Method for Studying Water Removal and Air Penetration during Through Air Drying of Tissue in Laboratory Scale

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Energy use, together with consumption of raw materials, machine clothing, and wet end chemicals, are some of the most critical aspects in successful tissue making today. This work was aimed at developing a laboratory-scale method of estimating dewatering mechanisms, vacuum efficiency, and energy use of Through Air Drying (TAD) of tissue. When compared to pilot data, the results of the new laboratory method for investigating dewatering during TAD were in the same magnitude, around 24 to 26% dryness after vacuum dewatering, and 27 to 29% dryness after TAD molding. Sheet properties, such as caliper and surface profile, were evaluated and compared to commercial tissue sheets. The results indicate that it will be possible to precisely measure accurate dryness development and penetrated air volume for tissue sheet forming and TAD molding at a laboratory scale. This can contribute to the efforts of implementing a circular forest-based bioeconomy by increasing the fundamental understanding of dewatering of tissue paper materials, which is facilitated by improvements in energy use. The new method developed in this work will make it easier to assess ideas that are difficult to bring to pilot scale or full scale before learning more of the dewatering capabilities. The authors are convinced that improved knowledge of tissue dewatering mechanisms, forming, and material transport during and after TAD dewatering can increase the efficiency of the industrial manufacturing processes.

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Keywords: Through air drying; TAD; Dewatering; Tissue; Papermaking

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INTRODUCTION

Energy use, together with consumption of raw materials, machine clothing, and wet end chemicals are some of the most critical aspects in successful tissue making today. While about half of the energy can be produced in-house by the mills using biomass residues (IEA 2017), this is almost never the case for tissue production. There is potential for making the processes more energy efficient (Håkansson 2010; Lahtinen and Karvinen 2010; Holmberg *et al.* 2013; Sjöstrand 2020).

The forming section in a tissue machine is typically much shorter than paper machines manufacturing other paper grades and is not aligned horizontally. The press section can be a single press nip against a Yankee cylinder. The sheet is pressed and adhered onto the Yankee surface, dried with steam inside the cylinder and in a covered gas-fired hood, and later creped off with a doctor blade (Klerelid 2000; Tysén 2018). This is called Dry Creped Tissue (DCT). Another concept of tissue manufacturing is Through Air Drying (TAD). In a TAD machine (Fig. 1), the press is replaced by a TAD cylinder, or in some machine configurations two or more cylinders, with a structured molding TAD fabric, where the sheet is transferred with vacuum boxes and much of the water is removed with hot air blown through sheet and fabric. The structured fabric provides the tissue sheet with its structure, bulk, and allows for efficient drying due to its open nature. There is also a speed difference between the forming section and TAD section, which has a big impact on sheet properties compared to DCT. The TAD method is less energy efficient but gives higher performing products when compared with DCT (Tysén 2018). Producing tissue differs from other grades relating to the basis weight of the network being much lower; thus, the efforts in dewatering are considerably lower compared to production of, for example, paperboard grades (Klerelid 2000; Tysén 2018). Nevertheless, energy efficiency becomes increasingly important for tissue producers, especially for the more energy demanding TAD method.

Tissue papers are mainly produced from fiber blends of softwood and hardwood mixtures (de Assis *et al.* 2018). Fiber type can affect drainage and dewatering, mainly by their varying fines content (de Assis *et al.* 2018). The fines have a negative effect on drainage by clogging drainage channels (de Assis *et al.* 2018; Hubbe *et al.* 2020). Conformability of individual fibers can also affect dewatering by sealing of forming fabric surface when using flexible fibers (Sjöstrand *et al.* 2019; Hubbe *et al.* 2020).

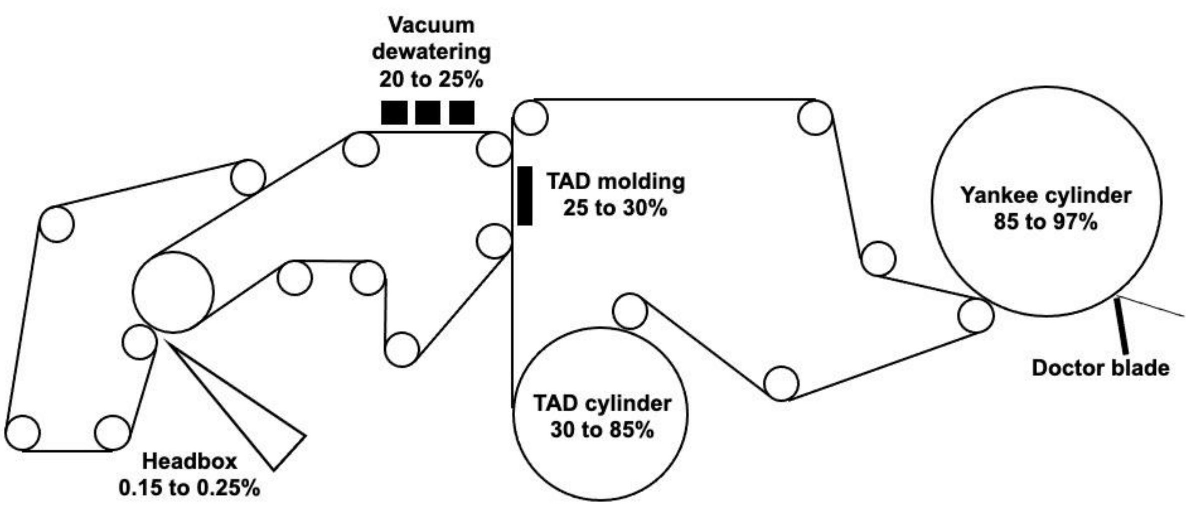

Fig. 1. Schematic drawing of a simplified TAD tissue machine, redrawn from Tysén (2018)

A long tradition of studying conventional vacuum dewatering can be found in literature. A compilation of these literature is shown in Table 1.

Table 1. Notable Publications Regarding Different Aspects of Vacuum Dewatering

Key Points	Citation
Developed and described a laboratory apparatus for vacuum dewatering investigations. Showed the influence on dryness development in vacuum dewatering with parameters such as: vacuum dwell times, slot widths, number of slots, vacuum levels, forming fabrics, beating levels, additives, temperatures, fines contents, and pH value. Showed diminishing returns for the dryness development.	Attwood 1962

Developed and described another laboratory apparatus for vacuum dewatering investigations. Described the dewatering mechanism before wet pressing as two separate mechanisms, drainage and vacuum dewatering. A compacted sheet provides a good vacuum response but it will be negative for the drainage effectiveness. Described effects of several parameters on vacuum dewatering: Basis weights, furnish, refining, and additives	Britt and Unbehend 1980
Further investigation of the two zones of dewatering. The “dry-line” of the paper machine was suggested to be the dividing position of the mechanisms where the solids content is around 4 to 7%. Discussed how different dewatering measurements actually matched the dewatering on the paper machine.	Britt and Unbehend 1985
Pilot machine trials of vacuum dewatering and creation of mathematical models for dryness development and air flow. Suggested that energy savings could be possible by increasing knowledge about vacuum box dewatering. Showed diminishing returns for the dryness development.	Neun 1994
Further pilot trials, focused on dewatering effects of furnish, solids before vacuum box, basis weights, vacuum levels, machine speed, and number of slots. Showed diminishing returns for the dryness development.	Neun 1996
Developed an updated mathematical model of vacuum dewatering and compared it with Gamma gauge field measurements. The updated model fit the diminishing returns of Neun (1994, 1996) but had a linear term added to respond to the drying mechanism by continuous flow of air through the sheet and fabric structure. Concluded that the most important parameters affecting vacuum dewatering are vacuum level and vacuum dwell time.	Räisänen *et al.* 1996
Using literature results and several case studies, argued for applying vacuum in progressively increasing levels due to the mechanism of diminishing returns. Additionally, higher vacuum levels in shorter time intervals and adapting vacuum dewatering strategy based on process conditions will be beneficial for machine performance.	Baldwin 1997
Examined vacuum dewatering of newsprint under commercial conditions with varying levels of ingoing solids to the vacuum boxes, vacuum levels, dwell times, and air flows.	Shands and Hardwick 2000
Comprehensive literature review and theoretical modelling of vacuum dewatering, air flow, and convective mass transfer of water from the sheet. Showed diminishing returns for the dryness development.	Ramaswamy 2003
Laboratory study of forming fabric influence on paper sheets with low basis weight in vacuum dewatering. Revealed the fabric parameters mainly affecting vacuum dewatering are fabric caliper, void volume, and air permeability.	Granevald *et al.* 2004
Experimental data from vacuum dewatering tests of dryness development and air flow are shown, the mechanism of air flow dewatering is described where final solids content linearly dependent on air flow through the wet sheet and fabric structure. Showed diminishing returns for the dryness development.	Pujara *et al.* 2008
Described a new apparatus for studying deformation of the sheet during and after vacuum dewatering. The sheets are shown to be noticeably compressed due to the pressure drop during vacuum dewatering and they expand afterwards. The dewatering mechanism of initial vacuum dewatering is suggested to be compression dewatering.	Åslund and Vomhoff 2008a

Literature review of dewatering mechanisms of vacuum dewatering. Three mechanisms are introduced: compression, displacement, and rewetting.	Åslund and Vomhoff 2008b
Pilot scale experiments and evaluation of vacuum suction box dewatering with an assisting membrane on top of the sheet to increase the compression dewatering and minimize the air flow through the structure. The results indicated possibilities to maintain outgoing dryness with less air flow and therefore less pump energy consumption.	Åslund and Vomhoff 2008c
Laboratory study of web deformation during membrane-assisted vacuum dewatering. High degree of rewetting was assumed to lower the effectiveness of membrane assisted dewatering.	Åslund and Vomhoff 2008d
Laboratory study of web deformation during vacuum dewatering, using the new method described in Åslund and Vomhoff (2008a), a variety of parameters were tested.	Åslund *et al.* 2008a
Described a new apparatus for studying external rewetting after vacuum dewatering. The sheets show a decrease in dryness, between 3 to 6%, caused by external rewetting.	Åslund *et al.* 2008b
Laboratory study of how beating levels and furnish mixtures of tissue grade paper sheets affects initial high vacuum dewatering. Paper properties were also investigated.	Kullander *et al.* 2012
Developed a two-dimensional model of the paper sheet in a numerical model for simulating vacuum dewatering.	Rezk et al. 2013
Developed a mathematical model for simulation of air flow during vacuum dewatering.	Nilsson 2014a
Presented different sets of air flow measurements of pilot scale and laboratory scale vacuum dewatering for utilizing designing of industrial equipment.	Nilsson 2014b
Developed a numerical model of vacuum dewatering as a two-phase flow in porous media simulation in two dimensions using a 3D model of the paper sheet.	Rezk *et al.* 2015
Creation and validation of a mathematical model based on the fiber properties, fiber width and fiber length, and density, which predict vacuum dewatering.	Stenström and Nilsson 2015

The overarching conclusion from earlier work is that the dewatering behavior of the vacuum suction boxes is consistent with the overall dewatering behavior of the papermaking process, with easy dewatering in the early parts and increasingly harder to remove water, diminishing returns (Attwood 1962; Neun 1994, 1996; Räisänen *et al.* 1996; Ramaswamy 2003; Pujara *et al.* 2008). The location of water within the sheet's structure is the reason why it becomes increasingly difficult to dewater. Water is removed in the following order: from in between fibers, from the lumen, and lastly, from the fiber walls (Paulapuro 2000; Stenström and Nilsson 2015). Other aspects, such as sheet basis weight, forming fabric, pulp beating, vacuum level, and dwell time, are shown to affect vacuum dewatering. The dewatering mechanisms are shown to be drainage, before the vacuum dewatering (Britt and Unbehend 1985), compression dewatering (Åslund and Vomhoff 2008a, 2008b), air displacement dewatering (Räisänen *et al.* 1996; Åslund and Vomhoff 2008b; Nilsson 2014a, 2014b), and external rewetting (Åslund *et al.* 2008b; Sjöstrand *et al.* 2015).

Work addressing laboratory TAD dewatering has been published by Tysén *et al.* (2015, 2018). They described the influence of grammage and pulp type on water removal with TAD in laboratory scale (Tysén *et al.* 2015) and assisting the TAD dewatering with infrared radiation (Tysén *et al.* 2018). The dewatering mechanism was suggested to be evaporation due to air flow. The increase in temperature by infrared radiation also increased drying capacity of the TAD. The dwell times were relatively long compared to industrial scale tissue production, which makes it hard to connect the experimental results with pilot and full-scale manufacturing.

This work was aimed at developing a laboratory scale method for measuring dewatering and air volume through the sheet under commercial conditions, and estimating vacuum efficiency and energy use, of TAD of tissue. The dewatering mechanism for water removal with laboratory TAD will be investigated.

EXPERIMENTAL

Fibers and Fabrics

Bleached chemical kraft hardwood pulp fibers from *Eucalyptus* were supplied by Valmet AB (Karlstad, Sweden), with a dryness of 96%. The hardwood pulp was characterized with a Valmet Fiber Image Analyzer (Valmet FS5, Valmet AB, Karlstad, Sweden). The fiber length was approximately 0.8 mm and the fiber width was 13 μm based on a single test in the FS5. The drainage resistance was measured with the Shopper-Riegler method, ISO 5267-1 (1999) to a value of 15.5 °SR.

Bleached chemical kraft softwood pulp fibers mixed from Norway spruce and Scots pine were supplied by StoraEnso AB (Skoghall, Sweden) with a dryness of 4%. The softwood pulp was characterized with an L&W Fiber Tester (ABB AB / Lorentzen and Wettre, Kista, Sweden). The fiber length was 2.2 mm, and the fiber width was 31 μm based on a single test in the Fiber Tester. For both FS5 and Fiber Tester the single values of fiber length were based on many images of individual fibers in the pulp samples. The drainage resistance was measured with the Shopper-Riegler method, ISO 5267-1 (1999) to a value of 23 °SR.

Two fabrics provided by Albany International Inc. (Rochester, NH, USA) were used in the experiments. One tissue grade triple layer forming fabric simulating the inner position in the TAD machine configuration, fabric number 2 in Fig. 1, and a TAD fabric, corresponding to fabric number 3 in Fig. 1 (molding fabric). The TAD fabric is a relatively coarse single layer fabric mainly used for towel tissue applications. Basic data for the two fabrics are summarized in Table 2.

Table 2. Yarn Set Up in Machine and Cross Machine Direction and Basic Data for Caliper and Permeability

	Yarn Density		**Yarn Diameter**		**Caliper**	**Air Perm.***	**Void Volume**
	MD	CD	MD	CD			
	(Yarns/cm)	(Yarns/cm)	(mm)	(mm)	(mm)	(cfm)	(%)
Forming fabric	75	54/10**	0.15	0.13/0.20**	0.645	380	59
TAD fabric	18	11.2	0.35	0.50	1.15	625	61
*ASTM D737-96 (2018) **Fine/coarse							

CD: cross machine direction; MD: machine direction

Methods

The fibers were mixed to a 75/25 weight ratio with 75% softwood and 25% hardwood. The fiber mixture was then diluted to 0.2% in tap water with no additional chemicals added, later referred to as the stock suspension. The stock solution was assumed to have a density of 1 g/cm^3; this assumption was valid because the fibers are a small part of the total weight and also completely saturated with the water. To form a tissue paper sheet of 20 g/m^2, 266 g stock suspension was measured on a scale and added to a modified sheet former together with an additional 3.5 L of tap water. The sheet former had a diameter of 18.4 cm and the sheet was formed directly on the commercial forming fabric. The forming fabric with the formed tissue sheet was removed from the sheet former and transferred to the vacuum dewatering equipment. This apparatus (Fig. 2) was described in detail by Granevald *et al.* (2004), and in this experiment a plate with a single 5-mm opening was used. The tissue paper, still on the forming fabric, was then subjected, triplet samples for each setting, to -30 kPa pressure drop during a number of different dwell times: 0, 1, 2.5, 5, 10, and 20 ms. The dwell times were designed to capture the dewatering during a typical suction box with the total dwell time of 20 ms. Before transfer to the vacuum dewatering equipment, and after each vacuum dewatering run, each tissue sheet was scraped off the forming fabric, and the dryness was measured according to ISO 638-1 (2022). Because the edges of the sheets are not completely dewatered, the middle part of the sheets with a diameter of 10 cm was used for dryness measurements. All dryness measurements were made at full rewetting, as rewetting was shown by Sjöstrand *et al.* (2015) to be complete in considerably faster than a second. For this reason, all dryness values are considered to represent dryness after rewetting.

A number of sheets dewatered 20 ms were manually transferred to the TAD fabric and brought back to the vacuum suction box, with no speed differential between fabrics. This time for another set of vacuum dewatering representing the transfer and TAD molding with -65 kPa and the following dwell times: 2.5, 5, 10, and 20 ms. After TAD dewatering, the whole sheets were measured for dryness according to ISO 638-1 (2022).

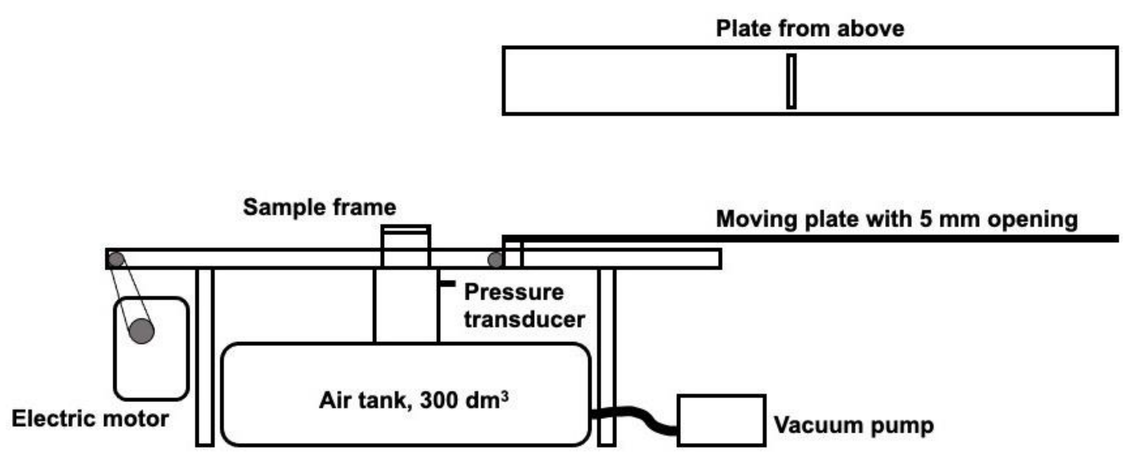

Fig. 2. Schematic drawing of the custom-built laboratory scale vacuum suction box. The pressure drop is varied with the vacuum pump and measured with the pressure transducer. The vacuum dwell time is varied with varying speeds of the moving plate, dwell time can be as small as 0.5 ms.

All sheets were supported by the forming fabric during vacuum dewatering and supported by the TAD fabric during TAD molding. This indicates that the sheets were in tension in a similar way as the sheets in the forming section of a pilot machine.

The pressure drops in the vacuum dewatering machine, both for forming fabric dewatering and TAD dewatering, were recorded during vacuum exposure for each sample. A typical recording is shown in Fig. 3. The vacuum level dropped during one test in accordance with Fig. 3, both for forming fabric and TAD dewatering. It was, however, always reset to original value before next sample. The logged pressure drops of the vacuum dewatering test were used to calculate the air volume that passed through the sheet using Eq. 1 (Granevald *et al.* 2004; Sjöstrand *et al.* 2016). The air volume for TAD sheets consists of the forming fabric dewatering air volume for 20 ms, added with the respective TAD dewatering air volume, because these sheets effectively are dewatered twice. Equation 1 is as follows,

$$V_{\text{air}} = \frac{V_{\text{tank}}}{P_{\text{atm}}} \times \Delta P \tag{1}$$

where V_{air} is the penetrated air volume (dm^3), V_{tank} is the volume of the tank (dm^3), P_{atm} is the atmospheric pressure (Pa), and ΔP is the change in pressure during the test (Pa), as explained by Granevald *et al.* (2004).

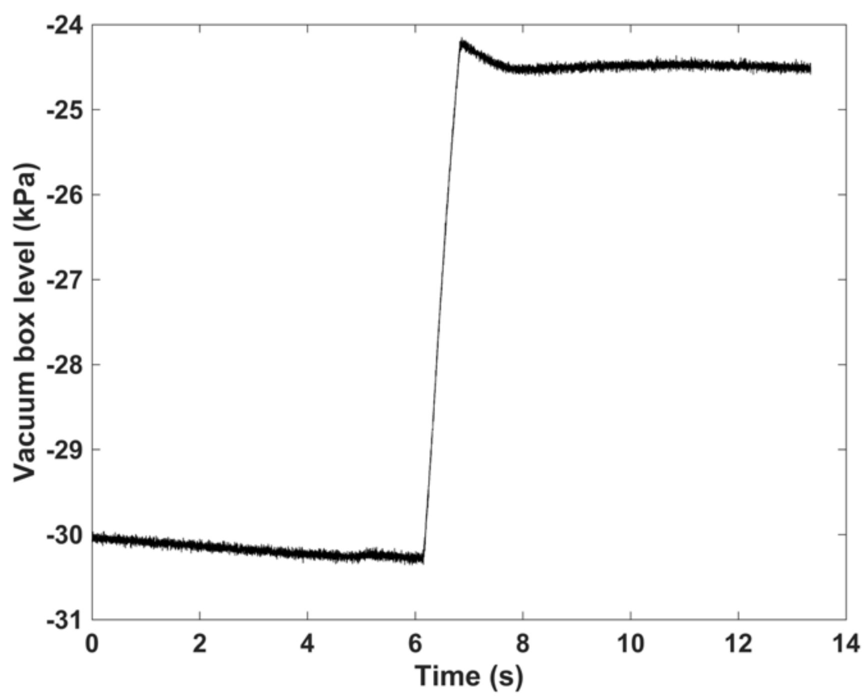

Fig. 3. Typical appearance of change in vacuum level during testing, this sample was dewatered on the forming fabric in -30 kPa and 20 ms

Sheets from both forming fabric dewatering and TAD dewatering were freely dried at room temperature, without prior pressing to conserve the structure, and analyzed once dry. Single ply thickness according to ISO 12625-3 (2014) was measured on laboratory forming fabric sheets, laboratory TAD sheets and commercial TAD sheets used for reference, thickness was measured on conditioned sheets according to ISO 187 (2022). The sheets' appearance was qualitatively captured with scanning electron microscopy (SEM) with a Hitachi SU-3500 (Tokyo, Japan) instrument, and also with X-ray microtomography (XRM) with a Bruker Skyscan 1172 (Karlsruhe, Germany). The SEM is an environmental SEM with normal conditions and no metal plating of the material. The XRM was used with a resolution of 0.95 μm/pixel, source voltage 32 kV, and current 192 μA. The global structural caliper of the SEM sheets was also estimated by measuring in the SEM images, this value was used as an indication on the achieved structure from the TAD fabric.

RESULTS AND DISCUSSION

Sheet formation and coverage are shown in Fig. 4. The image clearly indicates that the laboratory method was sufficiently proficient at forming tissue grade sheets. The mix of large softwood fibers and smaller hardwood fibers are visible in the image. The sheet is observed to be porous and would not impede water or air flowing to a large extent.

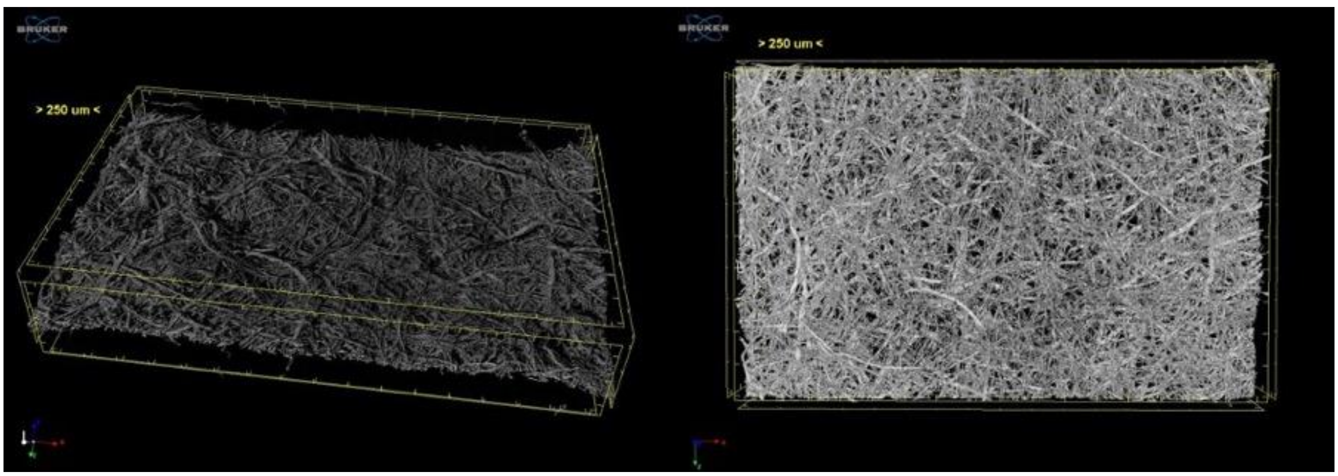

Fig. 4. XRM images of a laboratory made TAD tissue sheet

The development of solids content (%) for the tissue sheet in vacuum dewatering is shown in Fig. 5. The typical shape of the diminishing returns of the dewatering curve is consistent with both previous data from the same laboratory equipment (Sjöstrand *et al.* 2016, 2017, 2019; Rahman *et al.* 2018; Sjöstrand and Brolinson 2022), and with laboratory and pilot data from other publications of vacuum dewatering (Attwood 1962; Neun 1994, 1996; Räisänen *et al.* 1996; Ramaswamy 2003; Pujara *et al.* 2008). The shape of the dewatering curve shows the well-known dewatering mechanism for vacuum dewatering where water between the fibers is removed first, to an initial high dewatering rate, and as the water becomes increasingly less accessible the dewatering rate levels out, and gradually goes to zero. Comparable data from a pilot scale tissue machine, indicated by red markers in Fig. 5, confirm that the solids content after laboratory scale vacuum dewatering matches well with the pilot scale measurements. Note that the pilot results varied somewhat with regard to basis weight, fiber mixture, vacuum level, and dwell time.

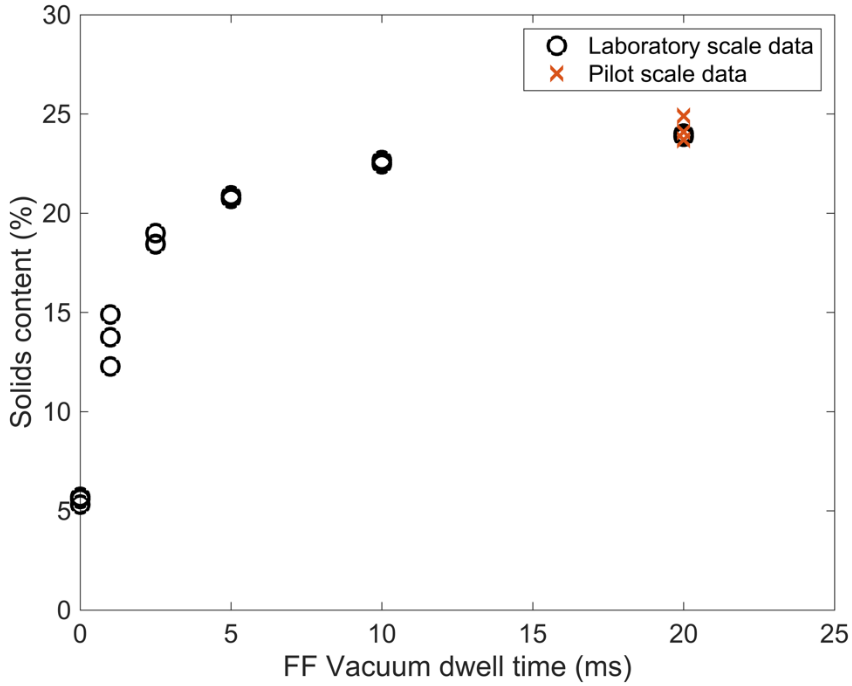

Fig. 5. Solids content development during vacuum dewatering on a conventional forming fabric. Note that the red 'x' markers indicate corresponding values from pilot scale testing.

After vacuum dewatering on a forming fabric, the sheet was transferred to the TAD fabric and subjected to another vacuum pulse. The development of solids content (%) is shown in Fig. 6.

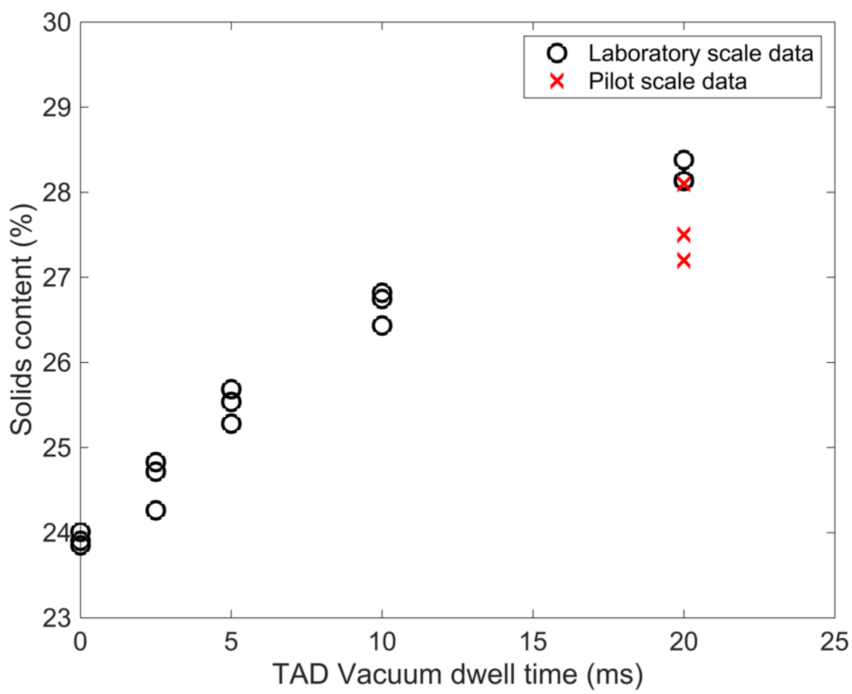

Fig. 6. Solids content development during vacuum dewatering on a TAD fabric. Note that the red 'x' markers indicate corresponding values from pilot scale testing.

The shape of the dewatering curve differed somewhat from the vacuum dewatering on a forming fabric in Fig. 5. The dewatering rate was more constant due to a more linear solids content *versus* dwell time graph. This indicates that the dewatering mechanism for laboratory, and possibly pilot and production scale, TAD molding is air displacement dewatering (Räisänen *et al.* 1996; Åslund and Vomhoff 2008b; Nilsson 2014a, 2014b). Air displacement dewatering is similar to drying with air of room temperature (20 °C) and is an energy-demanding process.

Figures 7 and 8 show the calculated penetrated air volume (using Eq. 1) for vacuum dewatering on a forming fabric and the TAD molding, respectively. The numbers are not compared with pilot or production scale tissue manufacturing but clearly show that TAD molding requires high pump capacity, based on the higher penetrated air volume, and is therefore concluded to require more energy. This is in line with the suggested dewatering mechanism. To further develop the laboratory method, tailored pilot trials could be performed to connect the penetrated air volume values to actual energy use. The presumed higher pump energy demand for TAD molding, relative DCT, leads to reasonable questioning regarding economic efficiency, mainly because pressing is not used in TAD.

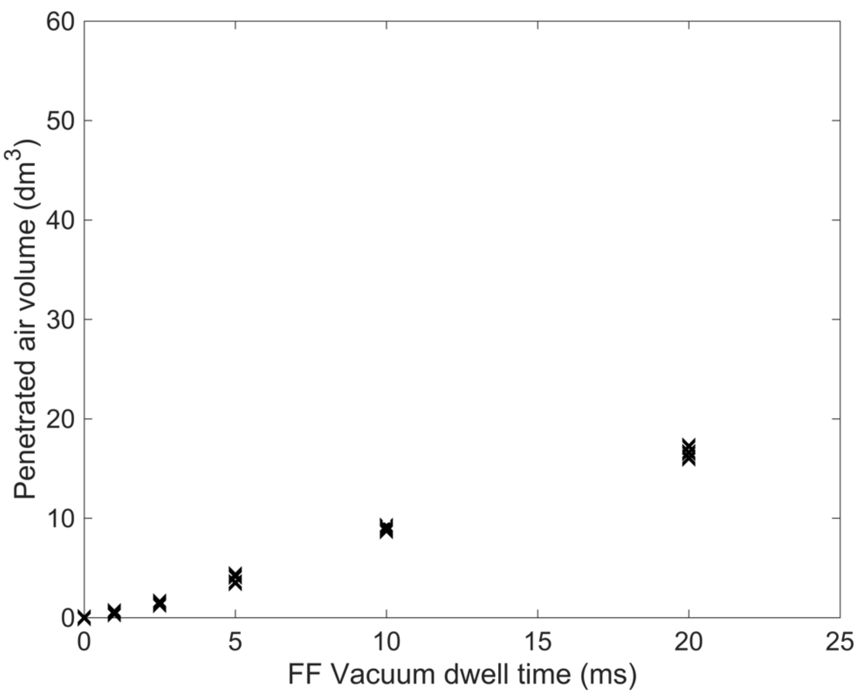

Fig. 7. Penetrated air volume during vacuum dewatering on a conventional forming fabric

An important aspect of TAD tissue manufacturing is the sheet properties. In this work the sheets were evaluated according to appearance from SEM images, mainly comparison between laboratory sheets dewatered on forming fabric, laboratory TAD sheets, and commercial TAD sheets. A rough global caliper estimation was made on the SEM images to show that the laboratory TAD sheets were similar to commercial ones.

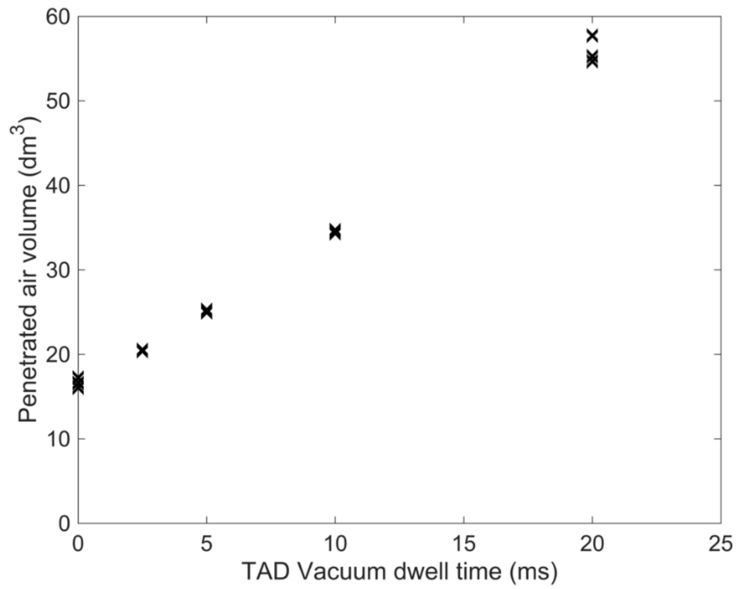

Fig. 8. Penetrated air volume during vacuum dewatering on a TAD fabric. Note that the air volume is representing both forming fabric vacuum dewatering and TAD dewatering.

Figure 9 shows the laboratory sheet before TAD (A) and after TAD molding (B), where a difference in global sheet caliper can be observed.

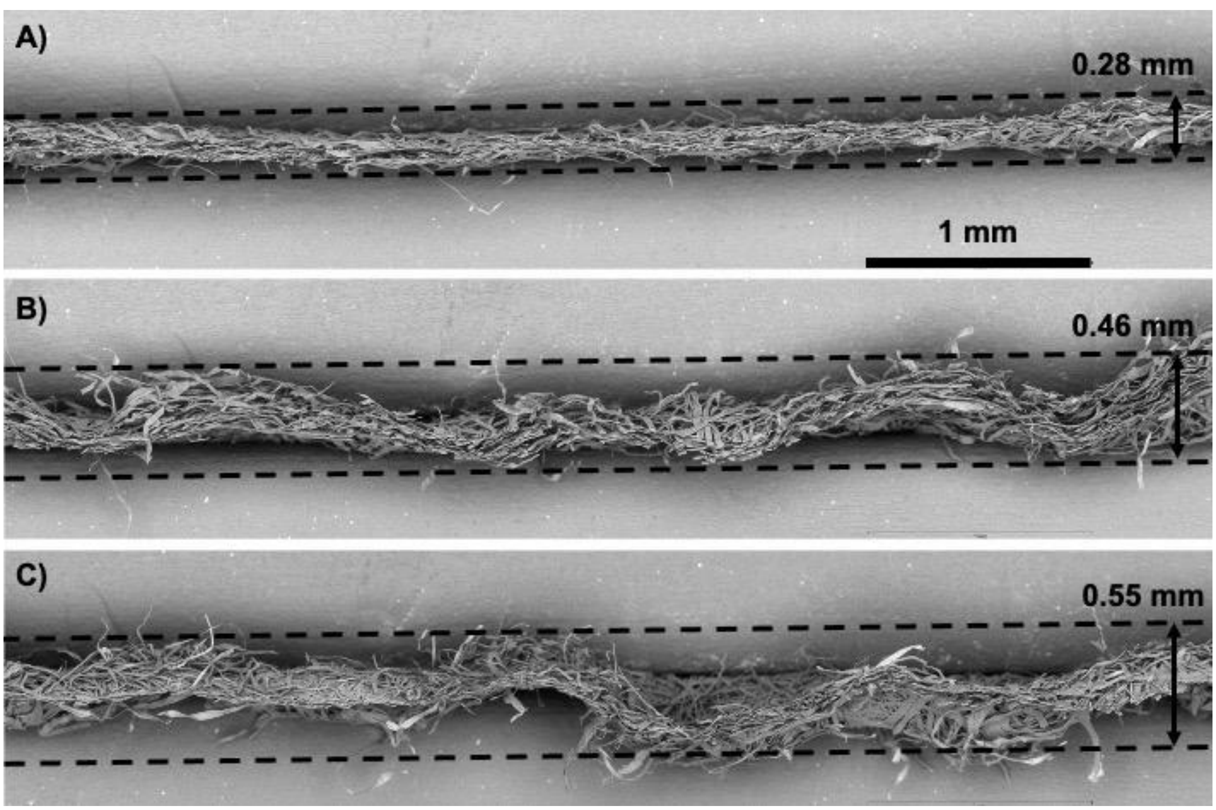

Fig. 9. SEM images of A) laboratory 20 g/m^2 sheet formed on a standard forming fabric, B) laboratory 20 g/m^2 sheet formed on a TAD fabric, and C) commercial 20 g/m^2 sheet formed on a TAD fabric

The tissue paper sheet before TAD (A) was measured as 0.28 mm, the laboratory TAD (B) was 0.46 mm, and the commercial TAD (C) was 0.55 mm. The qualitative appearance of the laboratory TAD sheet (B) was more similar to the commercial TAD (C) than the sheet formed on a forming fabric (A). When comparing the laboratory TAD (B) to the other two sheets (A and C) in Fig. 9, it was observed that the laboratory method of TAD molding produced sheets with similar properties of commercial TAD manufacturing processes.

The single-ply sheet caliper was also measured quantitatively with a thickness measurement (Fig. 10), which showed that the single ply thickness for the TAD sheets, both laboratory and commercial was slightly higher that the laboratory forming fabric sheets. This indicates that the structure generated by TAD molding was successfully achieved throughout the sheets that were produced. The single ply caliper was naturally lower than the global caliper estimation in Fig. 9 because the measurement relates to structural buckling of the sheet, as indicated in Fig. 9.

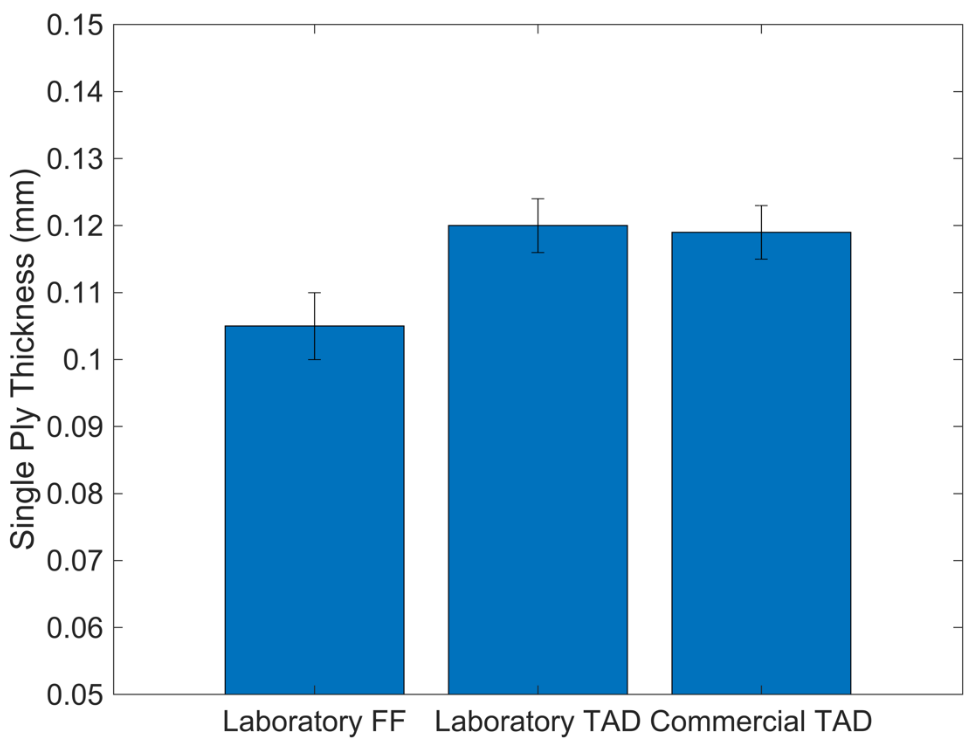

Fig. 10. Single-ply thickness measurements for laboratory forming fabric sheets, laboratory TAD sheets and commercial TAD sheets, with a 95% confidence interval shown with error bars, based on 10 measurements over five single ply sheets

CONCLUSIONS

1. This work describes a successful laboratory scale method of measuring dryness development and penetrated air volume of vacuum dewatering and through-air drying (TAD) molding of tissue paper. The method has commercial conditions of machine speed, vacuum level, and provides TAD sheets with similar properties as full scale production.

2. The dewatering mechanism of TAD molding is more closely related to drying than vacuum dewatering, and is proposed to be more energy demanding, based on measured penetrated air volume during laboratory testing. The dewatering mechanism is suggested to be air displacement dewatering.
3. This new laboratory method will allow investigation of multiple parameters affecting TAD dewatering.
4. The authors plan to validate the laboratory scale method further with support of more pilot scale and full-scale measurements, mainly to connect the penetrated air volume to actual energy consumption of the manufacturing processes.

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