Modeling the influence of forming fabric structure on vacuum box dewatering

BJÖRN SJÖSTRAND, CHRISTOPHE BARBIER, AND LARS NILSSON

ABSTRACT: This investigation used numerical models to describe forming section sheet dewatering at the high vacuum suction boxes. Three different fabric structures were examined with numerical models for single-phase flow of air and for two-phase flow of air and water. This was done to evaluate how forming fabric structure influences sheet dewatering. The numerical models were compared with an experimental study of the same fabrics investigated on a laboratory suction box. The small differences in dewatering rate in the experimental study could be simulated with the models, which confirmed the validity of the models. This implies that these numerical models can be used to describe new fabrics and how they will respond in the papermaking process.

Application: This article explains how numerical models can be used by manufacturers of paper machine clothing to obtain insights into how forming fabrics influence dewatering processes without investments in laboratory equipment and time-consuming experimental work.

Sheet dewatering is an important step of paper manufacturing. It demands huge amounts of energy over several unit operations, including dewatering by vacuum suction, pressing, and drying. An understanding of the mechanisms of dewatering in the different unit operations is fundamental to finding ways to reduce the energy requirements of paper manufacturing. This article focuses on sheet dewatering at the high vacuum suction boxes, and especially the forming fabrics' role in sheet dewatering. By using numerical models, the industry can obtain insights and vital information about dewatering processes without huge investments in laboratory equipment or costly manufacturing processes.

In the 1950s, Ergun [1] investigated single-phase flow through porous media and derived a calculation of flow rate as a result of pressure drop and material properties. We used Ergun's work as a foundation for calculations of flow of water and air through sheet and fabric in this study. Ergun's work combines the theory of high and low flow rates and is valid for a large interval of Reynolds numbers.

Li and Green [2] developed numerical models of the more complex system of fibers suspended in water and dewatered on a simple forming fabric. The fibers are added individually with random orientation to the simulated single sine-wave fabric. Surface roughness is measured as the topological differences of the resulting fiber mat. The bending stiffness of the fibers is considered, but Li and Green ultimately connected the greatest effect (over 50%) of surface roughness to the forming fabric structure. The dewatering velocity affects the bending of fibers and, therefore, the surface roughness [2].

Rezk et al. [3] described the dewatering of sheet and fabric structure in two-dimensional numerical models. They showed that two-phase flow simulations could be used to describe the dewatering of a sheet with fast initial dewatering and a certain amount of water being left in the sheet and steady state airflow toward the end. The calculated dewatering rate was twice as high as measured values, but the airflow matched the researchers' experimental data [3]. In a later article, Rezk et al. [4] concluded that the fabric structure was best described by using a combination of solid fabric yarns and flow resistance compared with only using flow resistance. After thus improving the description of the forming fabric, calculated and measured dewatering rates were in better agreement.

In the forming section, the forming fabric is known to affect sheet dewatering by its general design at the gravitational dewatering [5] and also more specifically by caliper, void volume, and air permeability at the high vacuum suction boxes [6]. Helmer et al. [5] used a high-speed digital imaging system to analyze dewatering during sheet forming and connected sheet properties and drainage behavior to fabric structure. The drainage velocity was different for different fabrics, and also for fabrics of identical weave pattern but different yarn diameter. The dewatering velocity was shown to affect sheet properties. Indirectly, the fabric structure is responsible for sheet properties and dewatering velocity [5].

According to Granevald et al. [6], the fabric parameters that affect sheet dewatering are fabric caliper, void volume, and air permeability. When these parameters are kept constant and the open area profiles of different fabrics are changed during high vacuum dewatering, Sjöstrand et al. [7] showed that different dewatering rates were obtained for different fabric structures. This difference in dewatering rate is seen at short dwell times (0–2.5 ms) and high pressure drops (40 kPa). The experimental work of Sjöstrand et al. [7] otherwise shows the same development of dewatering with dwell time in a suction box as previous studies [8,9].

This article builds and expands on previous experimental work [7] by performing a deeper study of measurement uncertainty and by using numerical models to simulate single-phase airflow through forming fabrics and two-phase flow of water and air through sheet and fabric. This article explains how numerical models can be used by the paper industry to obtain insights into the mechanisms of dewatering processes without huge investments in laboratory equipment or costly breaks in manufacturing.

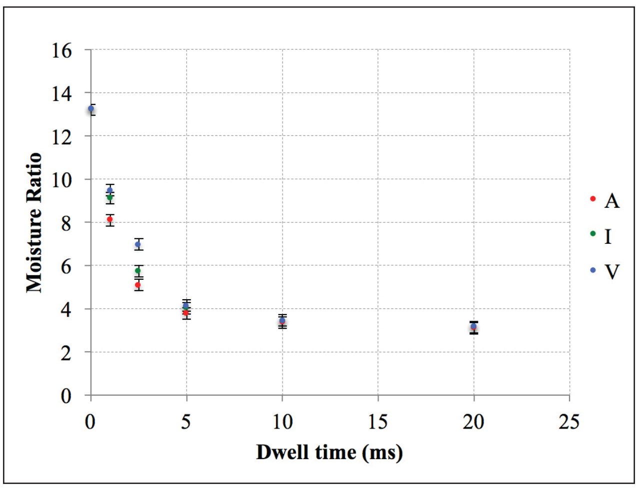
METHOD

All previous dryness measurements [7] were performed in triplets by the same researcher and on the same equipment. We therefore used pooled variance (Eq. [1]) on all measurement points to get the measurement uncertainty instead of using the variance on each separate triple measurement point.

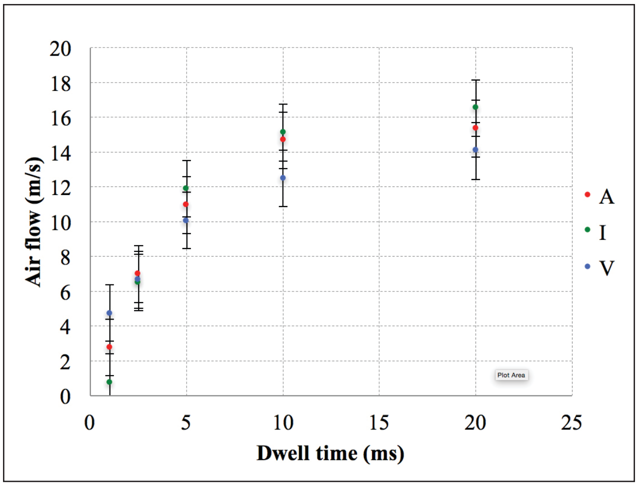
$$s^2 = \frac{\sum_{i=1}^{k}(n_i-1)s_i^2}{\sum_{i=1}^{k}(n_i-1)} \quad (1)$$

where the measurement series are numbered from 1 to k, s^2 is pooled variance, n_i is sample size of measurement series i, and s_i is standard deviation of measurement series i.

Figures 1 and **2** show results from the previous study [7], with the updated measurement uncertainty. This and the previous study [7] used the same fabrics in the experimental work presented by Sjöstrand et al. [7]. The fabrics had similar values for the caliper, void volume, and air permeability. They did, however, have different structures. The structures were defined by the open area profiles and were given the letters A, V, and I. The letters are based on the open area in the two bottlenecks where fabric A has a low open area in the sheet side bottleneck and high open area in the wear side bottle neck. Fabric V has a high open area in the sheet side bottleneck and low open area in the wear side bottleneck. Fabric I has an open area with values between those of fabrics A and V in sheet and wear sides.



1. Moisture ratio versus dwell time for the three fabrics of different open area profiles denoted as A, V, and I.



2. Airflow versus dwell time for the three fabrics of different open area profiles denoted as A, V, and I.

The open area profiles were obtained from the fabric manufacturer (**Fig. 3**). These were determined with x-ray microtomography. **Table I** shows more information regarding the three fabrics used. Moisture content of the sheets is expressed as moisture ratio (MR) and defined by Eq. (2):

$$MR = \frac{mass\ of\ water}{mass\ of\ dry\ content} \quad (2)$$

Single-phase numerical model

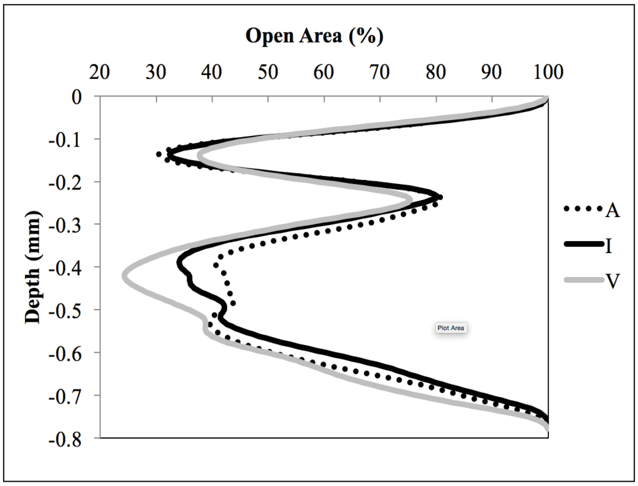
Ergun [1] developed an equation, Eq. (3), for flow through porous media, which can be used to formulate representative flow resistances of forming fabrics and paper sheets:

$$\frac{\Delta P}{L} g_e = 150 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu U_m}{{D_p}^2} + 1.75 \frac{1-\epsilon}{\epsilon^3} \frac{G U_m}{D_p} \quad (3)$$

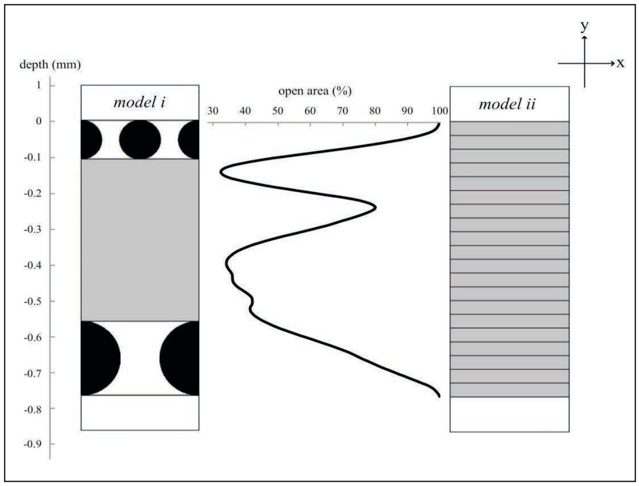
where ΔP is the pressure difference (Pa), L is the caliper (m), g_e is a gravitational constant (kg×m/N×s^2), ϵ is volume fraction solid, μ is the dynamic viscosity (Pa×s), U_m is fluid velocity (m/s), D_p is yarn/fiber diameter (m), and G is the mass flow rate (kg/s×m^2).

The flow resistance of the fabrics was evaluated experimentally at room temperature by applying different pressure drops between 30 Pa and 500 Pa and measuring the airflow through one of the fabrics (Fabric I). Fabric I was then modeled in two ways, model *i* and model *ii* (**Fig. 4**), both based on the open area curves (Fig. 3) of the fabric. The most basic way of modeling this is to use Eq. (3) for flow through porous media (model *iii*) [1].

Models *i* and *ii* were used in the modeling software COMSOL Multiphysics (COMSOL; Burlington, MA, USA), with size parameters from Table I and the stationary laminar single-phase flow



3. Open area profiles of the three fabrics.



4. Two ways of describing forming fabrics (i and ii).

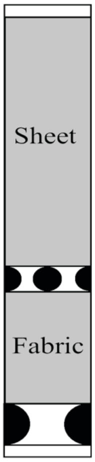
study. Both models are 0.32 mm wide and have a caliper of 0.76 mm. Each model has two additional rectangles, with y = 0.1-0 mm for one and y = 0.76-0.86 mm for the other. The purpose of the rectangles is to avoid flow issues at the corners and to provide an initial interface. They do not contribute to any flow resistance. The horizontal inlet boundaries (y = 0.1 mm) (Fig. 4) are set to atmospheric pressure and the horizontal outlet boundaries (y = -0.86 mm) to a pressure corresponding to the structure's varying pressure drop, according to the experimental data. The pressure difference between inlet and outlet drives the flow. The vertical boundaries are symmetry lines ($u_x = 0$) and the fabric yarn surfaces of model *i* are solid, no-slip walls where no flow can penetrate ($u_x = 0$; $u_y = 0$), where u is flow velocity. The flow is assumed to be incompressible and the temperature is set to 293.15 K. The flow resistances are built from [1] with yarn diameter and volume fraction solid from the actual values of the fabrics (**Table II**). The geometry of model *i* was also defined with yarn diameter and openness in sheet side and wear side and mean flow resistance between these yarn segments. Model *ii* was defined only by flow resistance and was divided into 20 layers with individually calculated mean volume fraction solid from the open area profiles (Fig. 3). For each layer, flow resistance was calculated from Eq. (3). Finally, the average volume fraction solid and average yarn diameter were used to model the flow according to the original form of the Ergun equation (Eq. [3]) without using any software. These three models were compared with the experimental data. For the first two models (*i* and *ii*), the resulting flow rates were not mesh-sensitive in the software and converged fast. The third model (*iii*) was solved analytically.

Profile	Caliper, mm	Void Volume, mm³/cm²	Permeability, cfm	Open Area Sheet Side, %	Open Area Wear Side, %	Sheet Side Yarn Diameter, mm	Wear Side Yarn Diameter, mm
A	0.78	47.5	356	30.5	39.5	0.11	0.18
V	0.78	43.6	330	37.7	24.4	0.13	0.21
I	0.76	45.9	362	32.4	34.1	0.11	0.18

I. Characteristics of the three versions of forming fabrics studied.

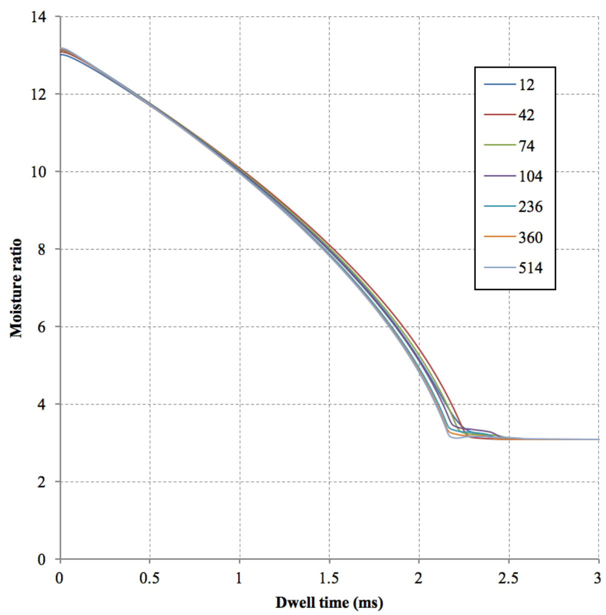
Dimension	Fabric A		Fabric V		Fabric I	
	Real	Model	Real	Model	Real	Model
Sheet side yarn diameter, mm	0.11	0.11	0.13	0.13	0.11	0.11
Sheet side openness, %	30.5	30.5	37.7	37.7	32.4	32.4
Wear side yarn diameter, mm	0.18	0.18	0.21	0.16	0.18	0.21
Wear side openness, %	39.5	43.1	24.4	23.3	34.1	35.5

II. Fabric dimensions for real fabrics and corresponding models.



5. Picture of the model of fabric and sheet used in the COMSOL Multiphysics program. This model has two rectangles, as do the previous models. Their purpose is to avoid flow issues that might affect the corners of the fabric models.

To take full advantage of symmetry lines in the simulation, the models' wear sides were slightly modified according to Table II. Fabric A, V, and I are simulated according to Table II in two-phase flow models.



6. Mesh sensitivity of dewatering of the two-phase model. The numbers 12-514 indicate the number of mesh elements in the small rectangle on top of the model; 12 is the coarsest and 514 is the finest mesh.

Two-phase numerical model

The structure of the fabric was thereafter described with model *i* with a sheet added on top of the fabric structure. The geometry of this numerical model (**Fig. 5**) was also built in COMSOL Multiphysics with size parameters from Table I modified according to Table II. This time, the study was a time-dependent laminar two-phase flow, otherwise with identical model structure except for the addition of the sheet and 40 kPa pressure drop over the structure. Two interface tracking methods were available in the software: level set and phase field. The phase field method uses two transport equations. It is more exact and demands more computational power than does the level set method, which uses one transport equation. We used the phase field method because we needed the interface calculations to be as detailed as possible, even though the calculation time increased with this. The flow resistance of the sheet was based on measured fiber width. The volume fraction solid was set to 0.45 to fit the experimental data. The wood fibers were characterized with a Lorentzen & Wettre fiber tester (ABB Process Automation Division; Kista, Sweden). The length-weighted mean width was 31 μm, with approximately 95% of the fibers ranging between 20 μm and 40 μm.

We evaluated the moisture ratio for the sheet during the dewatering by integrating volume fraction water over time for the sheet. After this, the model was used with the same geometry and basic settings and compressible steady state single-phase airflow to compare with the experimental data. The velocity was calculated by integrating over the outlet boundary with respect to flow velocity.

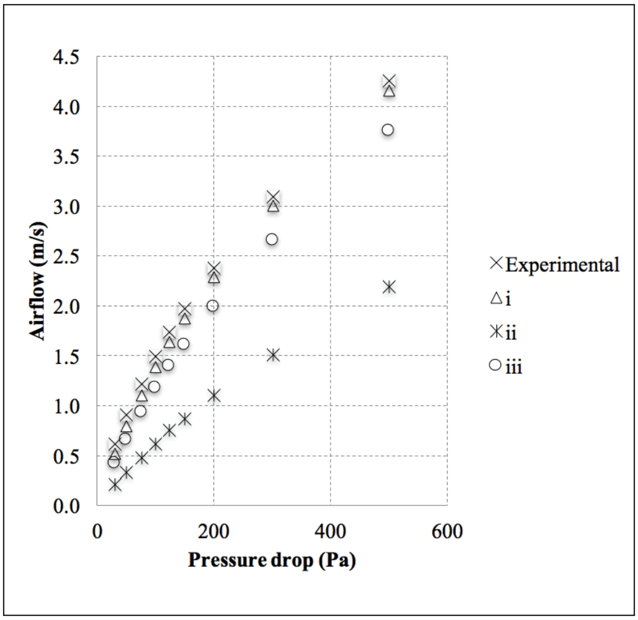
The model was mildly sensitive to the mesh (**Fig. 6**). The mesh of the model was varied between 12 and 514 mesh elements in the rectangle above the model. Figure 6 shows that the moisture ratio dependence on dwell time is almost exactly the same for the different mesh settings. The differences decline with every step of increasing mesh complexity. The largest time difference to reach a moisture ratio of 4 was 0.08 ms, which is negligible. The differences in mean dewatering rate are extremely small between the different mesh configurations.

Finer mesh leads to longer computation time. The mesh denoted "514" took about 8 h to run on an ordinary desktop computer. With respect to the appearance of Fig. 6 and the computational time, the results presented in this study are performed with the coarsest mesh.

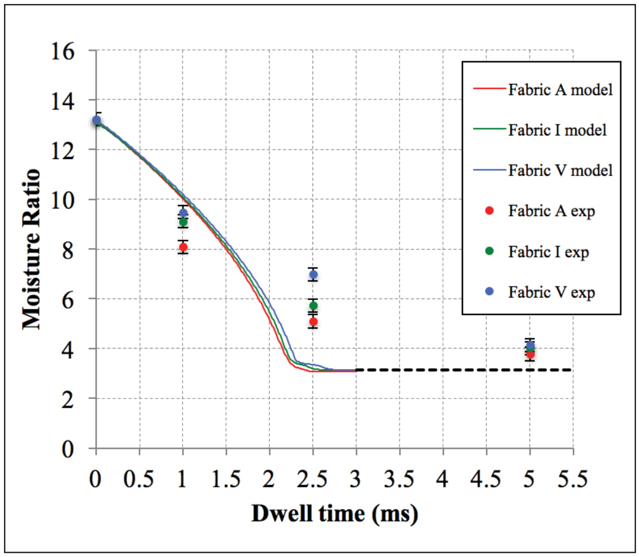
Fabric model *i* was based on the dimensions of the yarns in the actual fabrics. We needed to keep the dimensions in the sheet side intact and alter the wear side to fully use symmetry and thereby reduce the computation time. The wear side alteration was chosen over sheet side alteration because of sheet side influence on dewatering and paper properties [5]. Wear side geometry mainly affects machine runnability and is designed with higher yarn diameter than the sheet side [10].

The dewatering velocity was calculated for the experiments as the slope between the moisture ratio values of 0 ms and 2.5 ms (Fig. 1). The models' dewatering rates were calculated as the mean velocity for the entire dewatering process, which is approximately 2.5 ms.

Eq. (3) is suitable for a large interval of Reynolds numbers



7. Airflow versus pressure drop for the three ways of modeling the fabric and the experimental data.



8. Dewatering velocity versus dwell time for each model.

(N_{RE}), the highest N_{RE} in each model was calculated according to Eq. (4). The highest values of N_{RE} were 10 for the single-phase model with air (only fabric), 20 for the two-phase model with air, and 30 for the two-phase model with water.

$$N_{RE} = \frac{D_p \rho U_0}{4(1-\epsilon)\mu}, \qquad (4)$$

where D_p = yarn/fiber diameter (m), ρ = density (kg/m³), U_0 = velocity (m/s), ϵ = volume fraction solid, and μ = dynamic viscosity (Pa×s).

RESULTS AND DISCUSSION

Single-phase numerical model

Figure 7 shows the three single-phase models of the fabric and the experimental values of the pressure drop over the fabric.

Model *i* is in excellent agreement with the experimental data in Fig. 7. A fabric model similar to model *i* was previously shown to yield dewatering rates in fair agreement with experimental data [4]. The comparison between measured and calculated airflow further demonstrates that this type of model is useful, especially because no fitting parameters were needed to obtain the excellent agreement with experimental data. Initial work started with *i* based on results of Rezk et al. [4]. Model *i* involves partly describing the structure based on actual yarn diameters and local open area percentages and partly based on average flow resistance. The other two models (*ii* and *iii*) are not as capable of modeling the airflow as *i*, and based on Rezk et al. [4].

Looking at Fig. 7, it is challenging, at first, to understand why the third model (*iii*) is more efficient in describing the experiments than the more advanced numerical model (*ii*), which is based on flow resistance by the same equation. This can be explained by the nature of the equation. Eq. (3) describes the porous material as a continuum that is defined by two parameters, characteristic diameter and volume fraction solid. The equation was built with large amounts of data from materials that are much thicker than the characteristic diameter. Model *ii* is divided into 20 pieces that make every layer thinner than the yarn diameter; the thickness is about 30% of the yarn diameter in the example from Fig. 4. This can be one of the explanations why *iii* is closer to the experimental values than is *ii* in Fig. 7. The results of Fig. 7 show that even the simplest model can accurately model the actual airflow of fabrics.

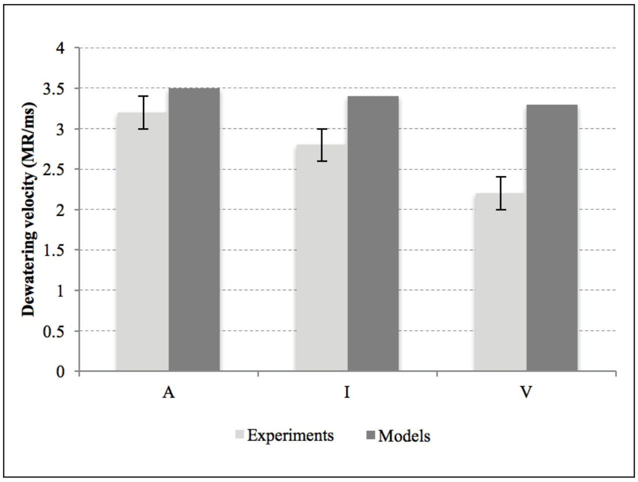
Two-phase numerical model

Figure 8 shows the moisture ratio for the dewatering for models and experiments. **Figure 9** compares the mean velocities.

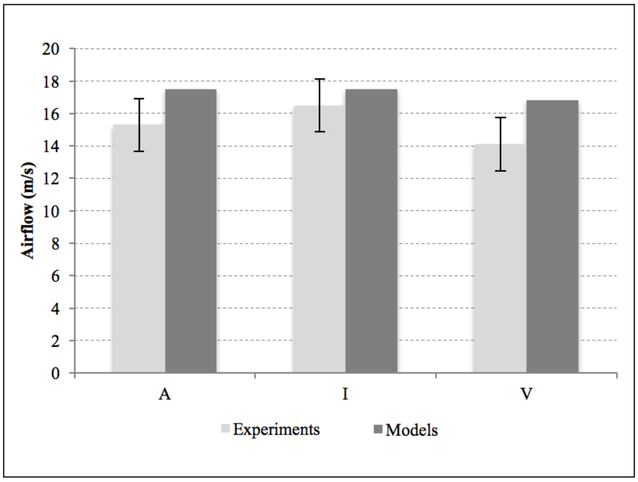
The curves in Fig. 8 differ. The dewatering velocity in the experimental data is fastest in the beginning and decreases toward the final moisture ratio. The models are slow in the beginning because of acceleration of the entire water column and speed up toward the end because of the absence of opposing forces such as capillary forces and other forces bonding water to the fibers. This makes it harder to compare dewatering velocity between the two than if the curves were more similar in shape.

The steady state airflow is almost identical for the models and lies within the confidence interval for the experimental values (**Fig. 10**). This is expected because of the small flow resistance the fabrics create, compared with the sheet. When the fabrics also are very similar, it seems natural that the airflow should be the same experimentally and from the numerical models.

The fabrics tested by Sjöstrand et al. [7] were very similar to each other. The results from the experimental study show



9. Mean dewatering velocities for experiments and models for the three fabrics.



10. Measured and calculated steady state airflow for the fabrics.

very little variation between the three. The fabric structure alone is only responsible for small differences in dewatering rate at certain conditions, such as the 40 kPa pressure drop and high flow resistance of the pulp [7]. All three fabrics are woven in the same fashion and the major parameters (caliper, void volume, and air permeability) are the same.

The geometry of the models was modified to enable symmetry lines. This gives dissimilar values for the wear side yarn diameter and open area compared with the real fabrics (Table II). It can be hard to draw conclusions on how and why the experiments by Sjöstrand et al. [7] turned out as they did, based on these models alone. That is not the most important reason for performing this study, however. The models are still very accurate. They can detect the minute differences between the fabrics that the experimental study show. The different dewatering rates in the experimental results could be seen in the numerical models. Figures 9 and 10 show almost identical dewatering velocity and airflow results for the numerical models and the experimental data. The model could be expanded to include some extreme fabrics that have different open area profiles or yarn diameter in the sheet side and wear side. The numerical models could in that case be used to find out how new fabric designs affect the dewatering.

CONCLUSION

Computational fluid dynamics flow models were made of forming fabrics with flow of air and water driven by pressure drop simulating high vacuum suction box dewatering. The models were based on previously performed experiments of vacuum dewatering with three different forming fabrics. The influence on dewatering by forming fabric structure was investigated. Single-phase models of the forming fabrics were in excellent agreement with the experimental results. Models of paper sheet and forming fabrics showed the same magnitude of the experimental results for both air velocity and dewatering rate. The small differences in dewatering rate that the experimental results showed between the different fabrics structures could be detected with the models. This implies that these numerical models can be used to test how new fabric designs will respond in the papermaking process. **TJ**

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ABOUT THE AUTHORS

The goal of this study was to investigate how the open area profile of forming fabrics affects the dewatering at high vacuum suction boxes and to expand the knowledge of how fabrics influence dewatering at the forming section.

This research builds on previous experimental work and adds the dimension of numerical models. A challenge in conducting the study was learning how to use the software. The software was previously unknown for me (Sjöstrand), which added some difficulties. I attended seminars and practices with colleagues.

A result of the study was learning how useful tools such as numerical modelling can be when designing forming fabrics. An interesting finding was that the equation from Ergun (1952) was accurate when modeling single-phase airflow through forming fabrics.

A benefit to mills and other researchers is that no expensive laboratory equipment is needed to perform simple investigations of flow of air and water through fabrics and sheets.

Sjöstrand

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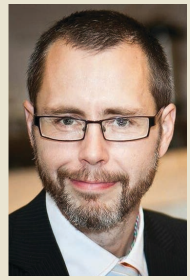

Barbier

Future studies might further develop the numerical models, perhaps to include rewetting and more complex sheet models.

Sjöstrand is a Ph.D. student and Nilsson is professor, Department of Engineering and Chemical Sciences, Karlstad University, Karlstad, Sweden. Barbier is paper physics specialist, R&D Gruvön, BillerudKorsnäs AB, Sweden. Email Sjöstrand at bjorn.sjostrand@kau.se.