Fluid Flow Through Woven Screens

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A packed bed model has been adopted to develop a general correlation applicable to the flow of Newtonian fluids through all types of woven metal screens. Both of the main theoretical approaches to studying pressure drop in packed systems have been used by visualizing the screen as a collection of submerged objects with surface area to unit volume ratio a for laminar flow, and as a bundle of tubes of diameter D for turbulent flow. In the usual manner viscous and inertial energy losses are added to give an expression for the total pressure loss. Rearrangement of the general equation to the form of a friction factor yields a unique definition of the Reynolds number for screens $N_{Re} = \rho u/\mu a^2 D$. Procedures are described for collection of pressure drop-velocity data for the flow of nitrogen and helium through plain square, full twill, fourdrinier, plain dutch, and twilled dutch weaves. The data are used to derive a viscous resistance coefficient $\alpha = 8.61$ and an inertial resistance coefficient $\beta = 0.52$. The validity of the correlation equation is tested by using additional data from the literature. The correlation successfully predicts pressure drop for a Reynolds number range of 0.1 to 1,000, void fractions from 0.35 to 0.76, screen pore diameters from 5 to 550 μ, mesh sizes from 30 to 2,400 wires/in., and surface area to unit volume ratios from 1,200 to 29,000 ft.$^{-1}$.

The flow of fluids through screens is important in many chemical engineering problems such as design of filters, thickeners, paper machines, coalescers, etc. The motivation for this work was the fact that there does not exist for the design engineer a general correlation to predict pressure drop across all types of screen weaves.

Several investigators have developed pressure drop correlations for a few specific and limited screen flow systems. Flow through rectangular mesh weaves has been treated by Wieghardt (*1*) and Cornell (*2*) as being analogous to flow around submerged cylinders, and by Lapple (*3*) based on a parallel orifice model. In the first cases a loss factor and in the second case a discharge coefficient is related graphically to a Reynolds number with the fractional open area as a major parameter. The use of the open area as a correlating parameter makes these correlations not applicable to complex weaves such as twilled dutch, since dutch screens have no open area in the direction of flow.

Ingmanson et al. (*4*), departing significantly from previous investigators, recognized the three-dimensional character of screens by treating them as thin packed beds or porous media. In the resulting correlation relating a friction factor to a Reynolds number, the screen geometry was characterized by the surface area to unit volume ratio a and the void volume ϵ, thus avoiding the use of fractional open area. However, experimental verification of the correlation was limited to only one screen class, fourdrinier weave (that is, semi twill), and one fluid, water, and it falls short of predicting pressure drop for plain dutch or twilled dutch weaves. As the author points out, one of the reasons for the success of the correlation may be the relatively narrow range of void fractions from 0.61 to 0.68. However, in the final analysis the work of Ingmanson et al. must be considered a major advance in studying flow through screens, since the value of treating screens as a three-dimensional network was demonstrated for the first time.

THEORY

The complex pattern developed as a fluid flows through a screen precludes an exact solution of the equations of motion. Thus, one is forced to seek useful pressure drop correlations via a somewhat less complicated flow model for which theoretical equations can be derived. In this study the screen is treated as a very thin packed bed. The pressure drop through the screen is considered to be the sum of both viscous and inertial resistances. The viscous resistance predominates in the laminar flow region, where losses are attributable to viscous drag (skin friction at the surface of the screen wires) and form drag. At high flow rates the effects of the viscous forces are negligible, and the inertial losses are assumed to result from turbulent eddies and the losses due to sudden enlargement and sudden contraction of channel cross section.

In the laminar region, the system is assumed to behave as that of creeping flow around spherical particles. For the case of an isolated spherical particle of radius r immersed in an infinite continuous fluid, the drag force has been shown by Stokes (5) to be

$$F = 6 \pi \mu r u \tag{1}$$

When one considers the force to act independently on each sphere, then the total drag force becomes

$$F_T = \left[\frac{3(1-\epsilon)B}{4 \pi r^3}\right] 6 \pi \mu r u \tag{2}$$

where $3(1-\epsilon)B/(4 \pi r^3)$ is the number of particles in a bed of unit cross-sectional area and thickness B.

It is reasonable that in any closely packed system the flow pattern around the individual particles is influenced by interaction with neighboring particles. This interaction increases as the distance between the particles decreases. As a first approximation, a multiple of the solid volume fraction $C(1-\epsilon)$ is taken as a measure of the degree of interaction. The toatl resistive force now becomes

$$F_T = C(1-\epsilon)\left[\frac{3(1-\epsilon)B}{4 \pi r^3}\right] 6 \pi \mu r \left(\frac{u}{\epsilon}\right) \tag{3}$$

where u/ϵ is the actual free stream velocity within the packing.

The force on the fluid must be equal to that produced by a pressure drop Δp across the bed. Then, since the free cross section of fluid is equal to ϵ (6)

$$\Delta p g_c \epsilon = C(1-\epsilon)\left[\frac{3(1-\epsilon)B}{4 \pi r^3}\right] 6 \pi \mu r^3 \left(\frac{u}{\epsilon}\right) \tag{4}$$

Introduction of the relationship between a and r for spheres

$$a = \frac{3(1-\epsilon)}{r} \tag{5}$$

makes the expression general and applicable to nonspherical packings. Equation (4) becomes, after rearrangement

$$\frac{\Delta p g_c}{B} = \frac{\alpha}{\epsilon^2} \mu a^2 u \tag{6}$$

Highly turbulent flow through a screen can be looked upon as flow through parallel interconnecting channels of varying cross sections. As an approximation of the proposed physical mechanism, the pressure drop can be related to the flow conditions through a modification of the relations available for friction losses in circular ducts (7, 8). For this case, since the friction factor for turbulent flow in ducts is essentially a constant

$$\frac{\Delta p g_c}{B} = \frac{\rho \left(\frac{u}{\epsilon}\right)^2}{2D} 4 f_0 \tag{7}$$

where f_0 is taken as the value of the friction factor, and D is the effective channel diameter. Thus

$$\frac{\Delta p g_c}{B} = \frac{\beta}{\epsilon^2} \rho \frac{u^2}{D} \tag{8}$$

When the equations for laminar flow and turbulent flow are added together, the resulting equation is

$$\frac{\Delta p g_c}{B} = \frac{\alpha}{\epsilon^2} \mu a^2 u + \frac{\beta}{\epsilon^2} \rho \frac{u^2}{D} \tag{9}$$

An implicit assumption made in this development is that the path traveled by the fluid is equal to the thickness of the screen B. In the case of a very complex, tightly woven screen such as twilled dutch, the fluid path is very tortuous, and the length is longer than B. Therefore, the true fluid path length expressed as QB should replace B in Equation (9). Letting

$$L = QB \tag{10}$$

and rearranging Equation (9), we obtain the screen friction factor as

$$f = \frac{\Delta p g_c \epsilon^2 D}{L \rho u^2} = \frac{\alpha}{\frac{\rho u}{\mu (a^2 D)}} + \beta \tag{11}$$

where the ratio of the inertial to the viscous resistance has yielded

$$N_{Re} = \frac{\rho u}{\mu (a^2 D)} \tag{12}$$

The final form of the equation is

$$f = \frac{\alpha}{N_{Re}} + \beta \tag{13}$$

GEOMETRY OF SCREENS

The screens included in this study represent five different weave patterns. These patterns are grouped as either plain or dutch weaves and are schown schematically in Figure 1. As seen, the dutch weaves are tightly woven and have no open area in the direction of flow.

In the development of the theory, the geometry of the screen is characterized by the parameters B, a, D, and ϵ. Table 1 lists the values of these quantities for the eighteen screens studied.

The thickness of a screen was determined by averaging a number of micrometer readings taken at various points along its surface.

The void fraction was experimentally obtained by determining the weight m and the screen volume V of a sample screen section. The relationship $\epsilon = 1 - m/\rho_s V$ gives the void fraction.

Photomicrography was used to determine the pore diameter D for the plain weave screens. Where the opening was not square (for example, fourdrinier) a simple arithmetic average of width and length was used. For the tightly woven dutch weaves, the screen particle retention rating as specified by the screen manufacturer was used as an effective screen pore diameter.

Shown also in Table 1 are the nominal wire counts specified by the screen manufacturer and the actual wire counts, as well as the wire diameters determined by photomicrography.

The values of the surface area to unit volume ratio given in Table 1 were not determined experimentally but were calculated from the derived equations presented in Table 2. The equations for a are based on the assumptions that the wires are uniformly cylindrical and in point contact.

With the exception of the dutch weave pore diameters, all of the screen parameters are derivable from the screen wire dimensions, namely, the number of warp and shute wires per inch and the diameters of the warp and shute wires. These equations are presented in Table 2. Although good agreement was found between measured and calculated values of B, D, and ϵ, for correlation purposes measured values were used in preference to calculated values.

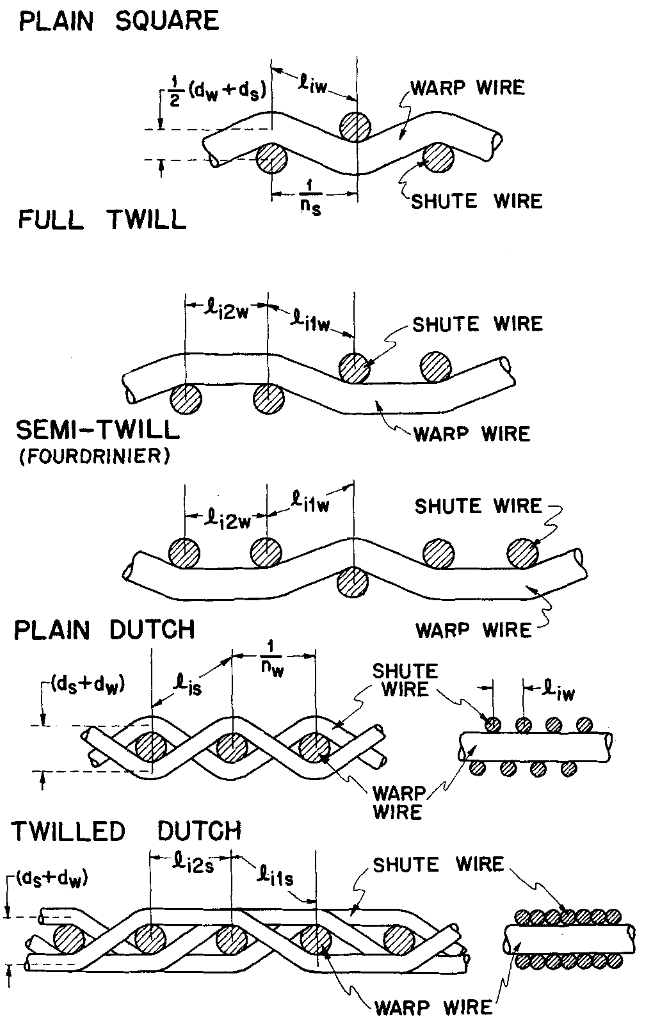

Fig. 1. Cross-sectional views of plain weave (plain square, full twill, and fourdrinier) and dutch weave (plain dutch and twilled dutch) screens.

EQUATION TO ESTIMATE TORTUOSITY FACTOR

In order to apply Equation (13), the tortuosity factor Q must also be known for each weave type. For the plain weaves the fluid path length and the screen thickness are essentially equal, so that $Q = 1$. The tortuosity factor for the dutch weaves can be estimated from a simple analysis of the weaving geometry.

If the shute and warp wires are assumed to be in point contact, the screen thickness is given by

$$B = \frac{1}{12}(2\ d_s + d_w) \tag{14}$$

and this represents the shortest path, L_1, a fluid element travels in passing through the screen. If there is no intercommunication between openings in the screen, the longest path, L_2, traveled by a fluid element can be estimated as the sum of one half the circumference of each of the wires making up the screen thickness; therefore

$$L_2 = \frac{1}{12}\left[\frac{1}{2}\pi\ d_s + \frac{1}{2}\pi\ d_w + \frac{1}{2}\pi\ d_s\right] \tag{15}$$

The nonweighted arithmetic average path length is

$$L = \frac{\frac{1}{12}\left[\left(\frac{1}{2}\pi\ d_s + \frac{1}{2}\pi\ d_w + \frac{1}{2}\pi\ d_s\right) + (2\ d_s + d_w)\right]}{2} \tag{16}$$

By definition $Q = L/B$; therefore

$$Q = \frac{\left(\frac{1}{2}\pi\ d_s + \frac{1}{2}\pi\ d_w + \frac{1}{2}\pi\ d_s\right) + (2\ d_s + d_w)}{2(2\ d_s + d_w)}$$

or

$$Q = \frac{\frac{\pi}{2} + 1}{2} = 1.28 \tag{17}$$

Table 1. Screen Geometry

Specified screen counts (wires/in.), n_w n_s	Measured screen counts (wires/in.), n_w n_s	Measured wire diameters (in. × 10^{-4}), d_w	d_s	Measured screen thickness (ft. × 10^{-4}), B	Measured void fraction ϵ	Measured pore diameter (ft. × 10^{-4}), D	Calculated surface area to unit volume ratio (ft.$^{-1}$), a
Plain square							
30 × 30	31 × 31	9.45	9.45	16.10	0.759	18.00	1,191
150 × 150	151 × 151	2.36	2.36	4.83	0.740	3.40	4,919
250 × 250	248 × 248	1.69	1.69	3.17	0.735	2.00	9,003
400 × 400	387 × 387	1.00	1.06	1.67	0.706	1.25	15,666
Full twill							
70 × 70	68 × 77	7.61	7.61	13.68	0.564	5.20	2,707
150 × 150	142 × 142	2.87	2.87	5.00	0.745	3.25	5,323
325 × 325	297 × 297	1.30	1.30	2.67	0.714	2.00	9,408
400 × 400	406 × 406	1.02	1.02	2.44	0.712	1.25	11,097
Fourdrinier							
56 × 32	55 × 32	9.45	13.80	26.30	0.688	10.00	1,181
65 × 44	63 × 43	7.87	10.60	19.90	0.676	8.80	1,547
75 × 62	76 × 60	7.00	7.50	14.20	0.634	6.40	2,249
80 × 72	79 × 62	7.61	7.86	12.60	0.633	6.30	2,832
Plain dutch							
24 × 110	24 × 113	14.50	9.80	25.40	0.575	3.40	2,015
30 × 150	30 × 152	8.80	6.90	17.30	0.624	2.83	2,583
50 × 250	51 × 257	5.50	4.28	10.00	0.592	1.84	4,622
Twilled dutch							
80 × 700	80 × 736	4.28	2.85	9.15	0.425	1.08	8,918
200 × 1,500	197 × 1,499	2.56	1.43	4.58	0.358	0.333	20,018
325 × 2,400	321 × 2,105	1.37	0.95	2.92	0.350	0.166	28,942

Table 2. Equations for Calculating Screen Geometric Properties

Screen	Thickness, B	Surface Area to Unit Volume ratio, a	Void fraction, ϵ	Pore diameter, D
Plain square	$\frac{1}{12}(d_s + d_w)$	$a = \frac{\pi n_s n_w}{B} [d_w l_{iw} + d_s l_{is}]$ where $l_{iw} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_s}\right)^2}$ and	$\epsilon = 1 - \frac{\pi n_s n_w}{48B} [d_w^2 l_{iw} + d_s^2 l_{is}]$ $l_{is} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_w}\right)^2}$	$D = \frac{1}{12} \sqrt{\frac{1 - n_s d_s - n_w d_w + n_s n_w d_s d_w}{n_s n_w}}$
Full twill	$\frac{1}{12}(d_s + d_w)$	$a = \frac{\pi}{2B} [n_s n_w l_{i1s} d_s + n_s d_s + n_s n_w l_{i1w} d_w + n_w d_w]$ where $l_{i1w} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_s}\right)^2}$ and	$\epsilon = 1 - \frac{\pi}{96B} [n_s n_w d_s^2 l_{i1s} + n_s d_s^2 + n_s n_w d_w^2 l_{i1w} + n_w d_w^2]$ $l_{i1s} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_w}\right)^2}$	$D = \frac{1}{12} \sqrt{\frac{1 - n_s d_s - n_w d_w + n_s n_w d_s d_w}{n_s n_w}}$
Fourdrinier	$\frac{1}{12}(d_s + d_w)$	$a = \frac{\pi}{3B} [n_s d_s + 2n_s n_w d_s l_{i1s} + n_w d_w + 2n_s n_w d_w l_{i1w}]$ where $l_{i1w} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_s}\right)^2}$ and	$\epsilon = 1 - \frac{\pi}{144B} [n_s d_s^2 + 2n_s n_w d_s^2 l_{i1s} + n_w d_w^2 + 2n_s n_w d_w^2 l_{i1w}]$ $l_{i1s} = \sqrt{\left(\frac{d_w + d_s}{2}\right)^2 + \left(\frac{1}{n_w}\right)^2}$	$D = \frac{1}{12} \sqrt{\frac{1 - n_s d_s - n_w d_w + n_s n_w d_s d_w}{n_s n_w}}$
Plain dutch	$\frac{1}{12}(d_w + 2d_s)$	$a = \frac{\pi}{B} [n_w d_w + n_s n_w d_s l_{is}]$ where $l_{is} = \sqrt{(d_w + d_s)^2 + \left(\frac{1}{n_w}\right)^2}$	$\epsilon = 1 - \frac{\pi}{48B} [n_w d_w^2 + n_s n_w d_s^2 l_{is}]$	—
Twilled dutch	$\frac{1}{12}(d_w + 2d_s)$	$a = \frac{\pi}{B} [n_w d_w + \frac{1}{2} n_s d_s + \frac{1}{2} n_s n_w d_s l_{i2s}]$ where $l_{i2s} = \sqrt{(d_w + d_s)^2 + \left(\frac{1}{n_w}\right)^2}$	$\epsilon = 1 - \frac{\pi}{48B} [n_w d_w^2 + \frac{1}{2} n_s d_s^2 + \frac{1}{2} n_s n_w d_s^2 l_{i2s}]$	—

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 2 is a schematic diagram of the screen flow apparatus used to collect nitrogen and helium pressure drop-flow rate data. The screen sample was held in a screen assembly which was in turn held in a flanged joint between two sections of a plexiglas flow tube. Details of the screen assembly complete with screen are also shown in Figure 2. Neoprene gaskets were used to seal the screen assembly to the flanged joint.

The velocity range from about 0.1 to 30 ft./sec. was covered with flow tubes of 2, 1, and 0.3 in. in diameter. The calming section was designed to allow for complete development of the flow upstream of the screen sample. The flow rate was measured by suitable rotameters.

The gas was fed into the system from a supply bottle and the flow regulated by a needle valve. The line pressure was measured at the entrance and exit of the rotameters. The temperature was metered at the exit of the rotameter with a dial thermometer. During all runs this temperature was 77° ± 2°F. Before it entered the calming section the gas passed through a filter, where any large dirt particles were removed. Pressure taps were located on both sides of the screen assembly. Manometer systems were used to measure the pressure drop. At low flow rates inclined manometers filled with methanol were used to magnify the pressure drops for precise readings. The exit gas was vented to the atmosphere.

The screen samples which covered five classes of screen types—plain square, full twill, fourdrinier, plain dutch and twilled dutch—were cleaned by scrubbing with a detergent solution and rinsing with distilled water and acetone. They were sealed firmly in the screen assembly with O rings. Pressure drop readings were taken at selected rotameter settings after the system reached equilibrium.

EXPERIMENTAL RESULTS

Pressure drop vs. velocity data were collected for nitrogen over the velocity range 0.1 to 30 ft./sec. and used to empirically determine the viscous and inertial resistance coefficients α and β and the tortuosity factor Q for dutch weave screens. With the aid of a computer values of α, β, and Q were obtained from a nonlinear, least squares, regression analysis on the log of the response variable f. The values of α and β were found to be 8.61 and 0.52, respectively. The tortuosity factor for the dutch weave screens was found to be 1.30, which compares favorably to the simple theoretical estimate of 1.28.

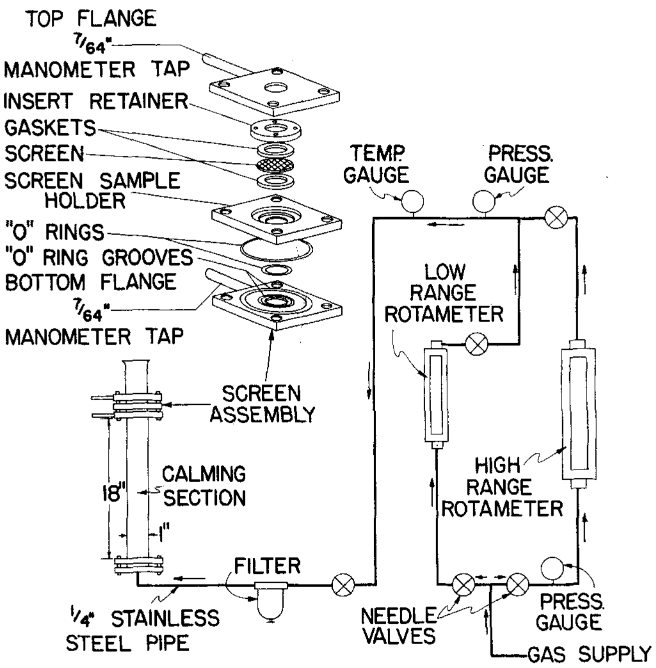

Fig. 2. Schematic of screen flow apparatus.

GENERAL CORRELATION

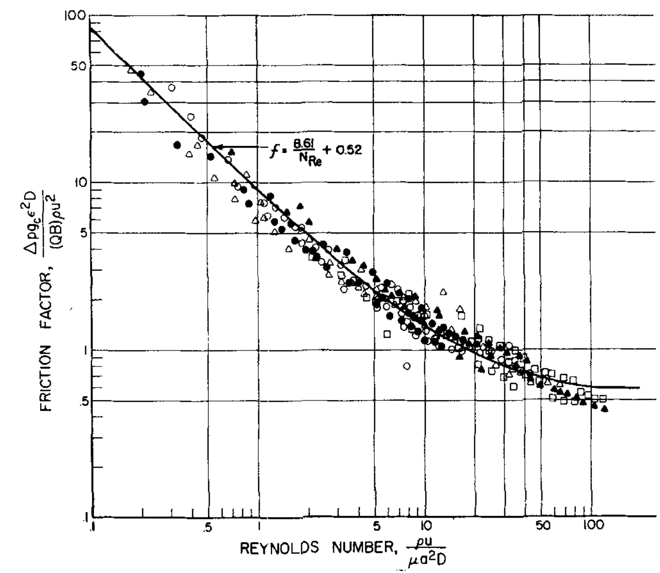

Fig. 3. Generalized screen flow correlation.

The correlation including constants is

$$f = \frac{8.61}{N_{Re}} + 0.52 \tag{18}$$

where

$$f = \frac{\Delta p g_c \epsilon^2 D}{QB\,\rho\,u^2}, \quad N_{Re} = \frac{\rho u}{\mu a^2 D}$$

and $Q = 1.0$ and 1.3 for plain and and "dutch" weaves, respectively.

Figure 3 shows a plot of Equation (18) together with data points for the eighteen screens representing five weave types. The correlation coefficient is 0.99.

To further validate the correlation, the data of Ingmanson (*4*) and Amneus (*9*) for flow of water through fourdrinier screens were plotted in accordance with the model. In addition, data were collected by the writers for flow of helium through plain dutch and twilled dutch screens, and the results are shown in Figure 4. Agreement between the experimental curve representing Equation (18) and these additional data is quite good.

The bulk of the water data of Ingmanson falls above the upper Reynolds number of about 100 obtained in the present work with nitrogen and extends the N_{Re} range to 1,000. Because Equation (18) is a two constant equation which has been extended tenfold outside the range for which the constants were determined, the fit of Ingmanson's data is acceptable. As a further check, a regression analysis similar to the one used to obtain α and β with the nitrogen data was applied to a combination of the nitrogen and water data of Ingmanson. The values of α and β were altered by less than 1 and 4%, respectively.

DISCUSSION

It should be emphasized that the theoretical approach taken here is just one of several which could be used in treating a screen as a three-dimensional packed bed or porous medium. For example, for both viscous and inertial losses the flow could be treated as flow past submerged spheres. Or, alternatively, for both flow regimes a capillary tube-bundle model could be used. In any case an expression for pressure drop per unit length analogous to Equation (9) results, but with different dependence on a, ϵ, and D in the two terms, and subsequently slightly different expressions for friction factor and Reynolds number. During the course of the research, several of these alternate theoretical approaches were investigated by examining f vs. N_{Re} plots similar to Figure 3. For each case the plot failed to correlate the nitrogen, helium, and water data for the five weave types.

It is concluded that visualizing a screen as a collection of submerged spheres with surface area to unit volume ratio a for laminar flow and as a bundle of tubes of diameter D for turbulent flow is an adequate and preferred model for flow through screens. This approach has led to a correlation which successfully predicts pressure drop for a Reynolds number range of 0.1 to 1,000, void fractions from 0.35 to 0.76, screen pore diameters from 5 to 550 μ, mesh sizes from 30 to 2,400 wires/in., and surface area to unit volume ratios from 1,200 to 29,000 ft.$^{-1}$.

SUMMARY

The success of Equation (18) in predicting pressure drop for such a diverse group of weave types has significant theoretical and practical implications. First, there exists the possibility of developing a similar correlation by a similar theoretical treatment for flow through grids, perforated plates, monofilament plastic screens, and possibly other materials made up of a well-ordered array of equisized holes. From a practical standpoint, Equations (9) and (18) or Figure 3 represent new predictive tools for the design engineer. For the first time, armed only with the manufacturer's specifications as to wire counts, wire diameters, aperture opening, and weave type, pressure drop can be predicted by a two constant equation.

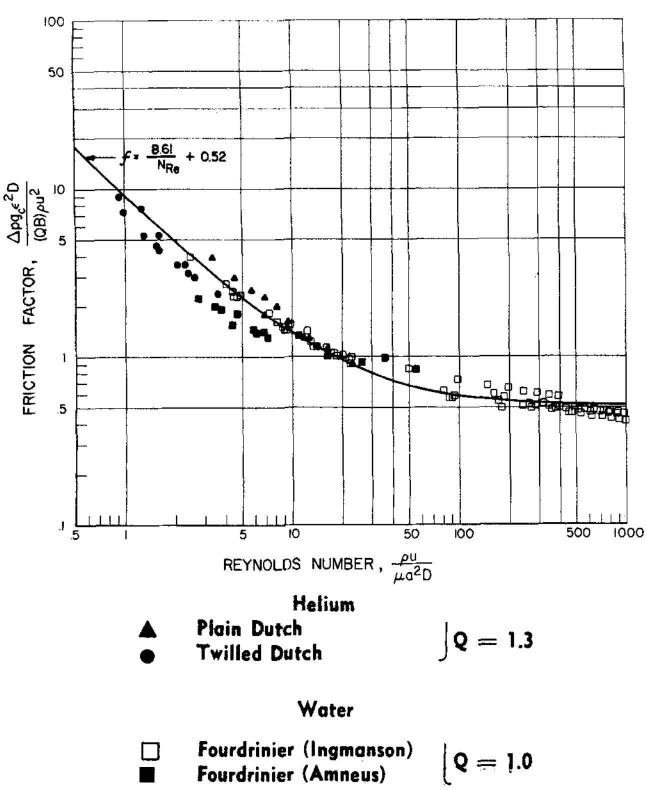

Fig. 4. Check of screen flow correlation.

ACKNOWLEDGMENT

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NOTATION

a = surface area to unit volume ratio of screen wire, ft.$^{-1}$
B = screen thickness, ft.
C = constant
d_s = diameter of shute wire, in.
d_w = diameter of warp wire, in.
D = screen pore diameter, ft.
f, f_0 = friction factor
F = drag force on single submerged sphere, lb.$_m$ ft./sec.^{2}
F_T = total drag force on a collection of submerged spheres, lb.$_m$ ft./sec.^{2}
g_c = dimensional conversion constant, lb.$_m$ ft./lb.$_f$ sec.^{2}
l_{iw}, l_{i1w}, l_{i2w} = length of warp wire segment, in.
l_{is}, l_{i1s}, l_{i2s} = length of shute wire segment, in.
L_1 = estimate of shortest path traveled by fluid element, ft.
L_2 = estimate of longest path traveled by fluid element, ft.
L = fluid path length, ft.
m = weight of screen sample, lb.$_m$
n_s = number of shute wires, wires/in.
n_w = number of warp wires, wires/in.
N_{Re} = Reynolds number
Δp = screen pressure drop, lb.$_f$/sq.ft.
Q = tortuosity factor
r = radius of equivalent sphere, ft.
u = fluid approach velocity, ft./sec.
V = volume of screen, cu.ft.

Greek Letters

α = viscous resistance coefficient
β = inertial resistance coefficient
ϵ = screen volume void fraction
μ = fluid viscosity, lb.$_m$/ft.sec.
ρ = fluid density, lb.$_m$/cu.ft.
ρ_s = density of wires making up screen, lb.$_m$/cu.ft.

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