

ABSTRACT

This paper describes an experimental method, based on a closed flow loop, for estimating the drainage resistance of the wire and the fiber mat. While most test devices use low approach velocities that are more representative of drainage over vacuum elements, this investigation focused on the high approach velocities that are found at the initial impingement of the jet. Design of the experimental setup and test methods, including results from machine measurements, are shown in detail. The results indicate that the closed-flow-loop method provides a realistic prediction of the flow resistance through the wire and fiber mat. These predictions can be used in the development of an analytical flow model in the jet impingement region on paper machines.

Application:

A laboratory method of predicting drainage resistance in the high-velocity region of jet impingement.

PREVIOUS RESEARCHERS HAVE studied the flow resistance of fiber mats formed in various devices (1-3). Typically, the specific filtration resistance (SFR) has been measured for relatively thick mats with basis weights up to 100-120 g/m². Although some of the results involved high drainage velocities (3), many have been done at low velocities of less than 20 mm/s. Drainage rates of this magnitude are usually associated with fiber mats formed after the dry line on the paper machine and often include factors that affect the flow resistance, such as compression.

The purpose of this work was to investigate the SFR and structure of very thin mats formed at the velocities that prevail at jet impingement and the early stages of the web development on the paper machine.

Investigation of thin fiber mats formed at high velocity

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THEORETICAL BACKGROUND

Gamma gauge measurements are frequently used in paper machine surveys to determine the mass balance over the wet end of the paper machine. Based on such surveys, average vertical drainage velocities can be calculated for each drainage element. **Figure 1** displays a typical drainage curve with vertical velocities and jet/stock thickness obtained from gamma gauge measurements (4). As shown in the figure, average drainage velocities of 0.66 m/s were achieved over the jet-impingement region. Average drainage rates over the low- and high-vacuum elements ranged from 0.030 to 0.100 m/s, more in line with drainage rates obtained in drainage jars and similar devices (1-3).

Initial jet impingement

This investigation is concerned with the drainage at the initial jet impingement, and the remainder of this paper focuses on this region. **Figure 2** depicts the initial impingement situation schematically for a single-wire case. The same situation also applies to a twin-wire case with preferential impingement on one wire. The driving pressure in such a situation is governed by the jet velocity v_j and the impingement angle β .

Wire drainage resistance

In the context of this analysis, we investigated both the drainage of the bare fabric and the combined drainage of the fabric and the fiber mat. The total pressure drop is assumed to be the superposition of pressure through the fabric and mat.

$$\Delta P_{\text{total}} = \Delta P_{\text{fabric}} + \Delta P_{\text{mat}} \quad (1)$$

The pressure loss across the fabric can be described by Eq. 2, which includes viscous and inertial terms.

$$\Delta P_{\text{fabric}} = \mu a_{\text{fabric}} V + \rho b_{\text{fabric}} V^2 \quad (2)$$

where

μ = viscosity

ρ = density of the suspension

V = drainage velocity

a = viscous drainage resistance coefficient

b = inertial drainage resistance coefficient

Pulp drainage resistance

The mat resistance is governed by the basis weight present on the wire, mat compressibility, and the geometrical arrangement of fibers on the wire. For very low basis weights, the compressibility of the mat is neglected. It is furthermore assumed that the fibers are uniformly distributed over the fabric. The pressure loss across the mat can then be described by Eq. 3.

$$\Delta P_{\text{mat}} = \mu a_{\text{mat}} V + \rho b_{\text{mat}} V^2 \quad (3)$$

If we consider low basis weights, we can further simplify Eq. 3 to:

$$\Delta P_{\text{mat}} = \mu a_{\text{mat}} V \quad (4)$$

The viscous coefficient a_{mat} contains the basis weight and the mat resistance. We can therefore rewrite Eq. 4 to include the basis weight (BW) and specific filtration resistance (SFR):

$$\Delta P_{\text{mat}} = \mu \times \text{SFR} \times \text{BW} \times V \quad (5)$$

$$\Delta P_{\text{total}} = \mu V [(\text{SFR} \times \text{BW}) + a_{\text{fabric}}] + \rho b_{\text{fabric}} V^2 \quad (6)$$

A high-velocity laboratory sheet former, capable of approach velocities of 2 m/s, was developed for the set of experiments. **Figure 3** shows the experimental setup schematically.

Wire drainage resistance

The measurement of pressure was extended over a range of forming fabrics with different water permeabilities, as seen in **Fig. 5**. The units for air permeability displayed in this figure ($\text{ft}^3/\text{min}/\text{ft}^2$) are commonly applied to forming fabrics in the context of papermaking.

The different porosities of the various forming fabrics clearly lead to different pressure differentials across the fabrics. Predictions of these pressure differentials can be obtained from the following equations, which determine the viscous and inertial drainage resistance coefficients of the fabrics:

$$a_{\text{fabric}} = s_1 \text{AP}^{-p_1} \quad (7a)$$

$$b_{\text{fabric}} = s_2 A P^{-p_2} \quad (7b)$$

AP = air permeability of the forming fabric
 s_1, s_2, p_1, p_2 = curve-fitting parameters that could be related to the geometry of the fabric design.

The figure is a dual-axis plot showing the relationship between Stock Thickness (mm) and Vertical Drainage Velocity (m/s) versus MD Distance (m). The Stock Thickness is represented by blue bars, and the Vertical Drainage Velocity is represented by a black line with blue diamond markers. The Stock Thickness starts at 0.05 m, peaks at 0.66 m/s, and then decreases. The Vertical Drainage Velocity starts at 0.7 m/s and decreases to 0.05 m/s. Arrows indicate the direction of flow: from the Stock Thickness bar towards the Vertical Drainage Velocity line, and from the Vertical Drainage Velocity line towards the Stock Thickness bar.

MD Distance (m)	Stock Thickness (mm)	Vertical Drainage Velocity (m/s)
0	0	0.7
0.05	9.5	0.55
1.31	0	0.5
2.79	1.0	0.45
4.59	0.7	0.4
6.23	0.9	0.35
7.87	1.6	0.3
10.17	0	0.3
11.97	0.7	0.1
14.60	0.5	0.1
15.58	0	0.05

Free jet

v_j

β

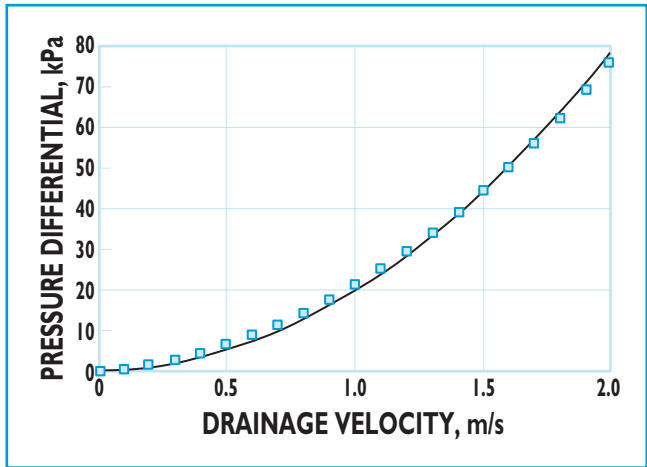
Wire

Fiber mat

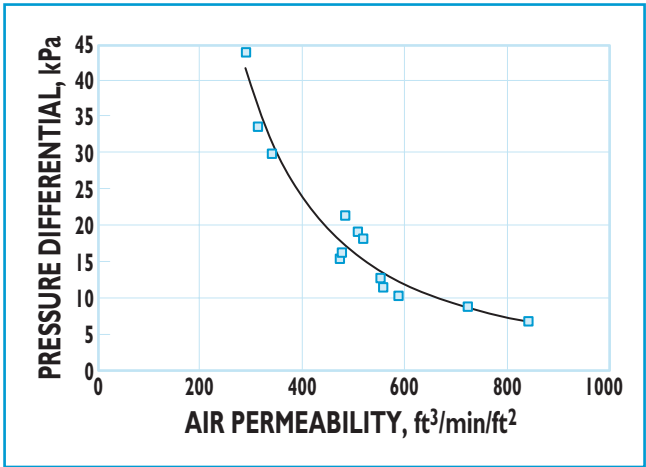
White water

The diagram illustrates a laboratory setup for studying pulp flow through a fabric and mat. The system consists of a pump at the bottom right, connected to a vertical tube. The tube contains a fabric and mat section. A pulp injection point is located on the left side of the tube. Two gate valves, labeled Gate valve 1 and Gate valve 2, are positioned along the tube. The total pressure difference across the fabric and mat is labeled ΔP_{total} , and the orifice pressure difference is labeled $\Delta P_{\text{orifice}}$.

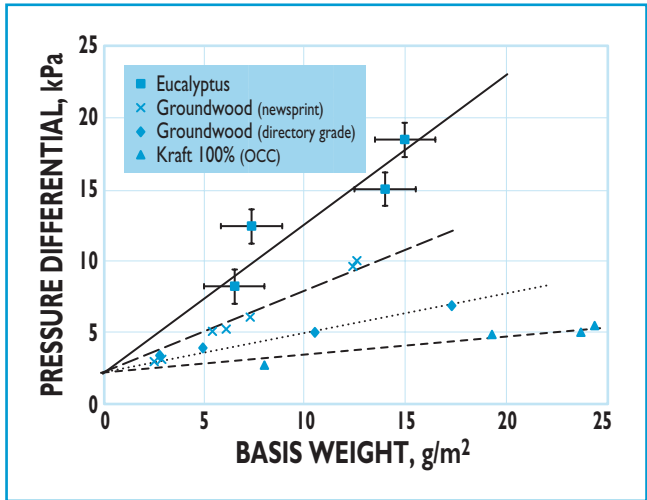
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4. Drainage resistance (pressure differential vs. drainage velocity) of the wire as measured on a high-velocity laboratory sheet former (air permeability of the forming fabric = 295 ft³/min)



5. Drainage resistance (pressure differential vs. air permeability) of the wire as measured on a high-velocity laboratory sheet former (drainage velocity = 1.5 m/s)



6. Drainage resistance (pressure differential vs. basis weight) of the fiber mat for four pulps as measured on a high-velocity laboratory sheet former (fine-mesh triple-layer fabric; drainage velocity = 0.66 m/s)

Pulp drainage resistance

Figure 6 shows the pressure differential vs. basis weight curves for four pulps. A fine-mesh triple-layer fabric was used for the experiment, and the approach velocity was set to 0.66 m/s and maintained at that level.

Over the basis-weight range investigated, the relationship between the two variables appears to be linear and agrees with earlier observations (5). For this group of pulp species, eucalyptus is the slowest draining pulp, resulting in the largest pressure differential across the fiber mat for any given basis weight. The kraft 100% OCC (old corrugated containers) pulp showed the least resistance to drainage, as indicated by the smallest pressure differentials across the fiber mat. Groundwood pulp was positioned between these two extremes. As reported in the

literature (1), the flow resistance of pulps can be ranked by the slopes of the curves, which reflect specific filtration resistance.

It is also of interest to note that for fast-draining pulp species, the wire resistance accounts for up to 70% of the total pressure differential at a 10-g/m² basis weight, while for slow-draining pulps, wire resistance contributes to less than 20% at the same basis weight. The relative importance of the wire and pulp drainage resistance at the initial impingement of the jet can be illustrated using the following example and equation:

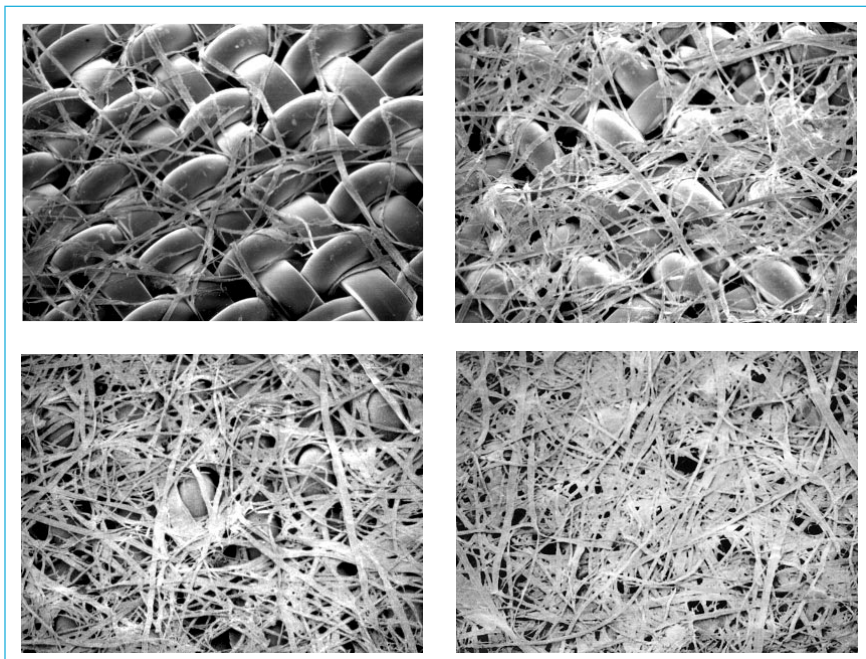
$$BW = \frac{Q_{dr} c_{HB} \rho R}{v_w} \tag{8}$$

where

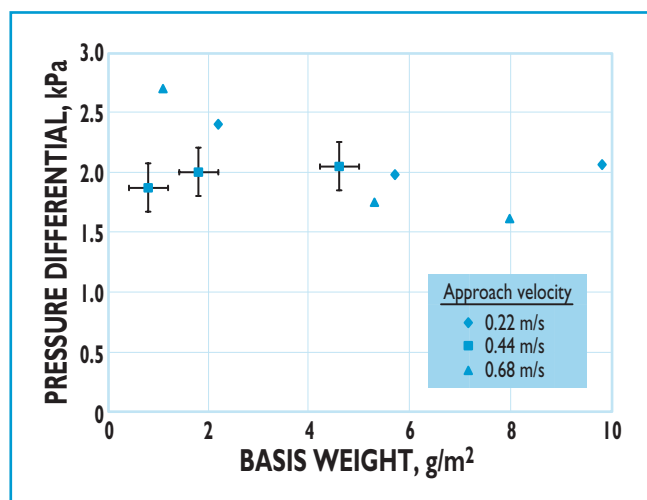
- Q_{dr} = volume drained at impingement
- c_{HB} = headbox consistency
- ρ = density of the fluid
- R = initial retention coefficient
- v_w = wire speed

Based on the newsprint case shown in Fig. 1, where the approach velocity at impingement is 0.66 m/s and using a headbox consistency of 0.6% and a retention of 50%, the basis weight estimated after the initial impingement is 6.7 g/m². At this point, the flow resistance of the mat/fabric composite is more than twice that of the fabric flow alone (Fig. 6).

The SEM images in Fig. 7 show the development of groundwood fiber mats on a triple-layer forming fabric. During the initial buildup of the fiber mat, the fibers are drawn preferentially to the openings in the top surface, adding hydraulic resistance. This process continues until a uniform fiber-mat pore structure is built on the wire such that the addition of more fibers would result in a



7. Fiber mat development (basis weights of 0.2, 4.0, 7.0, and 10.0 g/m²) for groundwood on a triple-layer fabric ($\times 45$ magnification)



8. Effect of approach velocity on SFR of groundwood pulp as measured on a high-velocity laboratory sheet former (fine-mesh triple-layer fabric; drainage velocities = 0.22, 0.44, 0.68 m/s)

densification of the fiber network over the fabric holes and a general increase of the mat thickness. The results of this investigation suggest that significant coverage of the knuckles of the forming fabric does not occur until basis weights greater than 10–15 g/m² are attained. Undoubtedly, this is the main reason that wire mark, for example, is invariably more pronounced for the fabric that is impinged by the jet.

In order to verify the sensitivity of the SFR to the approach velocity, similar basis weights were produced

	WIRE VELOCITY, m/min	
	381 (Mill A)	712 (Mill B)
SFR, 10 ⁹ m/kg		
Measured	1.3	2.8
Calculated	1.0	2.2

I. Measured and calculated SFR at low and high wire velocities

	WIRE TENSION, N/m	
	5000	3000
SFR, 10 ⁹ m/kg		
Measured	2.09	2.09
Calculated	2.21	1.25

II. Measured and calculated SFR at high and low wire tension

with different approach velocities. Figure 8 shows the results for groundwood pulp. Despite the scatter of the data, there appears to be little or no change on the SFR (or slope of the pressure/basis-weight curve) with increasing basis weight, as suggested by Eq. 6. One explanation for this behavior could be the slow response of the flow loop to sudden changes in basis weight, i.e., resistance. While a recent publication (6) showed the same linear pressure/basis-weight dependency, a nonlinear relationship between basis weight, drainage velocity, and SFR was also found based on data obtained with a high-speed data-acquisition system.

Verification of measurements

To test this simplified model, measurements were taken in several paper mills at the jet impingement. With these measurements, the flow rates, fiber length distribution, and fiber mass were determined. Based on the mass balance and the impingement geometry, an SFR value could be calculated using Eq. 8. Samples from the same mill were measured in the laboratory using the closed-loop system. Table I shows both measured and calculated results from two mills with different operating conditions. While there are some differences in the SFR results, the laboratory measurements show the same trend as the mill measurements. A possible reason for the differences between the measured and calculated results is that orientation effects were not taken into account at low basis weights because of the experimental arrangement in the flow loop.

The same methodology was used to determine the SFR for a pilot machine experiment. In this case, the SFR was evaluated based on the mass balance around a single blade between two fabrics (7). Table II shows two results for different operating conditions, i.e., high and low

tension settings on the paper machine.

At the higher tension, the agreement between measured and calculated values is quite good. However, at the low tension, the SFR calculated from machine flow data is much lower than the value measured in the laboratory.

SUMMARY AND RECOMMENDATIONS

A high-velocity laboratory sheet former can provide a realistic description of drainage through the forming fabric and the pulp mat. The water permeability of the forming fabric significantly contributes to the overall permeability of fabric and mat in cases of fast-draining pulps and over the initial impingement area. Past the impingement point, the overall drainage resistance is much more dependent on the fiber mat for slow-draining pulps.

The measurement of the specific filtration resistance at relatively high velocities enables prediction of drainage at the early stages of the paper forming process. However, further studies are required to investigate local orientation effects caused by either machine conditions or fabric topography. Furthermore, additional measurements are required to resolve the velocity/basis-weight/SFR relationship, which currently is assumed to be constant.

Based on these measurements, computational models can be developed to predict the drainage behavior on single- and twin-wire paper machines and to assess the influence of fabric and stock changes. **TJ**

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