

# Experimental study of foam flow in fibrous materials

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**ABSTRACT** *For studying radial foam flow, we constructed a cell in which compressed fibrous mats serve as the porous media. Foam is injected into the center hole of a compressed mat, and the radial spreading pattern is observed. We propose a two-parameter fluid model that incorporates a "critical pressure gradient" parameter and a mobility parameter to describe the interaction of the foam with the porous material. From the position at which the foam front stops, the critical pressure gradient for foam mobilization is quantified. By numerically integrating the equation for the frontal advance rate and using experimental data, a value is obtained for the foam mobility. Complementary studies indicate that the size of bubbles exiting a porous mat was independent of the bubble size of the foam entering the mat and dependent on the average pore size of the medium.*

## KEYWORDS

Analysis  
Coating  
Critical pressure gradient  
Foam  
Permeability

Foam flow through fiber networks falls into the general subject of multiphase flow through porous media. 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 foam may be 95% gas by volume, the energy required in the drying step is minimized.

This work was performed to gain a better understanding of the microscopic mechanism of foam flow through porous media in order to improve industrial processes that employ foams. The objectives were (a) to develop a suitable experimental

apparatus to study foam flow and (b) 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. We selected a radial flow geometry because the 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. A continuously varying pressure gradient allows us to characterize the mobility of the foam in the fiber network.

## Experimental procedures

### Apparatus

The apparatus is a modified version of a radial spreading apparatus used at TRI to study high-viscosity resin flow in fabrics (1). The device, depicted in Fig. 1, consists of a foam reservoir and the porous medium test cell. In addition, the apparatus in-

cludes 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, N.Y.). The foam flows into a reservoir that is pressurized to maintain a constant injection pressure in the radial flow cell. Since we studied foams with high gas volume fractions, there was minimal liquid drainage from the foam in the reservoir over the course 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 is compressed to the desired thickness. For this work, we chose Fiberglas® insulation as the porous medium because the porosity of a specimen can be varied simply by changing its thickness by compression. Specimens are 144 cm<sup>2</sup> 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

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of the moving foam front can be recorded on videotape.

The measurement involves the following sequence of events: The sample is compressed to a desired thickness by regulating the gas pressure delivered to four double-acting pneumatic cylinders (maximum rating 1700 kPa each). Foam is 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 are controlled by varying the liquid flow rate, the gas flow rate, and the agitation speed of the mechanical mixer. The liquid phase consists of a 2% aqueous solution by weight of nonionic surfactant (Tergitol NP-10, Union Carbide Corp.) in water. The reservoir is pressurized with air to the desired pressure. The injection valve is opened, the foam begins to spread radially through the glass fiber mat, and the process is recorded with a video camera. Numerical data for the radial position of the foam front as a function of time are subsequently read from the videotape.

#### Foam model and results

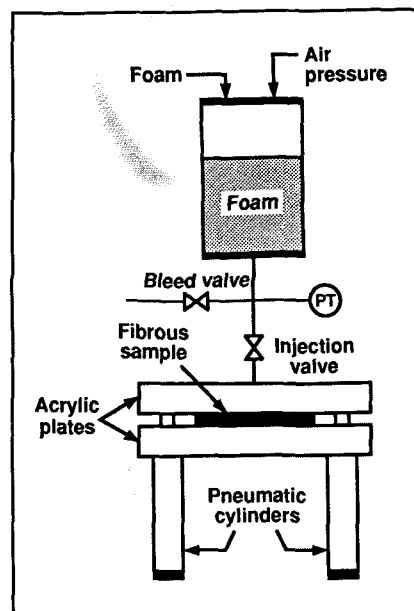
For these foams of high gas volume fraction, the front spreads to a certain radial position and then stops. This observation is particularly important because it allows us to observe the minimum pressure gradient below which the foam will not move, the critical pressure gradient. The critical pressure gradient,  $(dp/dr)_0$ , and the foam mobility,  $m$ , characterize the interaction between the foam and the porous structure and are the two parameters used to characterize foam flow velocity in the mat using a modified Darcy's law given by

$$v_0 = -m \left[ \frac{dp}{dr} - \left( \frac{dp}{dr} \right)_0 \right] \left| \frac{dp}{dr} \right| > \left| \left( \frac{dp}{dr} \right)_0 \right| \quad (1)$$

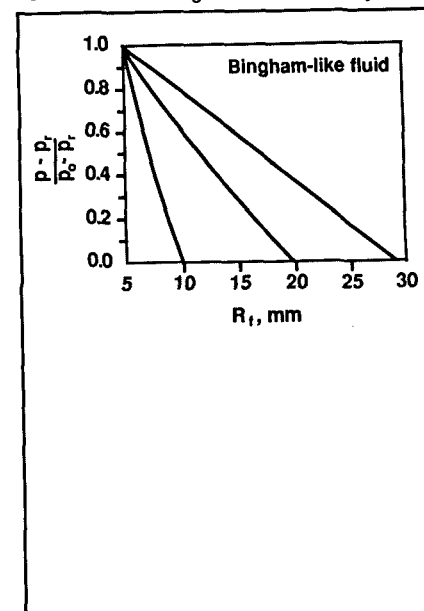
$$v_0 = 0 \quad \left| \frac{dp}{dr} \right| \leq \left| \left( \frac{dp}{dr} \right)_0 \right|$$

Combining the modified Darcy's law with the conservation of mass, we obtain an expression for the dimensionless radial pressure distribution given by

1. Diagram of the compression device and foam-injection reservoir



2. Dimensionless radial pressure distributions as a function of the position of a moving fluid front calculated using the modified Darcy's law



1. Experimental data for nonwoven mats

| Fiber material | Porosity, % | Permeability, darcy | Mobility, d/cp |
|----------------|-------------|---------------------|----------------|
| Glass          | 95          | 300                 | 2.4            |
| Polypropylene  | 93          | 280                 | 2.2            |
| Glass          | 81          | 50                  | 0.1            |

$$\frac{p - p_r}{p_0 - p_r} = \left[ 1 + \left( \frac{dp}{dr} \right)_0 \left( \frac{R_f - R_0}{p_0 - p_r} \right) \right] \ln(R_f/r) - \left( \frac{dp}{dr} \right)_0 \left( \frac{R_f - r}{p_0 - p_r} \right) \quad (2)$$

Figure 2 shows the dimensionless pressure distributions for a fluid obeying the modified Darcy's law. When the fluid front is at a position of 10 mm, the pressure distribution is somewhat logarithmic. As the fluid front moves farther from the center hole, the pressure distribution becomes more linear. In fact, when the front reaches the stopping radius ( $R_f^{eq} = 29$  mm in Fig. 2), the pressure distribution is linear. The slope of the distribution yields the pressure gradient, so the gradient of the linear pressure distribution at the stopping position is constant and is equal to the critical pressure gradient.

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. 3 describing the radial position of a foam front,  $R_f$ , as a function of time  $t$

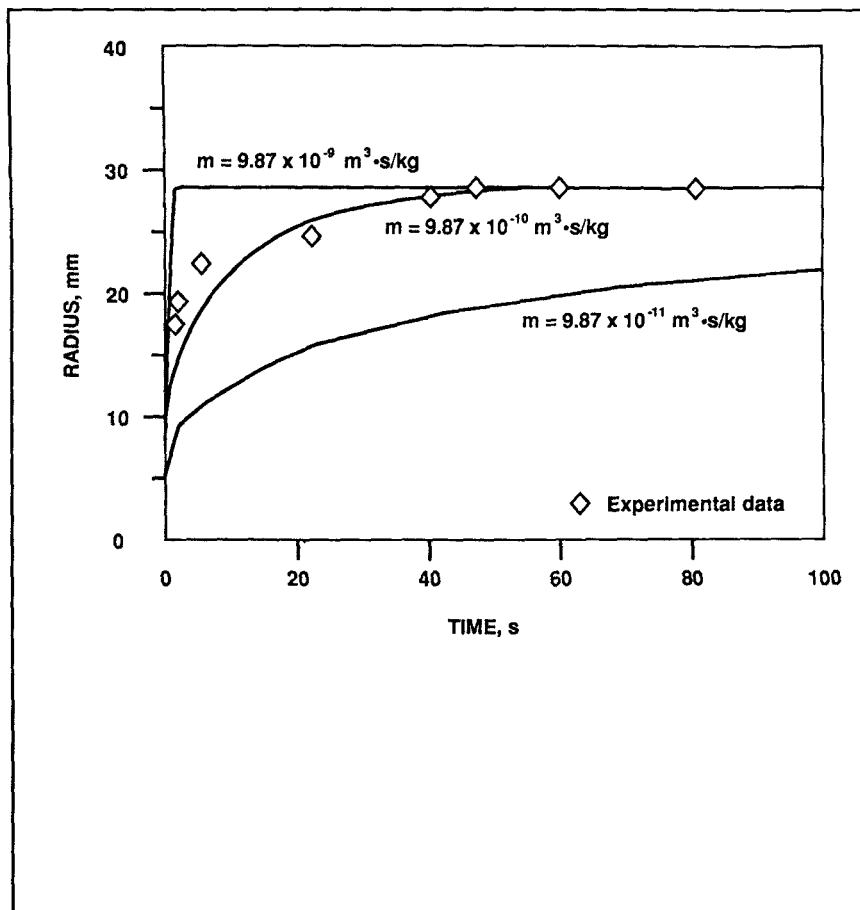
$$\frac{dR_f}{dt} = m \left[ \frac{(p_0 - p_r) + (dp/dr)_0 (R_f - R_0)}{\ln(R_f/R_0)} \right] \frac{1}{\epsilon R_f} \quad (3)$$

where

- $p_0$  = the pressure at the center injection hole of radius  $R_0$
- $p_r$  = the pressure at the advancing front
- $\epsilon$  = 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

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



$$\left(\frac{dp}{dr}\right)_0 = \left( \frac{p_0 - p_r}{R_0 - R_r} \right) \quad (4)$$

This definition of  $(dp/dr)_0$  is equivalent to the slope of the linear pressure distribution shown in Fig. 2. The equations are derived assuming that the foam is incompressible. The pressure drops in our experiments are less than 50 kPa, so the foam is reasonably approximated as incompressible.

Once  $(dp/dr)_0$  is known, the only unknown parameter in Eq. 3 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. 3, 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 Fig. 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. A value of  $m$  of  $9.87 \times 10^{-10} \text{ m}^3 \cdot \text{s/kg}$  (or 1 darcy per centipoise) most closely fits the experimental data. A computer program finds the optimum value of  $m$  by minimizing the sum of the squares of the residuals between the experimental data and the numerical solution. As Fig. 3 shows, the model does not fit the experimental data well at short times (i.e.,  $t < 10 \text{ s}$ ). This difficulty 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 (i.e.,  $t > 10 \text{ s}$ ), the pressure is stable, and, presumably, a more fully developed flow is attained, resulting in good agreement between the model and experiment.

Table I summarizes the results for several mobility experiments performed on two nonwovens. The permeabilities, obtained from radial spreading experiments with a New-

tonian fluid, for the two glass fiber mats were different because they were compressed to two different thicknesses. As the permeability decreases, so does the mobility. This result is expected since a material of lower permeability offers more resistance to flow and this difference is reflected in a lower mobility.

### Study of bubble size

Comparing the results in Table I for the glass mat, we observe that the mobility decreases 10-fold, while the permeability decrease is only six-fold. It is possible that this behavior arises from a change in bubble size during flow through a mat, since a foamed aqueous surfactant solution injected into a porous bed often exits with differently sized bubbles (2, 3). A subsequent study was performed that dealt quantitatively with the changes in foam bubble size induced by flow through a porous medium under a constant pressure gradient. Input and output bubble sizes for foam flowing through porous beds with different pore size distributions were compared. A major part of the work involved developing convenient methods to obtain three-dimensional bubble size parameters and bubble densities from two-dimensional images of the foams using computer image analysis (4, 5).

### Apparatus

A diagram of the experimental apparatus used for this study is shown in Fig. 4. Again, the surfactant solution from which the foams were generated was a 2% (by weight) aqueous solution of the nonionic surfactant Tergitol NP-10, and the foams were produced in an Oakes mechanical foam generator. The foam flow was directed from the mixer either directly to a viewing cell or first through a fiberglass bed and then to the viewing cell. Changes in foam bubble size caused by the flow through the porous structure could thus be observed.

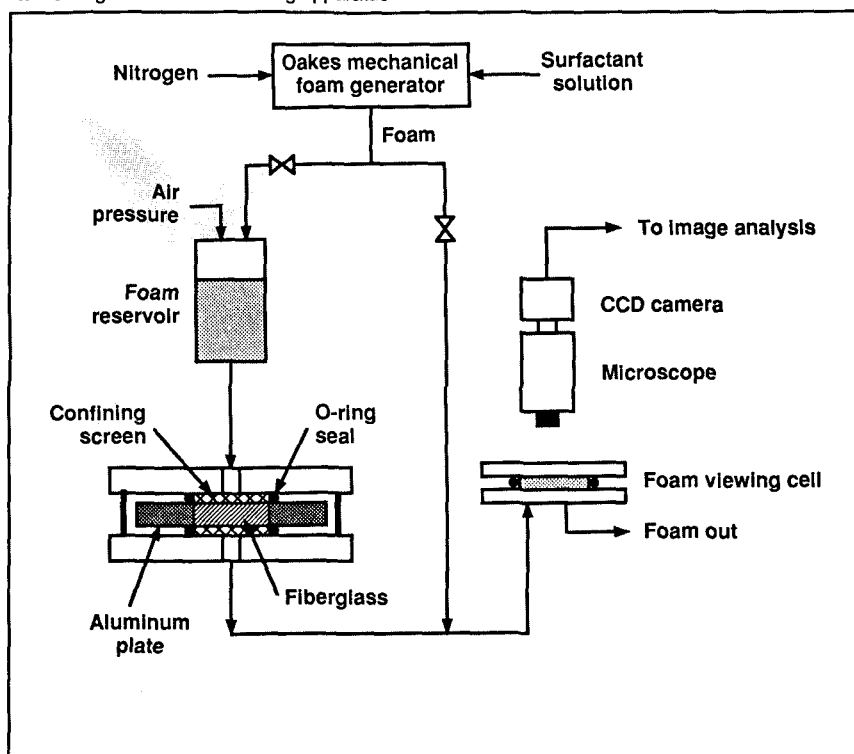
Foam was fed from the generator to a reservoir, which was pressurized to inject the foam through the bed. Pressure drops between 28 kPa and 35 kPa were used for all injections. The pressures used in this study were low enough so that size differences between inlet bubbles viewed at atmospheric pressure and those in-

jected into the fiberglass under a positive pressure were less than 10% (assuming ideal gas behavior). All foams were characterized in the viewing device at essentially atmospheric pressure.

The porous bed consisted of Owens/Corning Fiberglass® insulation, 51 mm nominal thickness, and an areal density of 0.75 kg/m<sup>2</sup>, compressed to a thickness of 6.4 mm, yielding a porosity of about 0.95. The average glass fiber diameter was 7 μm. Average pore diameter from pore volume distribution measurements at this compression was measured to be 90 μm. A circular sample of fiberglass (25.4 mm in diameter) was compressed and secured in a circular hole cut into a 6.4-mm-thick aluminum plate. The bed was held in place by stiff wire screens through which the foam had to flow during an experiment. The mesh of the screen was far coarser than the pore size in the bed and was assumed to have no effect on the inlet or outlet bubble size distributions. The fiberglass and aluminum plate assembly was then compressed between two acrylic plates separated by O-rings, as shown in Fig. 4. Foam was injected from the foam reservoir normal to the plane of the fiberglass mat.

The viewing cell used to examine foam bubbles consisted of two clear acrylic plates separated by a rubber O-ring. The foam flowed through an opening in the bottom plate into a space between the acrylic plates bounded by the O-ring and then exited through a second opening in the bottom plate. The spacing between the plates of the viewing cell was approximately 1 mm. The bubbles that were viewed had diameters on the order of 100 μm, so the plate spacing was roughly ten times greater than the bubble diameters. Magnified pictures of the foam in the viewing cell were taken using a Sanyo CCD video camera (Model VDC 3800) mounted on an Olympus stereomicroscope. Magnifications of 5–10X were used. Foam flow in the cell had to be temporarily stopped to obtain a sharp image. Pictures were taken within 15 s after stopping foam flow, before bubbles could coalesce and rearrange from their initial random configuration. The pictures taken by the CCD camera were fed into the computerized image analysis system.

4. Foam generation and viewing apparatus



Methods from quantitative stereology were used to calculate three-dimensional bubble sizes from the two-dimensional images of their intersections with the focal plane of the microscope. The circles in an original image represent cuts through the bubbles at focal planes and thus do not directly give bubble radii. The distribution of true, three-dimensional bubble radii requires factoring out the effect of the position distribution from the set of observed radii to leave only the true size distribution. This can be done by applying an algorithm given by Underwood (6) to the distribution of radii observed in the image. Alternatively, a number of empirical and semi-empirical correlations also are given by Underwood that allow the direct calculation of a number average bubble radius (7). Detailed descriptions of the applications of these stereological techniques can be found elsewhere (4).

## Results

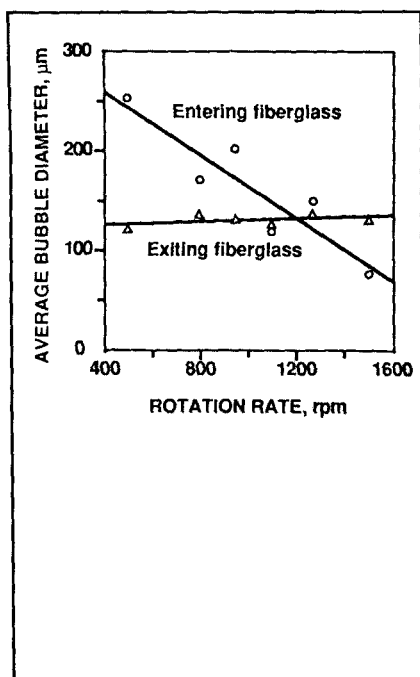
Figure 5 shows the results obtained for experiments using 90% quality foams that exhibited a decrease in bubble size with increased shear rate for the entering foam with some scatter observed. (Note that all averages discussed are number averages.) When the foams were forced through

the fiberglass bed, the bubble geometry was altered so that the output foams had bubbles with relatively constant average diameters, with an overall average exiting bubble diameter of 130 μm.

The important result from this portion of the work is that the average size of foam bubbles exiting the porous medium is independent of the bubble size of the foam injected into the medium. As noted in Fig. 5 at a rotation rate of 1500 rpm, this particular foam input to the fiberglass bed has a smaller average bubble diameter than the corresponding output foam, indicating that bubble coalescence may be occurring within the porous material. However, the scatter in the measured bubble size from the foam generator is relatively large, and since measurements of bubble sizes before and after the bed were made on different runs, the bubble size entering the bed at 1500 rpm may actually be close to the size of the exiting bubbles. The fact that the output bubble size is independent of the input bubble size tends to reinforce the ideas (a) that bubbles snap off, collapse, and reform, resulting in smaller bubbles, and (b) that bubbles coalesce, yielding larger bubbles.

These results indicate that the fibrous mat is controlling the bubble

5. Number average bubble diameter vs. rotation rate using quantitative stereology for 6.4-mm-thickness fiberglass bed at a foam quality of 90%



size during flow. A more compressed mat, having smaller pores, will generate smaller bubbles that possess a higher internal gas pressure, making them less deformable during passage through a porous structure. The deformability of bubbles is reflected in the mobility, offering a possible explanation for the nonlinear relationship between mobility and permeability.

## Summary

We used a radial spreading apparatus in conjunction with a modified Darcy's law to quantify two parameters that characterize the interaction of a foam with a fibrous material in a single experiment. The critical pressure gradient and foam mobility can be obtained experimentally by observing the rate at which a foam front flows to an equilibrium stopping position. Mobility results depend on the permeability of the porous structure, which leads us on to a subsequent study on foam bubble size.

In this study, we measured the size of aqueous foam bubbles before and after injection in a porous material. The sizes of the bubbles entering and exiting the mat were measured using a technique known as "quantitative stereology" that was coupled with an

image analysis system. Results indicated that the average size of foam bubbles exiting the porous medium was independent of the size of the bubbles injected into the mat. □

## Literature cited

1. Adams, K. L. and Rebenfeld, L., *Textile Res. J.*, 57(11): 647(1987).
2. Falls, A. H., Gauglitz, P. A., Hirasaki, G. J., Miller, D. D., Patzek, T. W., and Ratulowski, J., Development of a mechanistic foam simulator: the population balance and generation by snapoff, Society of Petroleum Engineers of AIME/U.S. Dept. of Energy, paper SPE/DOE 14961, presented at SPE/DOE Fifth Symposium on Enhanced Oil Recovery, 1986.
3. Radke, C. J. and Ranshoff, T. C., Mechanisms of foam regeneration in glass bead packs, 61st Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, New Orleans, 1986, Paper SPE 15441.
4. Gido, S. P., B.S.E. thesis, Dept. of Chemical Engineering, Princeton University, Princeton, New Jersey, 1988.
5. Gido, S. P., Hirt, D. E., Montgomery, S. M., Prud'homme, R. K., and Rebenfeld, L., Foam bubble size measured using image analysis before and after passage through a porous medium, *J. of Dispersion Science and Technology*, in press.
6. Underwood, E. E., *Quantitative Stereology*, Addison-Wesley, Reading, Mass., 1970, p. 116.
7. Underwood, E. E., in *Practical Applications of Quantitative Metallography*, ASTM STP 839, Philadelphia, 1984, p. 160.

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