Pressure drop measurements in dry-formed wood fiber webs

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ABSTRACT *Pressure drops across air-formed webs were measured to assess the effects of adding wood fiber of different fiber lengths to an air-forming unit. Wood pulp with a fiber length of 0.78 mm was used with web basis weights in the range of 27–422 g/m². A shorter fiber, 0.4–0.43 mm, was also tested in the basis weight range of 22–252 g/m². Relationships are presented that define the correlation between pressure drops across the webs with fiber length. Pressure drop proportionalities closely approximated the drag coefficient for cylinders.*

KEYWORDS
Air flow
Dry forming
Fiber
Pressure gradient
Softwood pulp

The pressure drop across the fiber web constitutes a substantial part of the pressure requirements of a dry-forming web-laying system. As shown in **Fig. 1**, the pulp fiber web ranges in thickness from zero on the back side up to the thickness of the final basis weight on the front side. For a linear increase in web thickness, the measured pressure drop across the forming zone should be approximately half of the value that would be observed for a web of the final basis weight. This pressure drop usually supplies up to 50% of the total energy requirements in the gas transport system. The work of Garner and Kerekes (*1*) is the only previous study related to the aerodynamic characterization of wood pulp fibers. Their results provide information on the bulk packing of dry fiber with application to fiber preparation and feeding systems.

In recent work on a forming system in our laboratories (*2*), we have observed that approximately 5-10% of the fiber passes through the forming wire in the form of pulp fines. This fiber, which is usually shorter than freshly milled pulp, could be continuously cycled back into the process and mixed with freshly milled fiber. The effect of this type of recycle stream on the pressure drop across dry formed webs was also studied.

Flow through porous media

Pressure drop for air-formed webs of wood pulp is characterized as a type of flow through porous media. Basic models describing such flow are divided into two classes (*3*):

1. Channel model: describing flow through a series of tortuous channels
2. Drag model: describing flow as affected primarily by drag.

Channel model

In the channel model, the packed bed array provides a series of equivalent hydraulic diameters for the fluid flow. This class of porous media includes regular bed packings such as spheres and berl saddles. The porosity (fraction of the bed volume unoccupied by packing) for such systems is usually 0.4 or less. The pressure drop for this case is given by the Ergun equation (*4*).

$$\Delta P/L = (150\mu V_s/D_p^2)(1-\epsilon)^2/\epsilon^3 + (1.75\rho V_s^2/D_p)(1-\epsilon)^2/\epsilon^3 \quad (1)$$

where

V_s = the superficial velocity through the bed

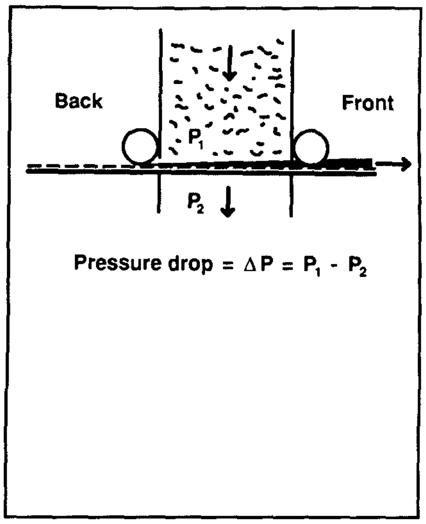
D_p = the equivalent diameter of a packing particle

ϵ = the void fraction of the packed bed.

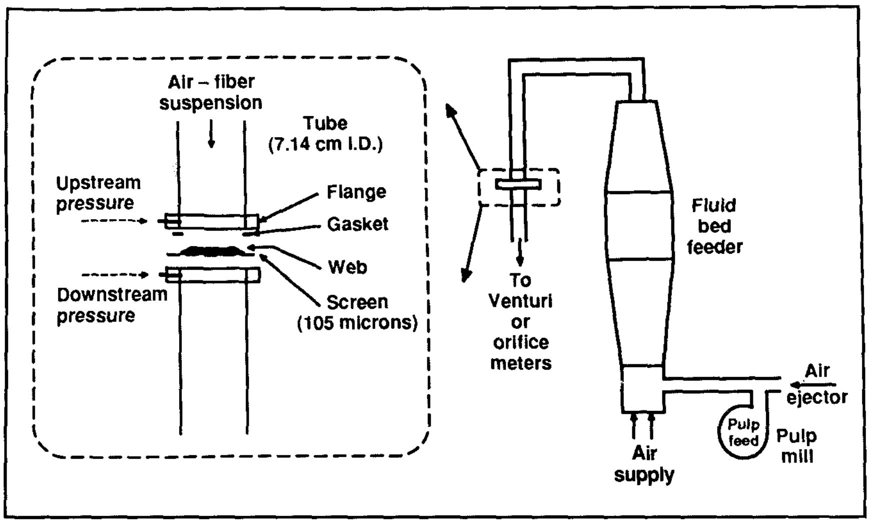
The superficial velocity is related to the velocity approaching the packed bed, V_0, by the equation $V_s = V_0/\epsilon$.

The first term on the right-hand side accounts for a laminar flow regime and is commonly called the Blake-Kozeny or Carman-Kozeny equation. The second term applies to the turbulent regime of flow through packed beds and is called the Burke-Plummer equation. The hydraulic diameter principle employed in developing the Carman-Kozeny equation is inappropriate for laminar flow; however, this type of correlation describes data well and has been widely applied (*5*). The Carman-Kozeny equation has also been applied successfully to studies of the permeability of paper handsheets (*6*). Garner and Kerekes (*1*) have employed similar principles in characterizing the aerodynamic properties of dry wood pulp fiber.

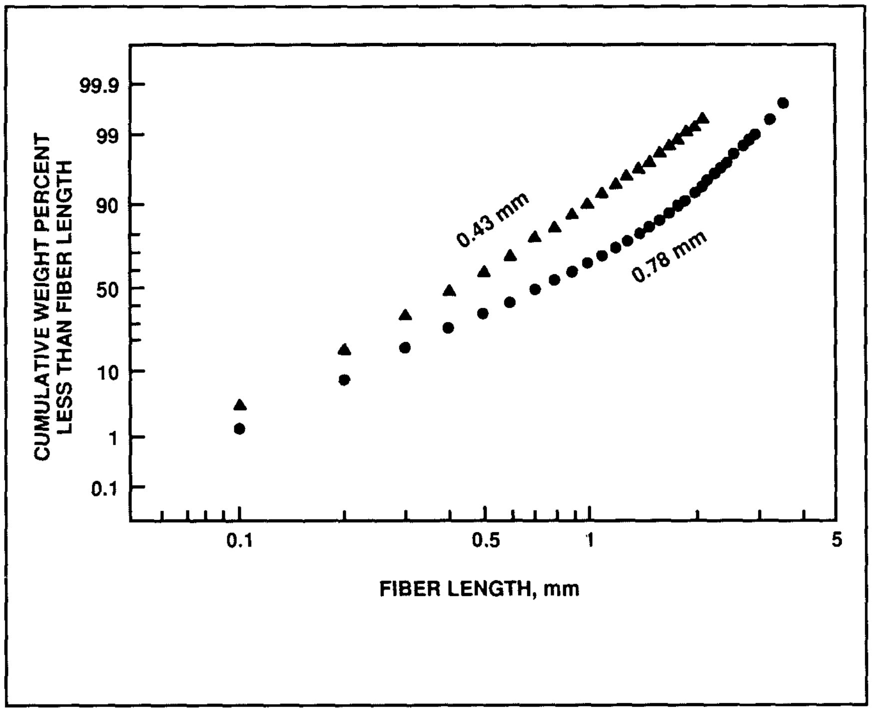
1. Diagram of a dry-forming web-laying system



2. Diagram of the system for testing pressure drop



3. Fiber length analysis for the softwood fiber used (Kajaani analysis)



Drag model

In fibrous beds of particles, the total drag force has been modeled as flow over discrete particles. This approach takes drag as the predominant form of flow dynamics and is employed where the void space is much higher than in the channel model. If we consider the fiber elements of a dry-formed web as a series of circular cylinders of diameter D_p in a fluid of density ρ and viscosity μ, we can express the drag force per unit cylinder length as

$$F_c = 0.5\, C_c \rho V_s^2 D_p \qquad (2)$$

where

F_c = drag force per unit cylinder length

C_c = drag coefficient for a cylinder.

This drag coefficient is expected to be a function of the Reynolds number (*7*):

$$N_{Re} = D_p \rho V_s / \mu \qquad (3)$$

The total drag force of interest here is the pressure drop across a dry-formed web of thickness L_f:

$$F_f = -\Delta P / L_f \qquad (4)$$

Accurate measurements of the web thickness may also be difficult to determine, but for thin webs we might assume that the web thickness L_f is proportional to the basis weight W:

$$L_f = k\, W \qquad (5)$$

where

k = a proportionality constant.

Hence, a drag coefficient across a pulp web with an average fiber length len_f can be expressed as

$$C_f = (2 \Delta P len_f \varepsilon^2) / \rho\, V_0^2\, k W D_p \qquad (6)$$

For a given wood species, the fiber diameter will be relatively constant, but the fiber length can depend on the method of preparing the fiber.

We measured pressure drops across relatively thin beds of wood pulp fiber to develop a method of characterizing pressure drops in terms of on-line measurements or simple, rapid, off-line test methods for dry forming. The measurements we made included basis weight, air flow rates, pressure drops, and fiber length. Detailed measurements of fiber diameter and porosity were not performed. A basis weight range of 25-400 g/m² was used as a target value with air velocities up

I. Pressure drop and velocity data for fiber lengths of 0.78, 0.43, and 0.4 mm

Basis weight, g/m²	Test section velocity, m/s	Pressure drop, kPa	Normalized pressure drop, kPa mm/(g s²)
		0.78 mm	
27.2	3.70-23.2	0.269-5.34	0.000569-0.001130
29.6	6.39-24.6	0.904-7.21	0.000627-0.001166
39.5	6.88-22.3	1.47-8.94	0.000710-0.001227
59.2	5.21-20.6	1.17-9.40	0.000583-0.001133
62.5	2.49-9.76	0.274-2.15	0.000565-0.00110
106	4.51-15.9	1.46-9.52	0.000556-0.001054
122	0.293-7.89	0.0483-3.36	0.000687-0.00718
123	4.09-17.2	1.27-10.7	0.000453-0.000961
138	3.18-15.4	1.02-11.6	0.000552-0.001138
232	0.199-8.04	0.0632-6.28	0.000652-0.0108
264	3.14-11.6	1.87-13.1	0.000576-0.001124
295	0.198-0.754	0.0738-0.358	0.00333-0.00999
370	2.61-10.3	1.45-13.8	0.000545-0.001028
375	2.60-9.61	2.34-14.0	0.000632-0.001447
422	2.60-8.68	2.33-14.2	0.000697-0.001280
		0.43 mm	
21.9	5.22-24.4	0.394-7.13	0.000471-0.000803
29.6	4.53-22.3	0.648-8.21	0.000468-0.000895
32.1	5.22-22.2	0.895-8.11	0.000443-0.000880
64.2	3.15-15.5	1.16-11.9	0.000661-0.00156
92.6	3.15-14.9	1.05-12.2	0.000510-0.000982
93.6	2.61-13.3	0.897-12.6	0.000654-0.00121
94.1	2.61-14.0	0.857-12.5	0.000585-0.00115
252	2.59-8.09	2.71-12.5	0.000714-0.00138
		0.4 mm	
42.5	0.225-7.73	0.00253-1.55	0.000487-0.00944
82.5	0.137-0.806	0.0612-0.374	0.00559-0.0317
170	0.197-0.806	0.148-0.777	0.00563-0.0180
175	0.167-0.807	0.122-0.761	0.00534-0.0200
187	0.200-6.85	0.121-4.85	0.000441-0.0128
195	0.183-7.07	0.120-4.86	0.000399-0.0147
202	0.181-0.808	0.140-0.580	0.000351-0.0125
222	0.215-4.84	0.157-4.29	0.000657-0.0122

Pressure drop = $2 \Delta P \, len_f / W V_0^2$

to 25 m/s in the forming zone. Tests were also performed with a shorter wood fiber of the same species to assess the effect of adding pulp fines of different fiber lengths to an air forming unit.

Experimental methods

The fiber and air flow system was a closed loop arrangement as diagrammed in **Fig. 2**. Air was supplied at room temperature by a blower (at 1775 rpm) with a maximum volumetric flow rate of 0.354 m^3/s and a delivery pressure of 17.4 kPa. The fiber was bleached softwood kraft pulp (black spruce), defibrillated with a Sybron-Brinkman ZM-1 laboratory cutting device. The mill was operated with a six-tooth rotor at a rotor speed of 20,000 rpm. A longer fiber was produced using 3-mm sieve screens in the mill.

A typical fiber length distribution for the pulp prepared in this fashion as measured by a Kajaani analyzer is shown in **Fig. 3**. The average fiber length for this distribution was 0.78 mm. The variation in fiber length produced by this type of milling device over a longer period of time is usually ±20% (*8*). We used two methods to obtain shorter fibers to act as pulp fines:

1. Collection of pulp fines from previous air-forming tests. This fiber had passed through the wire on our web-forming system during ongoing test programs. A fiber length distribution for this fiber as tested by a Kajaani analyzer is also shown in Fig. 3. The average fiber length from this analysis was 0.43 mm.
2. Production of additional, shorter fibers with a 0.5-mm-sieve screen in the milling unit. Previous experiments with this screen and the same pulp species produced average fiber lengths of 0.4 mm (*9*).

The fiber-air suspension from the mill was directed to an air ejector and fed to the mixing chamber. The air flow rate through the ejector, usually 0.01 m^3/s, was measured by an orifice meter. As shown in Fig. 2, the blower air was mixed with the incoming fiber-air suspension in a mixing chamber, and this suspension left the top part of the chamber. The fiber-air suspension flowed horizontally then vertically downward, and the milled pulp was laid on a 105-μm-mesh wire screen in a smooth-wall aluminum tube with an inside diameter of 7.14 cm.

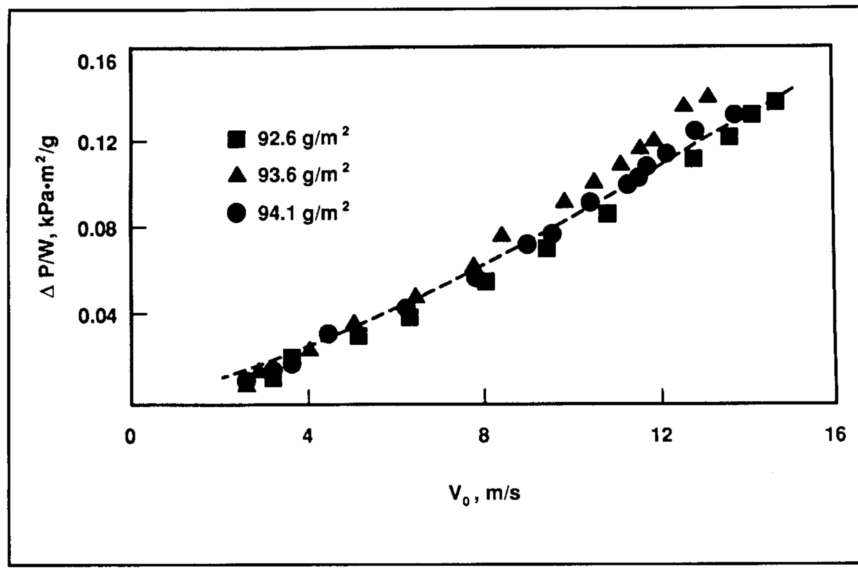
Separate pressure drop tests were performed on this forming screen to provide a correction to the true pressure drop. The pressure drop across this screen by itself was less than 10% of that observed in any of the webs examined in this study. The downstream side of this web collection unit was connected to the suction side of the blower. Scanning electron microscope observations on several random samples of both fiber and fines indicated that the diameter of the softwood pulp fiber used (usually 15 μm) was not substantially different from that of the pulp fines.

Pressure drop readings across the forming wire and dry-formed webs were made with two Datametrics Barocell transducers (25.4 and 254 cm H_2O) with a 0-10 V output to a Hewlett-Packard Model 5328A integrating voltmeter. Measurements of high flow rates, in the range of 3–25 m/s upstream of the forming section, were made with a venturi meter, while low readings, 0.2–10 m/s, were made with an orifice metering system. The overlap in these ranges allowed for a check on the consistency of flow rate measurements. Pressure was measured upstream of the web-forming section and across the venturi and orifice meters with Meriam fluid manometers (Meriam fluid specific gravity = 1.75).

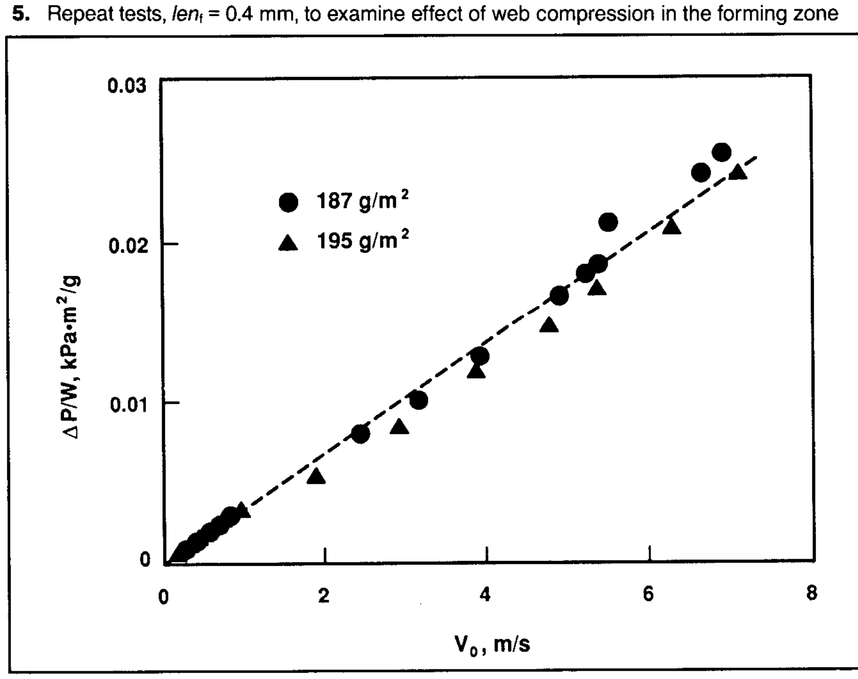
The dry-formed webs were prepared for pressure drop tests by feeding the appropriate amount of baled pulp to the mill and subsequently forming it on the wire screen in the test section. The pulp fines collected from previous runs were fed through the mill without a milling screen present and were formed in a web in the same manner. Tests were performed on 15 samples of dry-formed pulp in the basis weight range of 27–422 g/m³ and on 16 samples of fines in the range of 22–252 g/m². After preparing the sample in the web test section, we let the system run for several minutes to ensure that all fibers were retained on the forming screen. The air flow rate was then adjusted over a desired range for each test; in addition, the air flow rate was adjusted both up and down as a check for any hysteresis effects or temporary compression of the webs under different pressure drop conditions.

At the end of each test, the web and forming screen were removed from the web collection system, dried in an oven at 105°C, cooled in a desiccator, and weighed to provide an estimate of the final basis weight. Each test web was examined for formation over a light table, and the results for any webs exhibiting an uneven fiber distribution or pulp flocs were discarded.

4. Repeat tests for pressure drop with basis weight of 92–94 g/m² and len_f = 0.43 mm



5. Repeat tests, len_f = 0.4 mm, to examine effect of web compression in the forming zone



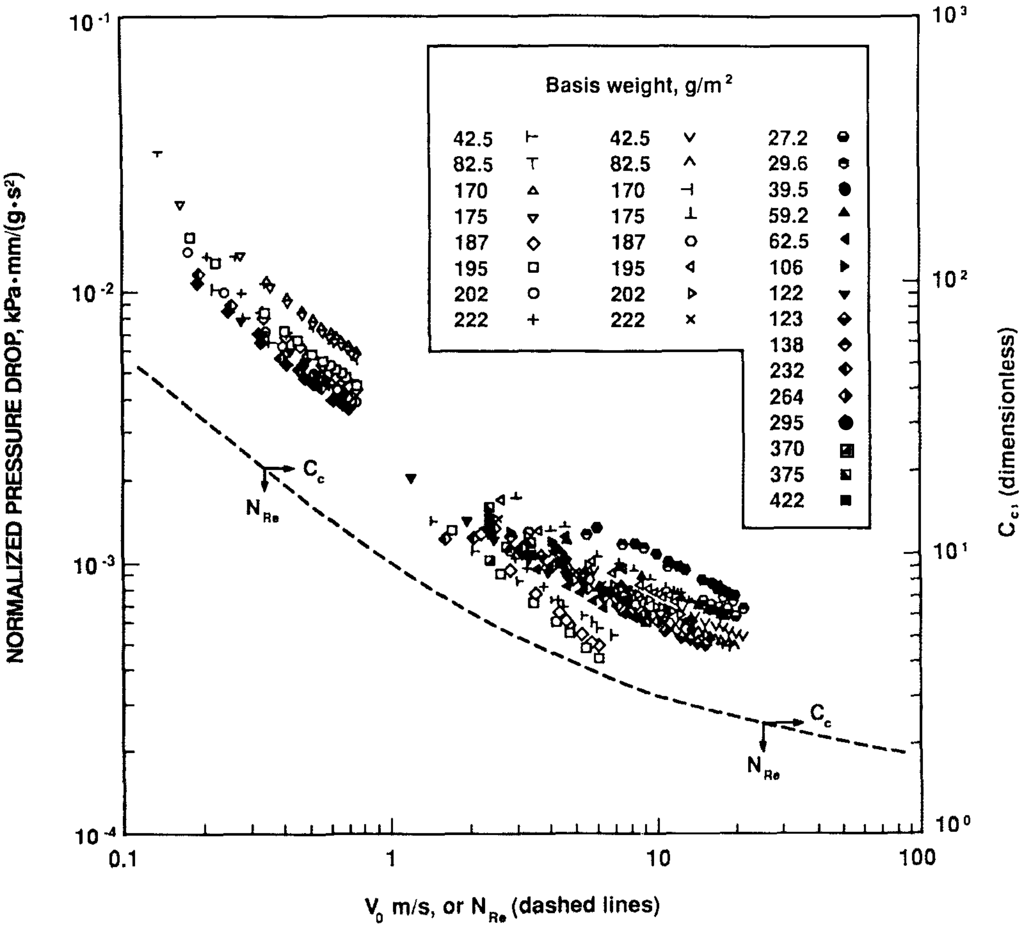
Results

The ranges of the primary results for the pressure drop tests are shown in **Table I** for the three different fiber lengths, 0.78, 0.43 and 0.4 mm. The test section velocities were chosen to correspond closely to the range of interest on our pilot forming system, usually 3–20 m/s. Tests were also performed at lower flow rates to include data for laminar flow through the air-formed webs. The basis weight range for the pulp fiber with len_f = 0.78 mm was in the range of 27–422 g/m²; for the shorter fibers, len_f = 0.43 and 0.4, the basis weight was 22–252 g/m². Several tests were also chosen at similar basis weights to act as a check on the magnitude and sources of experimental error.

The pressure drop across three webs with a basis weight in the range of 92–94 g/m² with fiber length of 0.43 mm is shown in **Fig. 4**. The pressure drop for these results is expressed as the measured pressure drop normalized with respect to the web basis weight. These tests were performed independently by forming a new web for each test. The results demonstrate that there is usually more scatter between repeat runs than there is within each test at a particular basis weight.

Webs were formed with the air flow system set to an intermediate flow rate with pressure drop measurements taken at higher and lower values as desired. To examine any permanent compressive effect on the

6. Pressure drop across air-formed webs for various basis weights and fiber lengths (data points) and the drag coefficient for flow over a cylinder (dashed line)



webs, tests were also performed by starting at low and high air flow rates in the forming step of the sample webs. Shown in **Fig. 5** are the results of these tests in which webs with basis weights of 187 and 195 g/m² were formed at high and low air flow rates, respectively. The pressure drop tests were then performed by increasing the test section velocity from 0.2 m/s to 8 m/s for the 187-g/m² web and decreasing the air flow rate over the same range for the 195-g/m² web.

This type of test should not be regarded as a repeat run similar to that which produced the data in Fig. 4. Data in Fig. 5 were obtained during a single test session and, hence, might show less variability in fiber preparation, air flow rate measurement error, etc. The scatter in the data in Fig. 5 for the two test conditions approximates that depicted in Fig. 4 for the repeated tests. Therefore, any compressive effect of the webs in this basis weight range was considered to be small relative to other errors associated with the measurements in this work.

The primary results of the tests include pressure drop measurements for pulp webs at selected basis weights, fiber lengths, and air velocities in the forming zone of the test apparatus depicted in Fig. 2. The data can be presented most easily in the form:

$$2\Delta P len_f / (W V_0^2) = C_f \rho D_f k/\epsilon^2 \quad (7)$$

as a function of the test section velocity,

$$V_0 = N_{Re}\mu\epsilon/(D_f\rho) \quad (8)$$

where

N_{Re} = Reynolds number based on a fiber diameter.

The data presented in this form are shown in **Fig. 6** for all the test conditions noted in Table I. Data for the longer fiber, 0.78 mm, are presented with shaded or partially shaded symbols, while the shorter fiber lengths, 0.43 and 0.4 mm, are displayed with unshaded symbols. Data for each basis weight follow a consistent pattern for each test with a greater variation between runs and for different fiber lengths. The friction factor curve for a cylinder (*7*) is also presented in Fig. 6 for comparison with the trends in our results. Note that the factor $\mu\epsilon/D_f\rho$ is close to unity for the case in which $D_f \cong 15\mu m$, $\epsilon \cong 0.8$ and fluid properties for air. Hence, the numerical values for the velocity axis depicted in Fig. 6 correspond closely to those of a dimensionless Reynolds number for a cylinder with a diameter similar to that of the fiber used in this study.

Correlating equations in dimensional form for the longer fiber (0.78 mm) and shorter fiber (0.43 and 0.4 mm) in the flow regimes of 0.2-1 m/s and 1-25 m/s are:

len_f = 0.78 mm and $0.2 \leq V_0 \leq 1$ m/s:

$$\Delta P = 0.00175 W V_0^{1.22} \quad (9)$$

len_f = 0.4 and 0.43 mm and $0.2 \leq V_0 \leq 1$ m/s:

$$\Delta P = 0.00442 W V_0^{1.15} \quad (10)$$

len_f = 0.78 mm and $1 \leq V_0 \leq 25$ m/s:

$$\Delta P = 0.000857 W V_0^{1.77} \quad (11)$$

len_f = 0.4 and 0.43 mm and $1 \leq V_0 \leq 25$ m/s:

$$\Delta P = 0.00181 W V_0^{1.77} \quad (12)$$

The units for each term in these equations are: kPa for ΔP, g/m² for W, and m/s for V_0.

The drag coefficient for a cylinder at low Reynolds number is of the form

$$C_c \propto N_{Re}^{-0.8}$$

The drag coefficient is

$$C_c \propto N_{Re}^{-0.3}$$

for $10 < N_{Re} < 1000$. This would suggest that $\Delta P \propto V_0^{1.2}$ at low Reynolds number and $\Delta P \propto V_0^{1.7}$ at higher Reynolds numbers. Our results are in reasonable agreement with these forms over the range of the data derived.

The fiber length measurements noted in Fig. 2 and the value of 0.4 mm for the fiber milled with the 0.5-mm screening system are intended to give representative estimates for the fiber used in this work. Previous work with this type milling system and the same type of softwood fiber produced a standard deviation of 0.084 mm for a fiber length in the range of 0.1-0.77 mm (*8*). With this type of error, we can thus expect that the data shown in Fig. 6 would be subject to errors of approximately ±20%. The assumption that porosity is constant may not be fully justified for the range of fiber lengths examined. However, the porosity is expected to be approximately 0.7 (*1*), and errors associated with the constant porosity assumption should be on the order of 5-10%. Other measurements, including flow rates, basis weights, and pressure readings were performed carefully, with experimental error of 2% or less.

The correlating relations for the pressure drops and the data depicted in Fig. 6 indicate that the flow rates of $V_0 < 1$ m/s correspond to a viscous flow region through the webs, while data above this range are in the region where inertia effects start to dominate. These two regions were explored experimentally, but the lower range was limited by the sensitivity of our instrumentation, and the higher range was restricted by the pressure capabilities of our blower system. The results indicate that adding fines to standard milled fiber will produce a higher pressure drop that is roughly proportional to the fiber length of the fines and the amount added to the fiber feed.

Conclusions

Pressure drop measurements have been made in air formed webs of pulp fiber with fiber lengths of 0.4, 0.43, and 0.78 mm. The range of air flow rates included the viscous flow regime, usually 0.2-1 m/s, through to the start of the regime where inertia effects are important at velocities up to 25 m/s. The pressure drop relations were proportional to $V_0^{1.7}$ at lower velocities and $V_0^{1.2}$ at higher velocities, in general agreement with the form for the drag coefficient over a cylinder.□

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