A New Technique to Study Foam Flow in Porous Media: Radial Flow in Fibrous Mats

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Foam flow through fiber networks falls into the general subject of fluid flow through porous media. In addition, foams are used in enhanced oil recovery operations where their low mobility in porous media makes them effective in controlling the flow of steam or CO_2. Our work was motivated by problems in coating fibrous materials where foam is found to be an excellent vehicle for delivering small amounts of fluid to the fiber surfaces. With conventional coating using bulk fluids, complete coating of the fibers is only achieved when the fibrous material is saturated, which means that significant amounts of liquid must be evaporated during drying. Since the foam may be 95% gas by volume, the energy required in the drying step is minimized.

The initial objectives of this work were to develop a suitable experimental apparatus to study foam flow, and to develop a mathematical model of the experiment from which foam mobility could be obtained. The apparatus produces radial spreading of a foam front in a fiber network as a function of time under a constant driving pressure. A radial flow geometry was selected because the resulting pressure gradient depends on radial position, as opposed to a linear geometry in which the pressure gradient is constant along the length of the porous medium. As will be seen later, a continuously varying pressure gradient allows us to characterize the mobility of the foam in the fiber network as a function of pressure gradient from a single experiment.

The apparatus is a modified version of a radial spreading apparatus used at the Textile Research Institute to study high viscosity resin flow in fabrics (Adams and Rebenfeld, 1987). The device, shown schematically in Figure 1, consists of a foam reservoir and the porous medium test cell. In addition, the apparatus includes an external foam generator and a video recorder (not shown). The foam of controlled gas volume fraction is generated externally in an Oakes mechanical foam generator (Oakes Machine Corp., Islip, NY), and flows into a reservoir that is pressurized to maintain a constant driving pressure in the radial flow cell. Since foams with high gas volume fractions were studied, there was minimal liquid drainage from the foam in the reservoir over the time scale of a single experiment.

In the radial foam spreading experiment, the fibrous material is placed between two 25.4 mm thick clear acrylic plates and compressed to the desired thickness. For the work discussed here, Fiberglas insulation was chosen as the porous medium because the porosity of a specimen can be varied simply by changing its thickness by compression. Square specimens were 144 cm^2 mm in area, with a hole 5 mm in radius cut in the center of the mat as the inlet hole for foam injection. Clear acrylic plates were used so that the radial position of the moving foam front could be recorded on videotape.

The measurement involved the following sequence of events. The sample was compressed to a desired thickness by regulating the gas pressure delivered to four double-acting pneumatic cylinders (maximum rating 1,700 kPa each). Foam was fed from the generator into the reservoir to fill the reservoir at least half full. The foam quality or volume fraction of gas (approximately 90%) and bubble size were controlled by varying the liquid flow rate, the gas flow rate, and the agitation speed of the mechanical mixer. The liquid phase consisted of a 2 wt. % solution of nonionic surfactant (Tergitol NP-10, Union Carbide Corp.) in water. The reservoir was pressurized with air to the desired driving pressure. When the injection valve was opened the foam spread radially through the glass fiber mat, and the process was recorded with a video camera. Numerical data for the radial position of the foam front as a function of time were subsequently read from the videotape.

It is observed for these high gas volume fraction foams that the front spreads to a certain radial position and then stops. This observation is particularly important because it allows us to observe the minimum (or critical) pressure gradient below which the foam will not move. The critical pressure gradient $(dp/dr)_o$ and the foam mobility m characterize the interaction between the foam and the porous structure and are the two

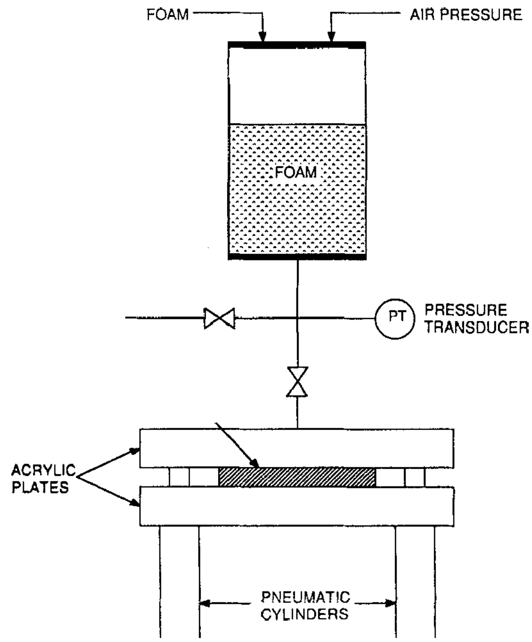

Figure 1. Compression device and foam-injection reservoir.

$$v_o = -m\left[\frac{dp}{dr} - \left(\frac{dp}{dr}\right)_o\right] \quad \left|\frac{dp}{dr}\right| > \left|\left(\frac{dp}{dr}\right)_o\right|$$
$$v_o = 0 \quad \left|\frac{dp}{dr}\right| \le \left|\left(\frac{dp}{dr}\right)_o\right| \qquad (1)$$

The analysis governing the flow of foam through a porous medium can be summarized as follows. Using the modified Darcy's law and applying the continuity equation, we derive Eq. 2 describing the radial position of a foam front R_f as a function of time t:

$$\frac{dR_f}{dt} = m\left[\frac{(p_o - p_f) + (dp/dr)_o(R_f - R_o)}{\ln(R_f/R_o)}\right]\frac{1}{\epsilon R_f}$$

where $(dp/dr)_o$ is the critical pressure gradient, m is the foam mobility, p_o is the pressure at the center injection hole of radius R_o, p_f is the pressure at the advancing front, and ϵ is the mat porosity. When the pressure gradient in the radial direction falls below the critical pressure gradient, the foam front ultimately stops at a position R_f^{eq} given by

$$\left(\frac{dp}{dr}\right)_o = \frac{p_o - p_f}{R_o - R_f^{eq}} \qquad (3)$$

The equations are derived assuming incompressibility. The pressure drops in our experiments are less than 50 kPa, so the foam is reasonably approximated as incompressible.

Several experiments were performed in which various driving pressures p_o were set, and the positions at which the foam front stopped, R_f^{eq}, were measured. These results are plotted in Figure 2; the slope of the least-squares line through the data provides an estimate of $(dp/dr)_o$.

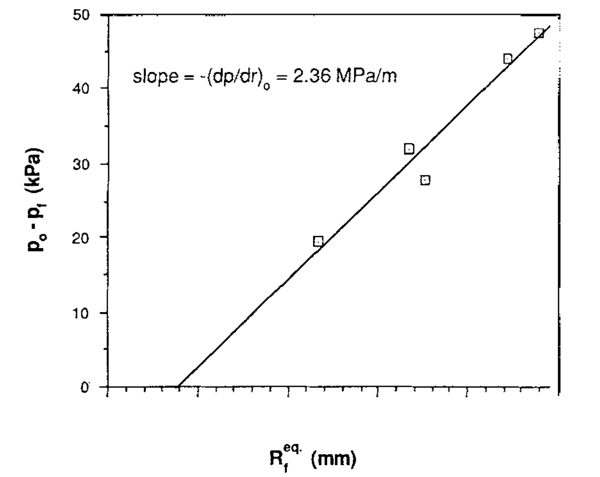

Figure 2. Plot of experimental data to obtain value for $(dp/dr)_o$.
Linear correlation of experimental data indicates a relatively constant $(dp/dr)_o = -2.36$ MPa/m

Once $(dp/dr)_o$ is known, the only unknown parameter in Eq. 2 for the time dependence of the position of the fluid front is the foam mobility m. Therefore, by choosing values for m, numerically integrating Eq. 2, and comparing the numerical results with experimental data (R_f vs. t), the best-fit value of the foam mobility can be obtained. An example of this analysis is shown in Figure 3. The results of the numerical integration for three values of foam mobility are shown, along with the experimental data for a typical foam flow experiment. It is evident that a value of m of 9.87×10^{-10} $m^3 \cdot s/kg$ (or 1 Darcy per centipoise) most closely fits the experimental data. It should be noted from Figure 3 that the model does not fit the experimental data well at short times ($t < 10$ s). This may be due to several factors, including bubble breakage and reformation and undeveloped flow causing slight pressure fluctuations in the first few seconds of experimental run time. However, for longer times ($t > 10$ s)

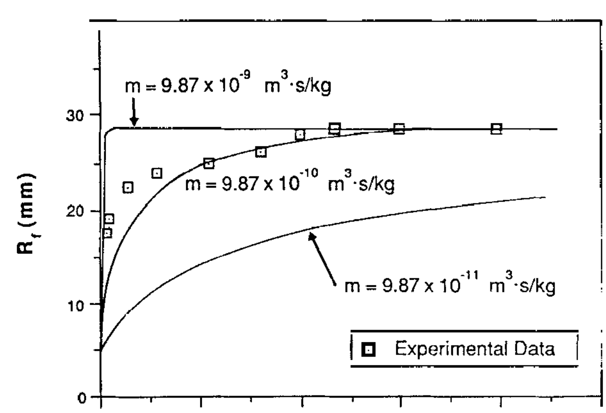

Figure 3. Radial position of moving foam front as a function of time.
Numerical solutions of Eq. 2 are shown as a function of mobility parameter m

the driving pressure is stable and, presumably, a more fully developed flow is attained, resulting in good agreement between the model and experiment.

The experimental device for studying foam flow in porous media should also be applicable in foam flow in oil recovery processes. It has the advantage that permeability of the medium can be varied by changing the compression of the mat. Using glass filter mats it is possible to obtain pore dimensions encountered in sandstone cores.

Notation

m = foam mobility, $m^3 \cdot s/kg$; 1 Darcy/cp = $9.87 \times 10^{-10}\ m^3 \cdot s/kg$
p = pressure, Pa
p_o = pressure at center injection hole, Pa
p_f = pressure at fluid front, Pa
r = radial position, m
R_f = radius of moving foam front, m
R_f^{eq} = radius at which foam front stops, m
R_o = radius of center injection hole, m
t = time, s
v_o = superficial fluid velocity, m/s
ϵ = porosity of porous medium

Literature Cited

Adams, K. L., and L. Rebenfeld, "In-Plane Flow of Fluids in Fabrics: Structure/Flow Characterization," *Textile Res. J.*, **57**(11), 647 (1987).

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