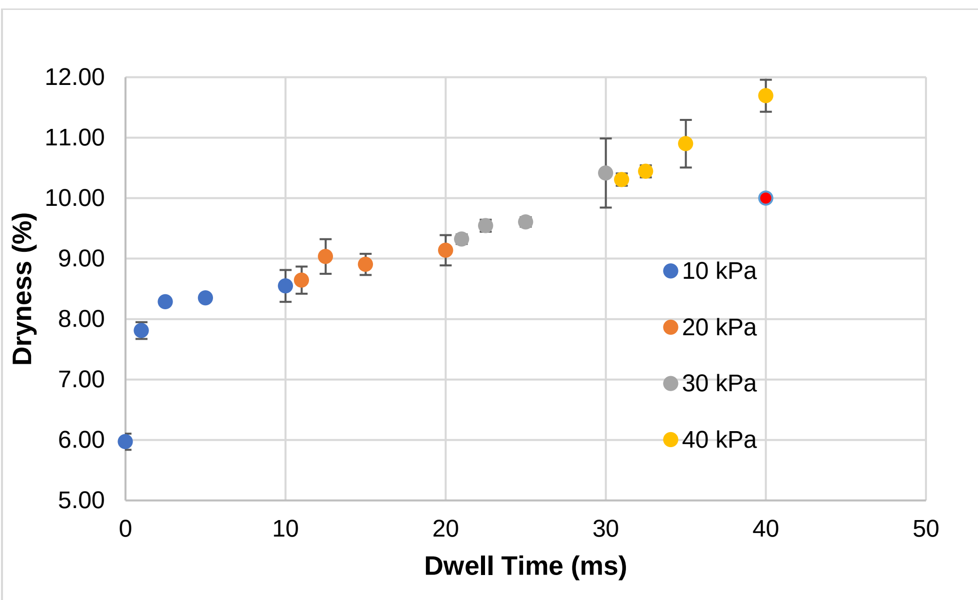

Fig. 5. Dryness over vacuum dwell time for 50 g/m^2 paper run over a simulative quadruple slit vacuum suction box, compared to a single vacuum slit run

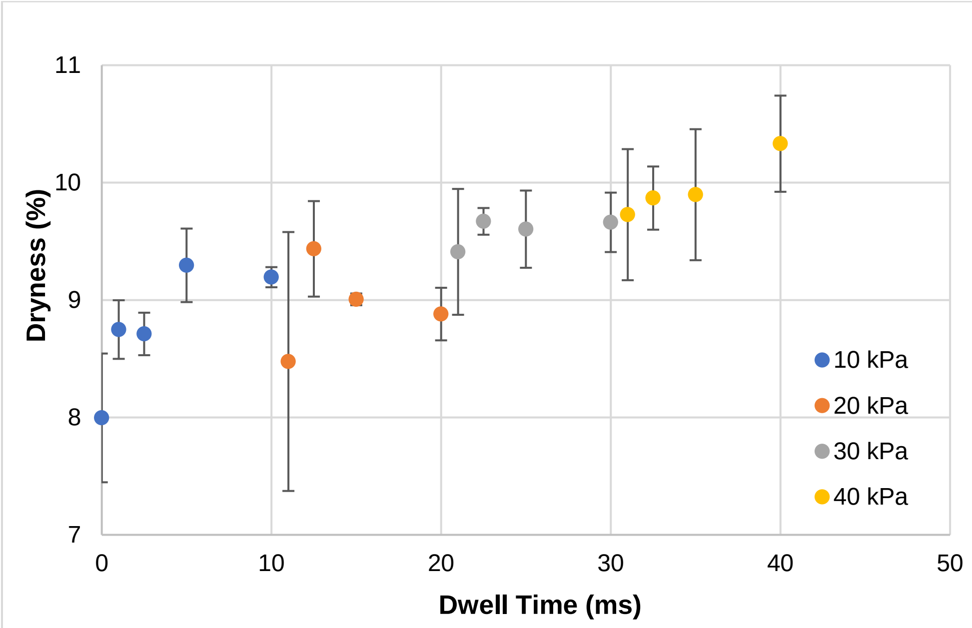

Fig. 6. Dryness over vacuum dwell time for 100 g/m^2 paper

Figure 5 shows that for the 50 g/m^2 paper, the dryness plateau had been reached for 10, and possibly for 20 kPa. For 30 and 40 kPa, the dryness seemingly increased linearly, thus implying that a higher dwell time could be utilized. Because the plateauing of the 10 and 20 kPa runs seemingly started to occur after 10 ms dwell time each, an increase in dwell time here would be energy wasted, as it would not yield an increased dryness. For 40 kPa, there seemed to be no plateauing occurring, whilst for 30 kPa, the standard deviation made for a tougher reading as it is harder to determine whether the plateau had been reached or not. This standard deviation could be due to numerous things, such as hand handling of the wet sheet, pin holes in the sheet, or clogging of the fabric, causing a worse or uneven dewatering. There could be a potential gain in dryness and efficiency if an increased dwell time were to be used for 40 kPa. This is in accordance with the water being the least reluctant early in the forming section, as the paper's dryness increases readily between 0 and 10 ms, followed by a lesser gain in dryness during the following slits, once again proving the benefits in energy savings of a low initial vacuum pressure (Hubbe *et al.* 2020).

In comparison, when run over 20 kPa vacuum pressure with a dwell time of 40 ms, a 50 g/m^2 paper reached a dryness of roughly 10%, while the final dryness of the multiple slit setups reached 11.7% for 50 g/m^2. Thus, a higher dryness is achieved when exposed to 40 ms of vacuum when using an increasing vacuum from 10 to 40 kPa, than achieved with a constant vacuum pressure of 20 kPa. This can be explained by looking at the pressure drops of the two, found in Table 2 below. Running a 50 g/m^2 paper over 20 kPa vacuum pressure with a dwell time of 33.3 ms gave a pressure drop of roughly 0.990 kPa, which would translate to roughly 2.93 dm^3 of air pulled through the paper, in comparison to the pressure difference of 1.01 kPa and an air volume of 2.98 dm^3 for the quadruple slit run of the 50 g/m^2 paper. This may be the result of the above-mentioned effect of air being pulled through the sheet rather than water being pulled from the paper (Hubbe *et al.* 2020). This can be seen in terms of dryness because the 33.3 ms run over 20 kPa vacuum pressure reached a dryness of roughly 10%, compared to the higher dryness of the quadruple slit run of 11.7%. Thus, for a paper of 50 g/m^2, a multiple vacuum slit box is beneficial in this laboratory study.

For the 100 g/m^2 paper, the standard deviation of the dryness makes for a tougher reading; it is difficult to draw conclusions when the results are not significantly different (Fig. 6). However, it is still visible in Fig. 6 that the dryness curve follows the expected pattern of dewatering, with a high initial dewatering for the lowest vacuum pressure; this is better displayed in Fig. 7, where outliers were removed. Outliers are defined as values that heavily differed from the mean and had a major effect on the standard deviation (Navidi 2008). Both with and without outliers removed, it can be concluded that the 20 kPa slit barely had any effect on the dryness, and that an increased level of vacuum would be needed. Just as for the 50 g/m^2 paper, it was hard to determine whether the 30 and 40 kPa slits reached their point of diminishing returns, or whether they could possibly utilize an increase in dwell time. Figure 7 suggests that the 10 and 40 kPa slits were the most efficient, meaning that a multiple-vacuum suction box for a heavier paper of 100 g/m^2 could operate on these two levels of vacuum pressure. The lesser gain in dryness between 20 kPa and 30 kPa also suggests that an increase in vacuum level is needed to achieve satisfactory levels of dryness. During vacuum dewatering of heavier paper, a higher vacuum level would thereby be considered beneficial in terms of dryness and energy utilization.

For the 100 g/m^2 paper, the difference in air volume being pulled through the paper was not as remarkable. With a pressure difference of 0.67 kPa, corresponding to an air volume of 1.98 dm^3 for the 100 g/m^2 paper ran over a 20 kPa vacuum pressure over a 33.3 ms dwell time, and a pressure difference of 0.44 kPa corresponding to an air volume of 1.29 dm^3 for the 100 g/m^2 quadruple vacuum slit setup, this implied that slightly more energy was wasted pulling air through the paper for the single slit vacuum box.

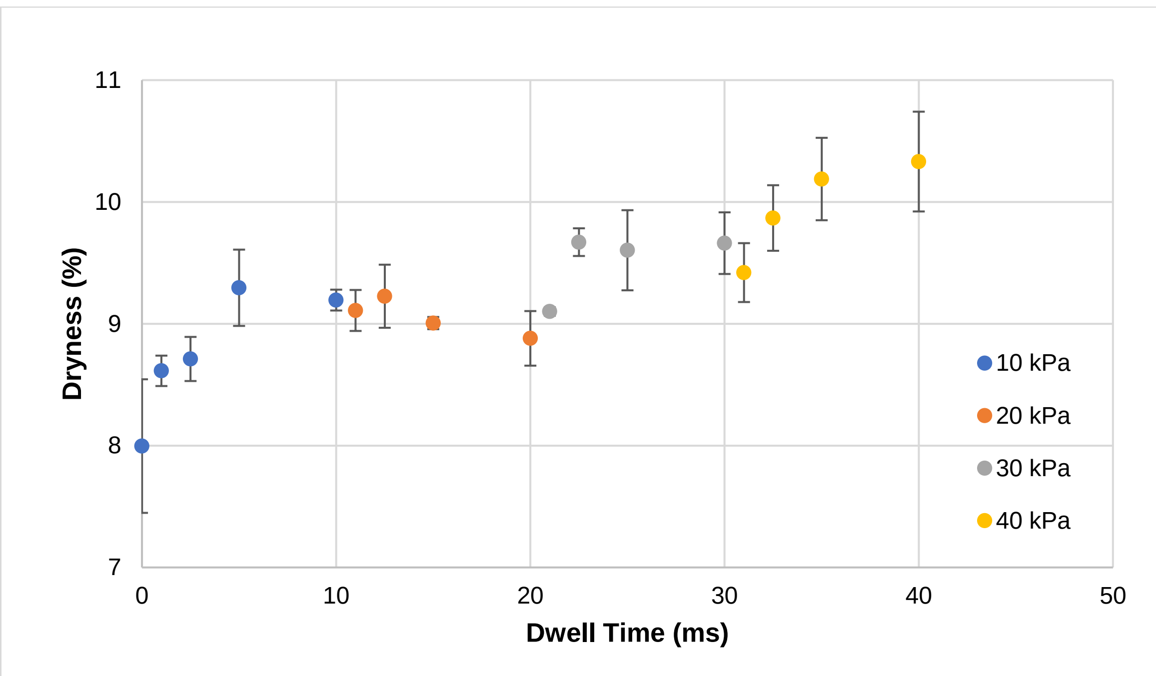

Fig. 7. Dryness over vacuum dwell time for 100 g/m^2 paper with outliers removed

Table 2. Air Volume Pulled Through Paper When Run Over Vacuum

Slit number	Vacuum Pressure (kPa)	50 g/m^2 Air Volume (dm^3)	100 g/m^2 Air Volume (dm^3)
1	10	0.911	0.987
2	10, 20	1.642	1.317
3	10, 20, 30	2.632	1.895
4	10, 20, 30, 40	2.975	2.246
Single Slit Box	20	2.93	2,15

As expected, the heavier paper showed greater resistance to being dewatered by vacuum (Koponen *et al.* 2023). The 100 g/m^2 paper reached a dryness of roughly 10.3%, whereas the 50 g/m^2 reached a higher, as suggested, 11.7%, dryness (Gülsoy and Şimşir 2017). Figure 8 below shows, side by side, the increase in dryness over dwell time for both 50 and 100 g/m^2 paper. It is clear that the 100 g/m^2 paper was more efficiently dewatered over gravity but harder to dewater over vacuum, with its 8% dryness after gravity, in comparison to the 6% dryness of the 50 g/m^2 paper. This behavior is likely due to the 100 g/m^2 paper being more compact, creating a higher naturally occurring vacuum over the paper, whereas for the 50 g/m^2 paper, air is more easily pulled through the sheet, creating less natural occurring vacuum in the hand sheet former when draining the water. This could mean that a heavier paper would not need to be dewatered at as high vacuum initially, meanwhile the more reluctant water would need an increased vacuum for these heavier papers. The opposite is found for the lighter paper, the gravitational dewatering is not as effective with nearly 2% difference in dryness between the two. Whereas the initial low-vacuum dewatering proved very effective, along with the most reluctant water not requiring as intense a vacuum.

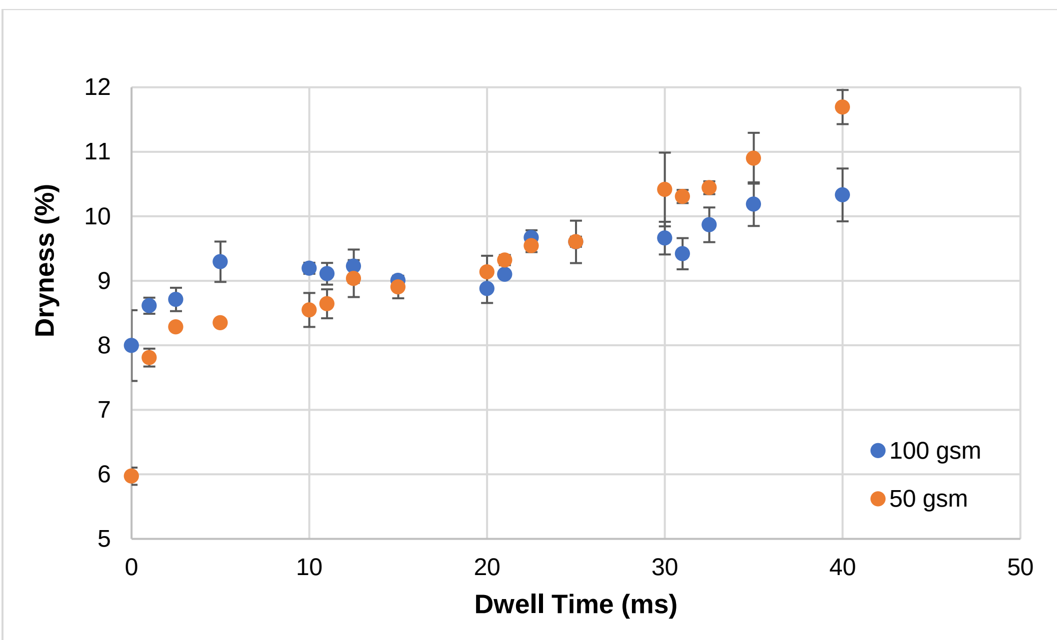

Fig. 8. Comparison of dryness of 50 and 100 g/m^2 paper over dwell time, excluding outliers

Figures 9 and 10 compare the quadruple vacuum suction boxes of both basis weights, respectively, to a single vacuum suction box. For the lighter paper, the slope of the dryness over air volume is slightly greater than for the single slit vacuum suction box, suggesting a more efficient dewatering in terms of energy. It also resulted in a greater dryness. This behavior is not as clear for the heavier paper, where the slopes of the two suggest a similar energy consumption, hand in hand with no major increase in paper dryness. This is however an expected result because the heavier paper should be harder to dewater than the lighter paper, proving the quadruple vacuum slit beneficial. However, because the air volume pulled through the paper was so slight for the 100 g/m^2 paper, see Table 2 below, it makes for a harder reading due to multiple drynesses given the same x-value. Removing these, *i.e.*, only taking the last dryness-level per constant air volume into account, yields more of an expected result, once again suggesting that the multiple slit vacuum box is more efficient. More testing for this heavier paper would be needed before such a conclusion can be drawn. Figure 11 below is altered to only show the highest achieved dryness per air volume, because multiple dwell times experienced the same amount of air volume pulled through the paper after leakage adjustments. This resulted in a greater slope in dryness for the heavier paper, also suggesting its efficiency over a single slit vacuum suction box.

Because the rewetting of a single slit vacuum suction box, found by Sjöstrand *et al.* (2015), and Åslund *et al.* (2008), yielded a decrease in dryness of 3 up to 6%, it is expected that an even greater rewetting would be experienced for this laboratory study due to the repeated reapplication of the paper. It is important to note that the sheet is not removed from the fabric during the reapplications. Hence, the dryness of the multiple slit compared to the single slit would increase, to yield a bigger gap between the two, in favor for the multiple slit box. However, no corrections in regard to rewetting were made in this study due to the lack of information on the amounts of rewetting for grease-proof paper.

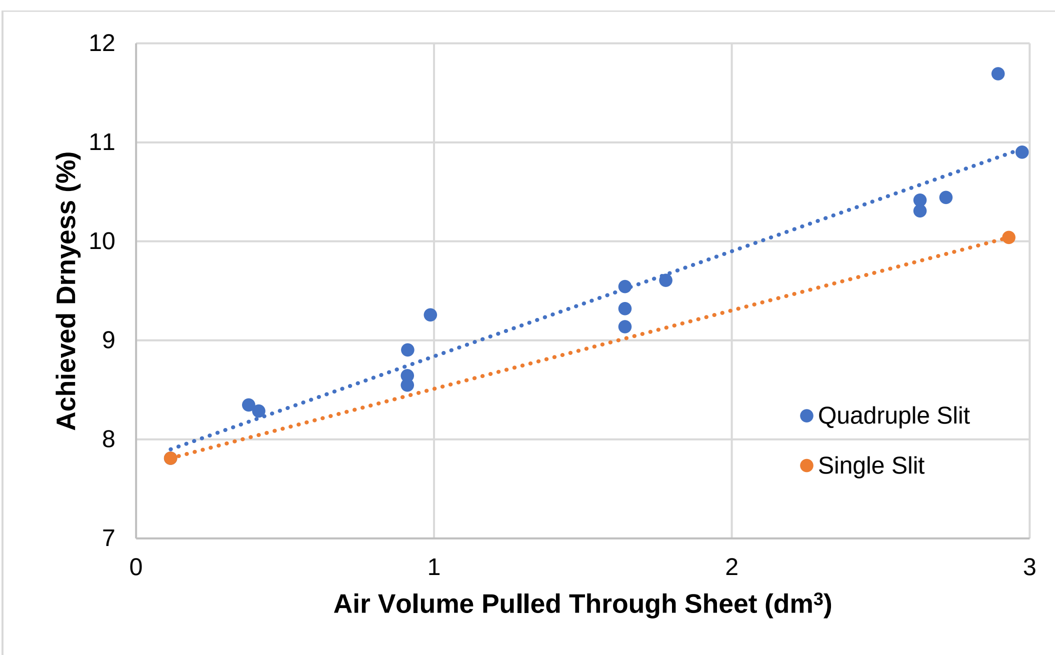

Fig. 9. Dryness as a function of amount of air pulled through the 50 g/m^2 paper, comparing the quadruple vacuum slits to a paper run over 20 kPa at a dwell time of 33.3 ms

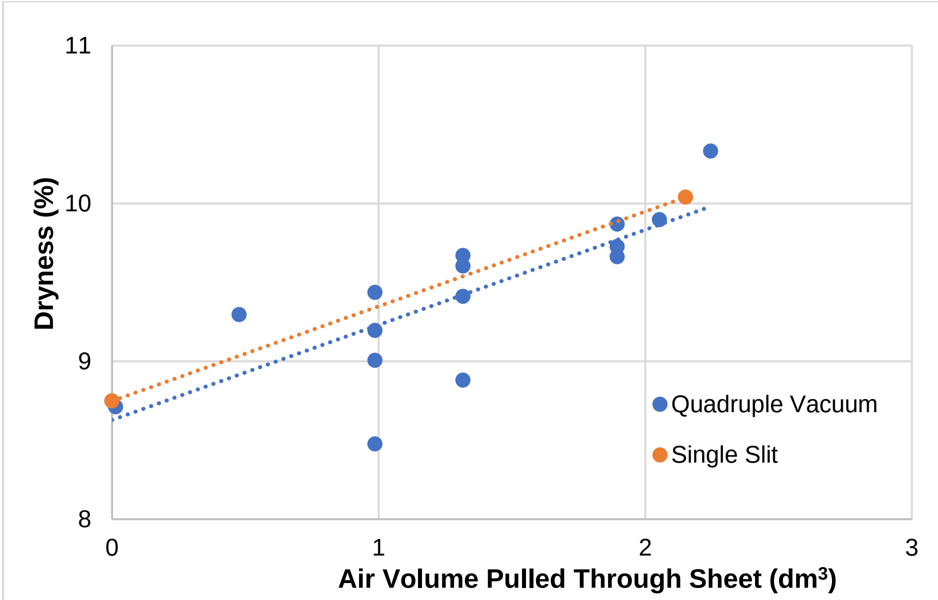

Fig. 10. Dryness as a function of amount of air pulled through the 100 g/m^2 paper, comparing the quadruple vacuum slits to a run over 20 kPa at a dwell time of 33.3 ms for a 50 g/m^2 paper

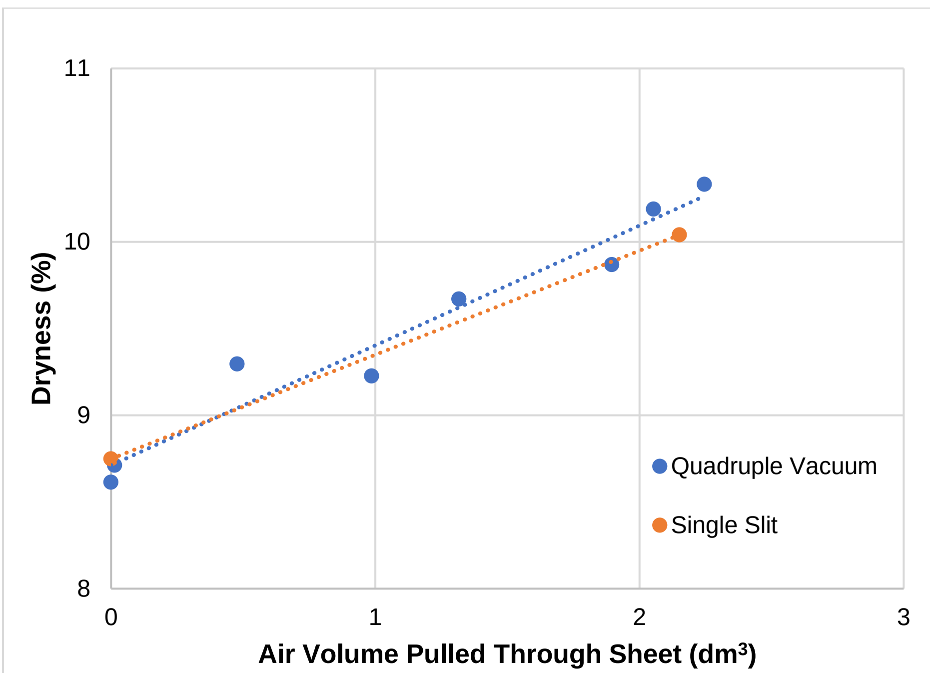

Fig. 11. Dryness, without two, or more, dryness's per dm^3, as a function of amount of air pulled through the 100 g/m^2 paper, comparing the quadruple vacuum slits to a run over 20 kPa at a dwell time of 33.3 ms for a 50 g/m^2 paper

Table 2 above also suggests that the fabric was experiencing clogging from the highly refined pulp, as almost 50 % of the total volume of air pulled through the 100 g/m^2 sheet was pulled already at 10 kPa. The remaining 50 % of the total air volume was pulled through the sheet during the three remaining runs over stronger vacuum. This behavior goes against literature, such as Sjöstrand *et al.* (2023), as well common sense. The same behavior is not as prominent for the lighter paper, as slightly less than a third of the total air volume is pulled during the 10 kPa. However, according to literature, this is still an unexpectedly high share of the total air volume. The lighter paper also experienced the least increase in air volume during the last, and strongest, vacuum, suggesting clogging for the lighter paper as well. Thus, the basis weight did not seem to affect the clogging, only the degree refining did. Less total air volume was pulled through the heavier sheet, as expected according to Gülsoy and Şimşir (2017) due to the greater permeability in the higher basis weight paper.

As in the expected dryness curves hypnotized by Baldwin (1997) above, the dryness and energy consumption of the multiple slit vacuum suction boxes are plotted over dwell time in Figs. 12 and 13, using the air volume through the sheet as the energy spent. Initially, for the lighter paper, the results were as expected according to literature. The dryness increased over dwell time, with an increase in the slope of the energy expenditure, until 40 kPa vacuum pressure, where the slope was very slight. This is probably due to the aforementioned clogging of the wire, preventing air from penetrating it. The same behavior is observed for the heavier paper as well but starting already at the second slit of 20 kPa. This is most likely due to the wire being slightly clogged from previous runs, along with clogging from the current run.

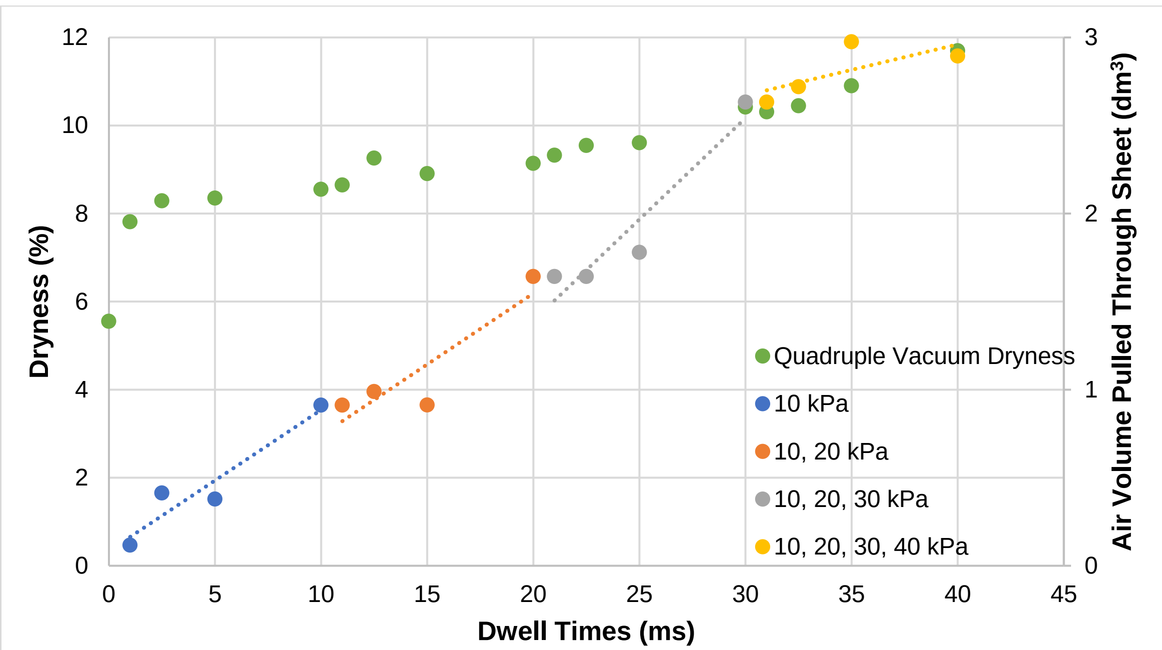

Fig. 12. Dryness and corresponding air volume pulled through the same 50 g/m^2 paper, both over dwell time. Quadruple vacuum box dryness on the left-hand side, and the air volume for each vacuum pressure level on the right-hand side

Overall, the results observed coincided with Baldwin's hypothetical triple vacuum suction box, yielding a greater dryness whilst the energy expenditure was kept lesser. A multiple slit vacuum suction box was deemed efficient in reducing the excessive energy expenditure, while maintaining an efficient dewatering, working optimally around the reluctancy of the water. The quadruple vacuum suction box proved to be more efficient in terms of end dryness along with a better dryness-to-energy-expenditure. This without the correction to rewetting. Meaning in pilot scale, it is expected to be even more efficient.

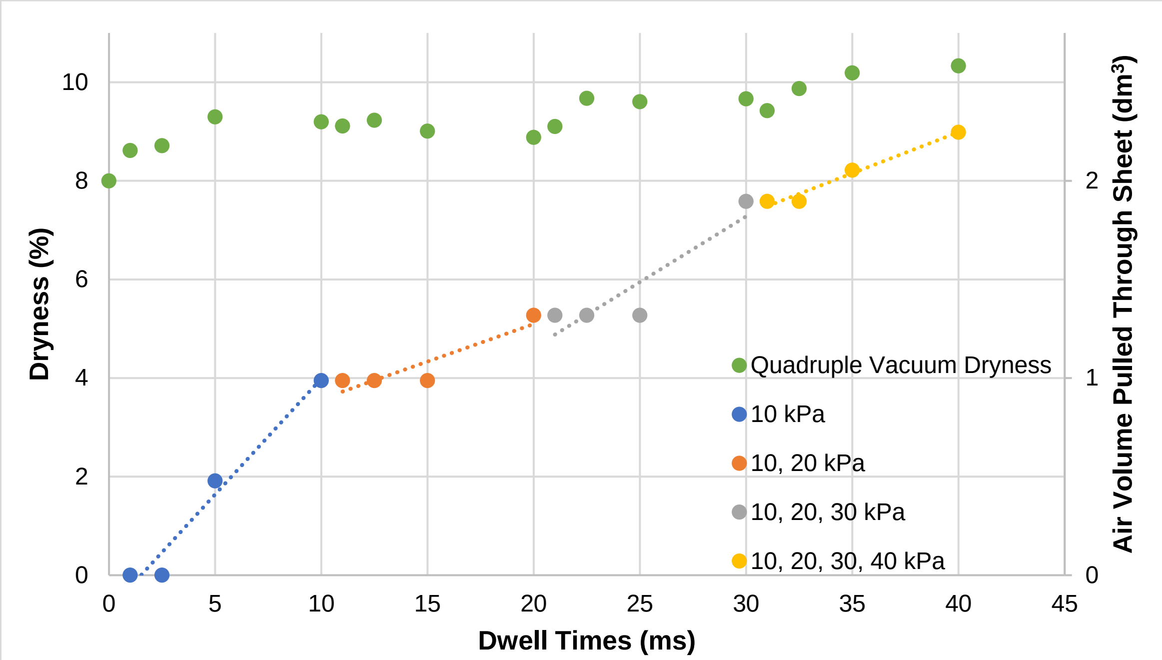

Fig. 13. Dryness and corresponding air volume pulled through the same 100 g/m^2 paper, both over dwell time. Quadruple vacuum box dryness on the left-hand side, and the air volume for each vacuum pressure level on the right-hand side

However, there are potential challenges in implementing a triple vacuum suction box in the forming section. It seems that a triple vacuum suction box is beneficial in laboratory scale, but it is just expected to yield the same benefits at a pilot scale. Therefore, dwell times and vacuum pressures needed for beneficial gains may differ. This goes hand in hand with the significant standard deviation which made for a harder reading whether the levels of vacuum pressure were efficient or not. Furthermore, testing various levels of vacuum pressures and machine speeds would be needed based on basis weights forming section fabrics. It would also be beneficial to test other pulps and pulp grades in order to get a better understanding of how the benefits of a triple vacuum suction box would transfer between paper grades as the dewatering would be significantly different between paper grades. Thus, there can be a challenge in correlating the results from one paper grade, or machine setting, to another.

CONCLUSIONS

1. Both 50 g/m^2 and 100 g/m^2 basis weight paper responded well to being vacuum dewatered over a multiple slit vacuum suction box, meaning that the utilization of a multi-slit vacuum suction box would yield great improvements in end dryness and an improved dryness-to-energy-consumption ratio for grease-proof paper. However, more testing is needed to optimize the levels of vacuum pressure.
2. Paper basis weight had a major role on the rate of dewatering, with a higher basis weight leading to a less efficient dewatering, showing the need of both higher dwell times and vacuum levels.

3. Because the initial dewatering was deemed efficient, applying a multi-slit vacuum suction box too soon in the forming section should be avoided to minimize the wire wear and to refrain from breaking the formation.

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