DRAINAGE DURING ROLL FORMING - MODEL VALIDATION USING PILOT PAPERMACHINE DATA

Vaughn J. Wildfong[1] and Jay A. Shands[2]
Forming Systems R&D
Beloit Corporation
Rockton, IL 61072

Douglas W. Bousfield and Joseph M. Genco
Professors of Chemical Engineering
University of Maine
Orono, ME 04469

ABSTRACT

The geometry and corresponding drainage over a forming roll on a papermachine twin wire gap former is examined. A twin wire gap former consists of a constant pressure-forming element, in this case a roll, followed by a variable pressure bladed section. In the current work, an analytical solution is presented to a phenomenological model describing the constant pressure forming process. The model output consists of filtrate volume drained over the roll. To test the validity of the model, a series of pilot papermachine trials were performed with furnishes typical of newsprint and free-sheet fine paper. Headbox samples were taken and tested in a drainage device to determine the drainage resistance coefficients required in the model. The drainage occurring over the former was the criteria used for determining model accuracy. The output from the drainage model matches the volumetric flow rate measured on the pilot machine data within 15%.

INTRODUCTION

Drainage of papermaking furnishes is an important consideration in the paper industry. Many tests and testers have been developed to quantify the process. Three of the most common procedures to measure the tendency of a pulp to drain are Canadian Standard Freeness (CSF), Schoppler-Riegler (SR), and TAPPI standard drainage time. These tests have proven useful as quick easy methods for determination of processing during pulp manufacture and refining. Mantar, Co and Genco (1995) and Wildfong (1998) have reviewed many of the early drainage testers. Unfortunately, many of the previous attempts to characterize pulp drainage in the laboratory have met with only limited success in terms of predicting pulp drainage performance on a papermachine. This result may be caused because a majority of the drainage devices are

[1] Dr. Wildfong is now employed with International Paper Company, West Chicago Illinois.
[2] Dr. Shands is now employed with Westvaco Corporation, Covington, Virginia.

predicated on measuring thick mats at low drainage velocities and use empirical measures or account only for viscous flow. Other limitations of previous work include a lack of evaluation of thin basis weight mats occurring at high drainage velocity. The drainage velocity and basis weight can significantly affect the retention, which affects the void volume of the mat and the corresponding resistance value. Resistances are also commonly reported as "averages". The resistance to flow can be a continuously changing quantity dependent on the stage of mat deposition. Many devices also used constant rate filtrations that allow for varying pressure differentials that make interpretation of the resistances difficult.

Furthermore, the conditions under which drainage occurred in these devices is often considerably different than those expected in an industrial setting. The conditions present during industrial sheet forming should be simulated when designing a drainage apparatus for the purpose of characterizing stock drainage on a papermachine. Wildfong and co-workers (2000) developed a rapid drainage tester where drainage conditions are similar to those encountered on commercial paper machines. The purpose of this development was to have a device that would yield data that could be used to predict drainage rates under realistic industrial conditions.

Objective and Scope

The objective of the present paper is to present an analytical drainage model that can be used to predict drainage that takes place across a forming roll. Input to the model are data on drainage resistance for the stock that was obtained from the high-speed drainage apparatus described by Wildfong and co-workers (2000A). The output from the drainage model is the volume drained and was compared to experimental data obtained from a roll-blade pilot paper. In these experiments, the machine was equipped with wears that could measure the volumetric drainage rates along the various drainage elements. These data are reported in this paper. The data for the volumetric flow rate outward over the forming roll was measured and compared to the model.

Roll Drainage Model

A detailed description of the roll drainage model is given in Appendix A. In the model described here, the filtration equations are used with the wire tension and the roll radius generating the pressure driving force, and the roll wrap and machine speed gives the time for filtration. This treatment leads to an analytical solution for the total flow rate exiting over the roll (q) per unit roll width (w)

$$\frac{q}{w} = u\left(\frac{C_M}{C_{HB} - C_{WW}}\right)\sqrt{\left(\frac{a_o}{a}\right)^2 + \frac{2\left(\frac{T}{R} - P_A\right)}{a}\frac{S}{u}\left(\frac{C_{HB} - C_{WW}}{C_M}\right)} \qquad (1)$$

in terms of the machine parameters, notably the machine speed (u), the tension in the forming fabric (T), the roll radius (R) and the length of roll wrap (S) and the pressure surrounding the wire (P_A). In the case of a solid roll, P_A would be atmospheric pressure. Also, the drainage on the machine is related to the level of retention on the machine and is reflected in the consistencies in the headbox (C_{HB}), white water (C_{WW}) and in the deposited mat (C_M).

The coefficients (a_o) and (a) represent the viscous resistance coefficients for the forming fabric (a_o) and the mat (a). Irmay (1958) represented the "turbulent" form of the Kozeny equation by retaining the inertia terms of the Navier Stokes equations (Geankoplish, 1983) for flow in microscopic channels and then applied the hydraulic radius model of Kozeny with the modification by Carman. The solution matched the equation previously proposed by Forcheimer with the viscous resistance represented by the coefficient (a) given in equation (A-1) and the inertial resistance term given by the coefficient (b). Inertial resistance contributions were small when compared to contributions from fine material when determining the resistances of commercial paper machine furnishes in laboratory drainage studies, and thus were neglected (Wildfong et. al. 2000B). The inertial contributions to the total resistance of a forming fabric (b_o) are more substantial than inertial terms for the mat (b) but would be small compared to the viscous term for the mat (a_o) and were excluded to simplify the model.

PILOT PAPERMACHINE EXPERIMENTS

Pilot paper machine trials were performed utilizing the three furnishes, newsprint and two fine paper furnishes. The fine paper furnishes contained the same ratio of hardwood and softwood, but contained different hardwood pulps. A comparison was made between the pilot paper machine trials and filtration resistance curves for the three furnishes determined in a recently developed drainage apparatus (Wildfong et. al, 2000A). This was done to provide a link between filtration resistance numbers generated with the laboratory apparatus and the pilot papermachine trials.

Description of the Pilot Machine

Pilot machine trials were performed at the Beloit Corporation Rockton Research facility. The trials were conducted on the number three experimental paper machine. The wet-end of this machine was equipped with a six-channel Concept IV-MH headbox having an 18.75-inch pondside width and a Bel Baie RCB (roll-counterblade) horizontal gap former.

Former. As the stock moves through the forming zone the drainage volume that occurs can be collected and measured. The papermachine was set up to collect the drainages at several points on the machine as shown in **Figure 1**. The drainage volumes were collected at various points along the length of the machine in separate channels. The volumetric flow rate at the various measurement points was determined by measuring the height of the collected filtrate in V-notch weirs within the collection channels. For this trial the papermachine was set up to collect the drainage from six areas of the machine (see Figure 1). The downward drainage segments consist of 1) the roll, or drainage into the roll and opposite the autoslice blade, 2) the counter blades (CB) and deflector, involving drainage opposite the two curved inverted vacuum boxes (CIVB), including the opposed blades, and 3) the sheet transfer that involves the drainage at the suction and transfer boxes at the outlet of the top unit. The upward drainage segments consist of 1) the autoslice, and includes drainage opposite the roll and immediately preceding the autoslice blade, 2) the drainage into CIVB 1, and 3) the drainage into CIVB 2. These drainage collection points are represented in Figure 1.

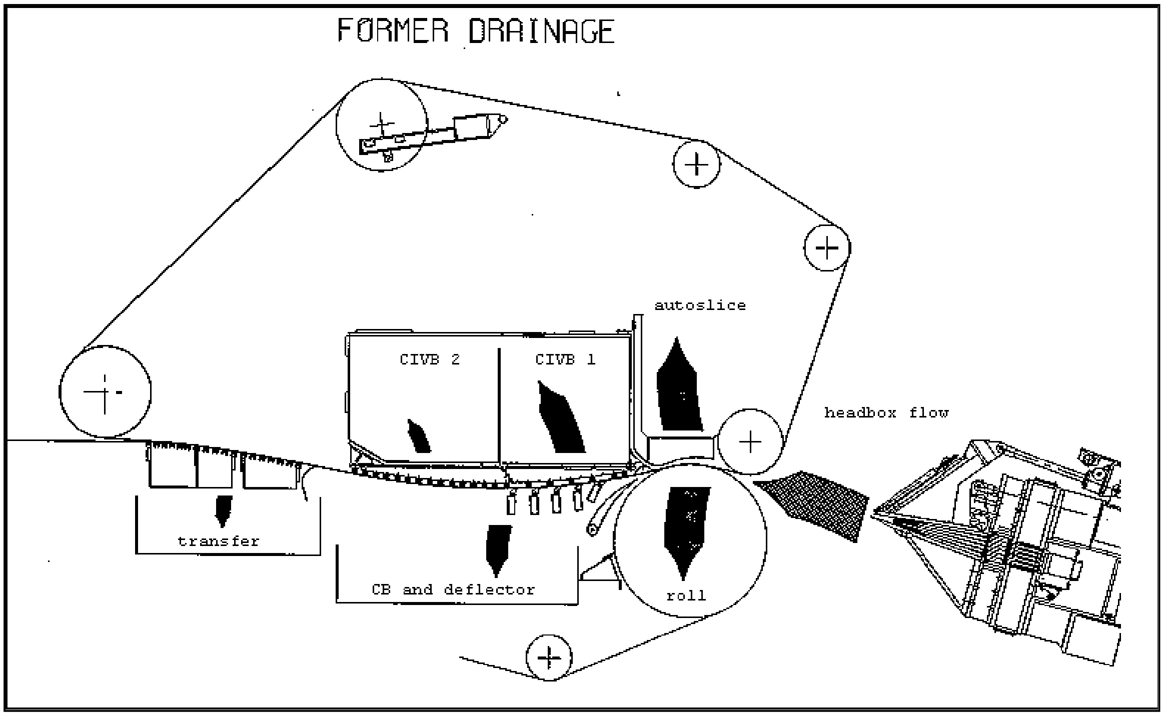

Figure 1. Experimental papermachine set up as a Horizontal Roll/Blade Gap Former showing collection points.

Furnish Characterization

The rapid drainage device was used to measure the viscous resistance coefficients for three furnishes examined in this work (Wildfong et. al, 2000A). The rapid drainage device is a constant-pressure device. Consequently, the resistance values obtained from it best represent drainage that occurs at constant-pressure, such as over a forming roll. **Table 1** summarizes the three furnishes used in the pilot papermachine. The values for the filtration resistance change with basis weight. In this work, average values were used reflective of the basis weights of interest. Wildfong and co-workers (2000B) report values for the viscous resistance coefficient (a) as a function of basis weight. Average values for the filtration resistance is summarized in Table 1. These values were used as input to the model.

	Fine Paper Furnish No.1	**Fine Paper Furnish No.2**	**Newsprint Furnish No.2**
Fiber composition (%) Refining (HPD/ton)	75 / 25 HW / SW 4.33 / 5.4	75 / 25 HW / SW 4.33 / 6.1	Repulped roll-stock Repulped only
Thick stock CSF (mL)	450	370	125
% Filler in headbox	23.8	28.8	2.0
Filler type	PCC	PCC	Recycle
Headbox consistency	0.674	0.698	0.596
Headbox CSF (ml)	295	150	45
"Average" filtration resistance (a) $(kg/m^3\text{-sec})$	1.4×10^8	5.1×10^8	6.2×10^8

Table 1. Characteristics of the pilot papermachine furnishes.

In all three furnishes, the difference between the headbox and thick stock freeness values are substantial which further demonstrates the importance of using headbox stock as opposed to thick stock if drainage characteristics are desired. The thick stock freeness values suggest that all three furnishes will have different drainage characteristics with the two fine paper furnishes being similar. Conversely, the viscous resistance coefficient values suggest that fine paper No. 2 and newsprint No. 2 will behave in a similar manner. During the freeness test, almost all of the fine material is retained and contributes to the output. On a papermachine, and during resistance coefficient measurements, different furnishes will have different retentions and only the retained material can contribute to the drainage resistance. For example, retention values on newsprint machines are usually lower than fine paper machines. Also not all of the fine particles will be retained on the papermachine, but a large fraction will be retained in the freeness tester. Therefore, it would be expected that freeness values for newsprint would predict high values for the flow resistance relative to actual performance. In fact, the newsprint furnish had drainage rates in a manner similar to the Fine paper machine furnish No.2.

Characterization of Forming Fabric

The resistance of the forming fabric (a_o) was determined by measuring the pressure drop across the forming fabric in a flow loop (see **Figure 2**) at several different velocities. This flow loop is similar to that recently reported by Herzig and Johnson (1999). The pressure drop data across the wire (ΔP_W) were then fit to the Forcheimer relationship.

$$\Delta P_W = (aL)v + (bL)v^2 \tag{2}$$

$$\Delta P = a_o v + b_o v^2 \tag{3}$$

Both the viscous (a_o) and inertial (b_o) coefficients were determined from the experimental data (see **Figure 3**). Note that the caliper of the forming fabric was incorporated into the viscous and inertial resistance coefficients.

Using a bed of packed beads of known geometry the coefficients could be theoretically calculated to validate this approach. Based upon these results the method was then thought to be reliable for characterizing the flow resistance terms for the media. This information can then be applied to a variant of the Forcheimer formula to obtain resistance coefficients as previously given in equation [2-4].

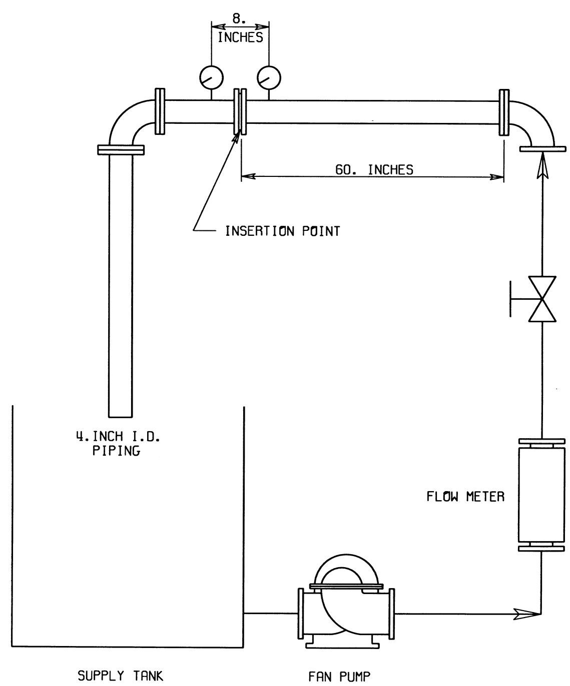

Figure 2. Flow loop used to measure the flow resistance of the forming fabric.

The viscous resistance of the forming fabric was measured as $a_0 = 625$ g/cm^2-sec and the inertial resistance was measured as $b_0 = 95$ g/cm^3. The inertial contributions to the total forming fabric resistance, although significant, were neglected to simplify the model.

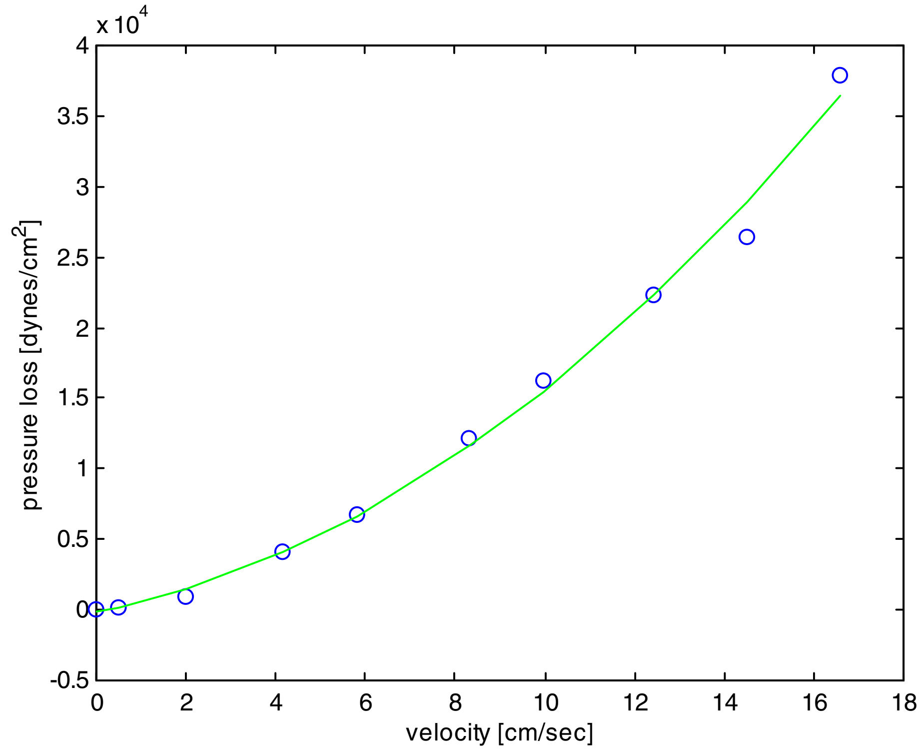

Figure 3. Flow resistance measured for the forming fabric.

RESULTS

Pilot Papermachine Drainage Results

The drainage velocities (**Table B1**), operational parameter (**Table B2**), and drainage measurements for each compartment (**Table B3**) obtained in the pilot paper machine experiments are summarized in Appendix B. The drainage results are further summarized in **Table 2**. The data in Table 2 are presented in GPM per inch of machine width. In all cases the major contribution to dewatering occurred at the autoslice and over the roll. Also, the drainage was equally split between the autoslice and the roll. The highest or most rapid drainage occurred for Fine Paper No. 1 while the slowest drainage occurred for Newsprint No. 2. This disparity in drainage rate between the newsprint and the fine paper furnishes was thought to result from the high level of mechanical pulp and the fines present in the newsprint furnish. This is reflected in the high value for the filtration resistance shown in Table 1 for the newsprint furnish (6.2×10^8 Kg/M^3 Sec).

	Fine Paper No.1 Volumetric flow Rate (gpm/in) [% Headbox flow]	Fine Paper No.2 Volumetric flow Rate (gpm/in) [% Headbox flow]	Newsprint No.2 Volumetric flow Rate (gpm/in) [% Headbox flow]
Headbox Flow	90 [100%]	95 [100%]	75 [100%]
Autoslice	33.8 [37.6%]	26.8 [28.2%]	24.7 [35.3%]
Roll	33.8 [37.6%]	28.2 [29.7%]	27.5 [39.3] Volumes combined
Counterblades and Deflector	3.9 [4.3%]	12.0 [12.6%]	
Continuous inverted Vacuum box (CIVB)#1	9.6 [10.6%]	12.1 [12.9%]	3.8 [5.4%]
Continuous inverted Vacuum box (CIVB)#2	1.9 [2.1%]	3.9 [4.1%]	1.5 [2.2%]
Transfer box	4.0 [4.5%]	3.5 [3.7%]	3.2 [4.5%]

Table 2. Summary of drainage results obtained in the pilot plant trials.

Input to Drainage Model

For each of the three conditions listed in Table1, one for each furnish, the analytical solution was applied to estimate the drainage over the roll based on machine operating parameters and the measured values of the viscous resistance coefficients for each furnish. The model input for each of the three cases is summarized in **Table 3**. The length the slurry is exposed to the pressure caused by the roll wrap was estimated based on the degrees of wrap and the roll radius.

$$\boldsymbol{S} = \frac{\text{degrees of wrap}}{360} \cdot 2\boldsymbol{\pi} \cdot \boldsymbol{R} \qquad (4)$$

The analytical model needs an "average" viscous resistance coefficient based on the basis weight that is formed on one wire over the roll. This value was determined based on half the resistance value associated with the basis weight formed on a particular wire over the roll (see Table 1).

This analytical solution has several shortcomings and is only an approximation to the actual conditions on commercial machines. It was developed to assess the feasibility of applying the viscous resistance coefficient (a) measured in the rapid drainage apparatus to predictive drainage modeling for design or process changes on twin wire formers. Values of the viscous resistance coefficient measured in this work can be incorporated into more representative models of the forming process provided some evidence is found illustrating the validity of the data.

The output from the analytic model and comparison to the experimental data is summarized in **Table 4** in terms of gallons per minute per inch of machine width (gpm/in). The corresponding pilot papermachine measured drainage rates over the roll are also presented for comparison. Good agreement was found between predicted and measured values. For all three cases studied, the predicted values for the drainage rate are within 15% of the data obtained from the weir measurements.

Description		**Fine Paper Furnish No.1**	**Fine Paper Furnish No.2**	**News-print Furnish No.2**	**Units**
Mat consistency	C_M	0.07	0.07	0.07	
Headbox consistency	C_{HB}	0.0067	0.0068	0.0060	
Whitewater consistency	C_{ww}	0.0017	0.0026	0.0021	
Wire tension	T	6,400			N/m
Roll radius	R	0.5			m
Roll vacuum	P	0			N/m^2
Wire speed	u	1,000			m/min
Machine width	w	0.45			m
Length of wrap	S	0.21			m
Resistance of forming fabric	a_o	6,000			kg/m^2-sec
Average viscous filtration resistance	a	1.4×10^8	5.1×10^8	6.2×10^8	kg/m^3-sec

Table 3. Input data to analytical model.

The model, coupled with the data for the resistance coefficient from the drainage test device, could also predict trends as well. The drainage rate data for Fine paper No.2 (26. 8 gpm per inch) and Newsprint No.2 (24.7 gpm per inch) are similar in nature and would be expected from the data for viscous resistance coefficients measured in the drainage devise; 5.1×10^8 kg/m^3 sec. and (6.2×10^8 kg/m^3 sec. respectively. The drainage rate of Fine paper No.1 (33.8 gpm/inch) was much higher than either Fine paper No.2 (26.8 gpm/inch) or newsprint No.2 (24.7 gpm/inch). The increased drainage behavior of fine paper No.1 was not suggested by examining the freeness of either the headbox or thick stock samples for the furnishes, but was suggested by the measured viscous resistance coefficient obtained in the drainage devise (1.4×10^8 kg/m^3 second). These positive results suggest that the viscous resistance data obtained from the laboratory apparatus is capable of predicting drainage trends, and can also be used as a predictive tool for design and estimating drainage volumes on a commercial papermachines.

Furnish Designation	Weir Measurement (gpm/in)	Model Output (gpm/in)	Model output % difference from experimental
Fine Paper No.1	33.8	36.2	+7.1
Fine Paper No.2	26.8	23.4	- 12.6
Newsprint No.2	24.7	24.9	+0.8

Table 4. Comparison of the analytical model to measured drainages rates.

CONCLUSIONS

The major conclusion drawn from the work presented here is that the viscous filtration resistance term is the major contribution to the total resistance during filtration on commercial paper machines. The headbox freeness did not correlate with the drainage over a forming roll in the pilot plant trials. These results also strongly support the premise that the headbox freeness is not a good method for estimating the drainage that would be expected on commercial paper machines. The roll-forming model presented here can accurately predict the drainage over a roll-forming device within about 15% of the actual values. To use the model, data for the viscous filtration resistance are required. The high-speed filtration test device produced useful data for making predictions on commercial formers. When used in conjunction with machine parameters, estimates can be made for the dewatering that would occur over a forming roll operating at high speeds.

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APPENDIX A
Analytical Solution to the Roll Drainage Equations

One method for determining the validity of the drainage resistance measurements is to input the resistance values into a drainage model. **Figure 1A** illustrates the geometry present in the roll-forming model.

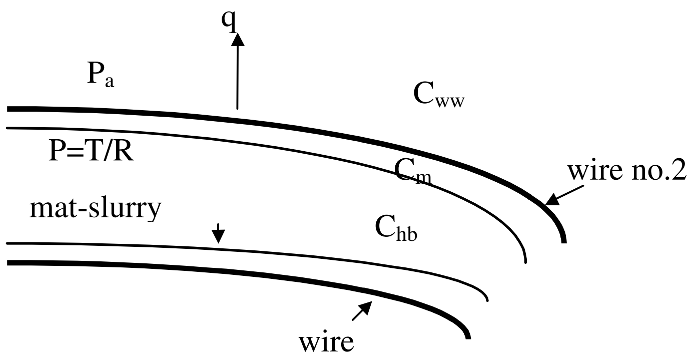

Figure A1. Schematic Representation of Roll Forming.

The pressure drop across the mat and the wire, with viscous resistance coefficients (a and a_o) when the mat thickness is (L) gives a standard expression relating pressure and velocity through the mat.

$$\boldsymbol{v = \frac{P - P_a}{a_o + a \cdot L}} \qquad \text{(A-1)}$$

For this work, the pressure generated between the forming fabrics by wrapping a forming roll will be approximated as the wire tension divided by the radius of the roll.

$$\boldsymbol{P = \frac{T}{R}} \qquad \text{(A-2)}$$

The continuity equation relates the total volume drained through the wire (V) to the mat thickness (L) and the consistencies in the headbox (C_{HB}), mat (C_M) and white water (C_{WW}).

$$\boldsymbol{AC_M L = VC_{HB} - VC_{WW}} \qquad \text{(A-3)}$$

The continuity equation can be rearranged to solve for the thickness (L).

By definition, the drainage velocity (v) is the volumetric flow rate (dV/dt) divided by the area (A). Using this definition and substitution of equation (A-3) into equation (A-1) yields an equation for the superficial velocity (v) through the mat.

$$v = \frac{1}{A} * \frac{dV}{dt} = \frac{P - P_a}{a_o + \frac{aV}{A}\left(\frac{C_{HB} - C_{WW}}{C_M}\right)} \qquad \text{(A-4)}$$

Equation [A-4] can be readily integrated using the boundary condition that the total volume drained through the forming fabric must be zero (V = 0) at the time that the sheet initially impinges upon the forming roll (t = 0).

$$\frac{a_o V}{A} + \frac{a V^2}{2 A^2} \left(\frac{C_M}{C_{HB} - C_{WW}}\right) = (P - P_a)\, t \qquad \text{(A-5)}$$

Equation (A-6) can be rewritten in terms of mat thickness by use of the continuity equation (A-3).

$$\boldsymbol{L} = \sqrt{\left(\frac{\boldsymbol{a_o}}{\boldsymbol{a}}\right)^2 + \frac{2(\boldsymbol{P} - \boldsymbol{P_a})\boldsymbol{t}}{\boldsymbol{a}} \left(\frac{\boldsymbol{C_{HB}} - \boldsymbol{C_{WW}}}{\boldsymbol{C_M}}\right)} - \frac{\boldsymbol{a_o}}{\boldsymbol{a}} \qquad \text{(A-6)}$$

Equation (A-6) can readily be modified to represent the mat thickness as a function of machine parameters. Parameters of interest are the length of roll wrap (S)

$$\boldsymbol{S} = \frac{\text{degrees of wrap}}{360} \cdot 2\boldsymbol{\pi} \cdot \boldsymbol{R} \qquad \text{(A-7)}$$

and the machine speed (u). The time that the web spends in contact with the roll is simply the wrap divided by the machine speed.

$$\boldsymbol{t} = \frac{\boldsymbol{S}}{\boldsymbol{u}} \qquad \text{(A-8)}$$

Similarly the pressure between the two forming fabrics can be eliminated in favor of the wire tension (T) and roll radius (R) by using equation (A-2). Making appropriate substitutions, the mat thickness (L) becomes

$$L = \sqrt{\left(\frac{a_o}{a}\right)^2 + \frac{2\left(\frac{T}{R} - P_a\right)}{a} \frac{S}{u} \left(\frac{C_{HB} - C_{WW}}{C_M}\right)} - \frac{a_o}{a} \qquad \text{(A-9)}$$

The drainage velocity can be determined by substituting Equation (A-9) into equation (8-1).

$$v = \frac{\left(\frac{T}{R} - P_a\right)}{a_o + a \cdot \sqrt{\left(\frac{a_o}{a}\right)^2 + \frac{2\left(\frac{T}{R} - P_a\right)}{a} \frac{S}{u} \left(\frac{C_{HB} - C_{WW}}{C_M}\right)} - \frac{a_o}{a}} \qquad \text{(A-10)}$$

The total flow rate of fluid (q) can be obtained by integrating the drainage velocity over the wrapped portion of the roll and the width of the machine (W).

$$\boldsymbol{q} = \int_0^{\boldsymbol{W}} \int_0^{\boldsymbol{S}} \boldsymbol{v} \, \boldsymbol{dS} \, \boldsymbol{dW} \qquad \text{(A-11)}$$

This arithmetic results in Equation (1) shown in the text for the flow rate of fluid per unit width of the machine (q/w). Details of this integration and a more detailed description of the model are given by Wildfong (1998, PhD Dissertation).

APPENDIX B
PILOT PAPERMACHINE OPERATIONAL PARAMETERS AND RESULTS

Collection Point	**Average Drainage Velocity (cm/sec)**		
	Fine Paper Furnish No.1	**Fine Paper Furnish No.2**	**Newsprint Furnish No.2**
Number 1 wire (top)			
Over Roll	11.8	9.4	8.7
CIVB #1	1.5	1.8	0.6
CIVB #2	0.3	0.7	0.3
Number 2 wire (bottom)			
Down at Roll	11.8	9.9	
Counter blades and opposite CIVB 1,2	0.2	0.7	
Transfer Box	0.9	0.8	0.8

Table B1. Drainage velocities for selected points on the paper machine.

	Fine Paper Furnish No.1	**Fine Paper Furnish No.2**	**Newsprint Furnish No.2**
Filtration resistance			
Headbox CSF	295	150	95
Headbox consistency	0.67	0.69	0.60
First pass retention	70.0	62.6	63.3
Basis weight (gsm)	75	75	45
Headbox Flow (gpm/in)	90	95	75
Pilot Papermachine Operating Conditions			
Roll vacuum (inches of water)	20	10	20
CIVB #1 vacuum (inches of water)	28	30	29
CIVB #2 vacuum (inches of water)	34	40	40
Number of counter blades loaded	3	4	3
Suction box #1 vacuum (inches of Hg)	3	5	5
Suction box #2 vacuum (inches of Hg)	4	6	6
Transfer box vacuum (inches of Hg)	6.5	7	7

Table B2. Pilot paper machine operating parameters.

	Fine Paper Furnish No.1	Fine Paper Furnish No.2	Newsprint Furnish No.2
Flow Splits (% headbox flow)	**(%)**	**(%)**	**(%)**
#1 wire (top)			
Over Roll	37.6	28.2	35.3
CIVB #1	10.6	12.9	5.4
CIVB #2	2.1	4.1	2.2
Total #1 wire drainage	(50.3)	(45.1)	(42.9)
#2 wire (bottom)			
Down at Roll	37.6	29.7	
Counter blades and opposite CIVB 1,2	4.3	12.6	39.3
Transfer Box	4.5	3.7	4.5
Total #2 wire drainage	(46.4)	(46.0)	(43.8)
Flow Splits (gpm/in)	**(gpm/in)**	**(gpm/in)**	**(gpm/in)**
#1 wire (top)			
Over Roll	33.8	26.8	24.7
CIVB #1	9.6	12.2	3.8
CIVB #2	1.9	3.9	1.5
Total #1 wire drainage	(45.3)	(42.9)	(30.0)
#2 wire (bottom)			
Down at Roll	33.8	28.2	-
Counter blades and opposite CIVB 1,2	3.9	12.0	27.5
Transfer Box	4.0	3.5	3.2
Total #2 wire drainage	(41.7)	(43.7)	-

Table B3. Drainage at various locations on the pilot former.