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The Effect of Filter Cakes on Filter Medium Resistance

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ABSTRACT

The high resistance of a filter medium to fluid flow is a universal problem affecting many industries. The small thickness of the filter media makes local pressure and porosity measurements impractical. Analysis of the continuum equations and boundary conditions provide a basis for defining a relative medium resistance. Experiments are conducted on three particulate materials and on three different high flow rate filter media. The results show that the increase in medium resistance varies up to about four times the resistance of a clean filter medium with no cake present. The results also show that in most cases the relative resistance is dependent upon cake height.

INTRODUCTION

The resistance of flow through filter media and their effect on filter cake performance is a universal problem. Fluid/particle separations by passing the fluid through a porous medium are encountered in operations such as membrane separation, reverse osmosis, crossflow filtration, baghouses, cartridges, aquifers, and operations involving colloids and macromolecules. From laundries, restaurants, and air conditioning to clean rooms, injection wells, sugar refining, beverage production, and the chemical industry, the effect of high medium resistance due to clogging adversely affects the performance of the operations.

In cake filtration, two significant parameters are the pressure drop across the filter cake and the pressure drop across the filter medium. The pressure drop across the filter cake depends upon the particle packing arrangement and the height of the cake. When the cake is compressive (or compactable), the particle structure changes with the stress as the stress changes with time.

The pressure drop across a filter medium can be affected by the particles in the filter cake. Small particles can penetrate into the pores of the filter medium and cause pore clogging. Larger particles can block off the entrance to pores and thus divert the fluid flow to other pores. Also, if the filter medium is compressive, the stress of the cake can squeeze the medium and reduce the pore cross-sectional area available for flow. All three of these effects can cause an increase in the pressure drop across the medium.

It is the combined effects of both pressure drops across the cake and the medium which limit the operation of the filtration. There are different ways of approaching this problem. The approach taken here is to consider the filter cake, the filter medium, and the porous support plate under the filter medium each to be separate and distinct multiphase continuum regions. Because the filter medium and support plate are very thin, we cannot measure local positional dependence of properties such as pressure or porosity. Hence, for the filter medium and support plate, we must relate plausible mechanisms to the conditions at the boundaries.

Hermans and Bredée (1) were among the first to study the problem of filter cake resistance. They suggested two possible mechanisms of complete blocking and standard blocking for the clogging of filter media. Grace (2) studied the increase in resistance for a number of filter media and showed that the standard blocking model could account for the observed clogging. Kehat et al. (3) derived a simple relation for the effective medium resistance that holds for both complete and standard blocking. Rushton and Rushton (4) evaluated the relation between the filter medium pore size and the particle size on the medium resistance, and they concluded that the medium resistance is different for different filter cake materials.

Marecek (5) pointed out that literature gives more attention to determining the specific cake resistance than to determining the medium resistance. This is partly due to the practical constraints on selection of filter media (e.g., chemical resistance, cake adhesion, and mechanical strength) which tend to dominate the selection process.

In the above references the filter medium resistances are evaluated based upon data of the combined pressure drop across the cake and filter medium. The use of local pressure measurements is a more direct approach to quantify the medium resistance and is applied in this paper.

The continuum perspective is often used in literature to evaluate the filter cake, but little is done with the filter medium. The objective of this paper is to evaluate the interactions of the filter medium with the filter cake from a continuum perspective. Because the medium is so thin, local measurements cannot be made within the filter medium to relate to the continuum differential equations. These equations must be interpreted in integral form using macroscale pressure drop data. Experiments are run to measure the filter medium resistance at different cake heights and flow rates for comparison with the clean medium with no cake present.

CONTINUUM ANALYSIS

The continuum analysis is based on the volume averaged theory for flows through porous media (6–8). This approach has been applied previously to study filter cakes (9–11).

The filtration operation is considered to be isothermal, with no chemical reactions or mass transfer between the phases. The filtration is a one-dimensional pressure filtration as shown in Fig. 1. The slurry and cake consist of a fluid phase and a solid phase. While the materials that make up the solid phases are different in the cake compared to the filter medium and the porous support plate, the same continuum equations can be used to model the medium and support plate. The only differences between modeling the different regions are the constitutive functions and material parameters.

Of particular interest to this paper is the macroscopic fluid-phase mo-

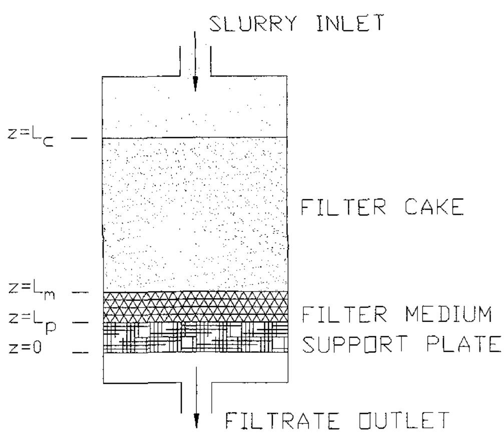

FIG. 1 One-dimensional filter cake assembly.

mentum balance,

$$\Delta P_{\mathrm{MEDIUM}} = -\int_{L_p}^{L_m} \frac{F_z^d}{\epsilon^f} dz \tag{1}$$

which relates the pressure drop across the medium to the interphase drag force within the medium.

From the continuum perspective the drag force within the medium is obtained from the pressure gradient in the continuum scale fluid-phase momentum balance,

$$\epsilon^f \frac{\partial P}{\partial z} + F_z^d = 0 \tag{2}$$

which requires local measurements of porosity and pressure. However, the thickness of the medium is too small to allow such local measurements. The alternative is to measure the pressure drop across the filter medium and to relate it to macroscopic quantities through an assumed process correlation or model.

The simplest model for the drag force sets the drag force proportional to the velocity difference between the phases:

$$F_z^d = R^f(v_z^f - v_z^s) \tag{3}$$

where R^f is a resistance function. Neglecting the solid-phase velocity in the medium, then the fluid-phase velocity can be related to the volumetric flow rate, Q, the area for filtration, A, and the local porosity, ϵ^f, to obtain

$$\frac{\partial P}{\partial z} = \frac{R^f Q}{\epsilon^{f^2} A} \tag{4}$$

When Eq. (4) is integrated over the depth of the medium, assuming that the porosity is uniform over position, the pressure drop across the medium is obtained as

$$\Delta P_{\mathrm{MEDIUM}} = \frac{R^f Q}{\epsilon^{f^2} A} (L_m - L_p) \tag{5}$$

Equation (5) can be compared with Darcy's law for flows through porous materials. Darcy's law gives the medium pressure drop as

$$\Delta P_{\mathrm{MEDIUM}} = \frac{\mu(L_m - L_p)}{K} \frac{Q}{A} \tag{6}$$

where K is the Darcian permeability. K is related to the resistance function in Eq. (4), R^f, by

$$K = \mu \epsilon^{f^2} / R^f \tag{7}$$

Either Eq. (5) or (6) can be used to evaluate experimental data. Using Eq. (5), we can define a relative medium resistance, R, which is the ratio of the medium resistance with cake present to the resistance of the clean medium before the cake is formed. R is given by

$$R = \frac{(R^{f}/\epsilon^{f^2})^{\text{WITH CAKE}}\big|_Q}{(R^{f}/\epsilon^{f^2})^{\text{NO CAKE}}\big|_Q} \tag{8}$$

where the numerator and denominator on the right side of the equation are both evaluated at the same flow rate, Q. To relate the relative medium resistance to measurable quantities, the porosities are included in the terms on the right side of Eq. (8).

Combining Eq. (8) with Eq. (5), we get

$$R = \frac{(\Delta P_{\text{MEDIUM}})^{\text{WITH CAKE}}\big|_Q}{(\Delta P_{\text{MEDIUM}})^{\text{NO CAKE}}\big|_Q} \tag{9}$$

A plot of the relative medium resistance R versus the flow rate Q indicates how the presence of the cake changes the resistance behavior of the medium at different flow rates. Further, R can be evaluated at different cake heights to show how the cake height may affect the medium resistance by changing the stress of the cake on the medium at the cake–medium boundary.

EXPERIMENTAL

Experiments are run with water as the liquid phase. Three powder materials are used as the solid phase: a fibrous cellulose powder, Solka Floc; a glassy volcanic rock, perlite; and a polymer, Geon. The Solka Floc has a wide range of particle sizes and shapes, and it forms a compressive filter cake as reported previously (10). Perlite particles are very small, with most less than 40 μm, and form a slightly compressive filter cake as determined from local pressure measurements within the cake. The Geon particles are also very small, with most particle sizes less than 40 μm. The Geon particles form an incompressible filter cake as determined from local pressure measurements in the cake.

The experiments are conducted using a paper, a woven cloth, and a nonwoven felt filter media supported by the same wire cloth support plate. All three filter media are rated as fast or high flow rate media. The paper medium is Whatman 113 used for coarse gelatinous precipitates, the woven cloth from the Avery Filter Corporation has a tight weave of polypropylene fibers and a satin finish for easy cake removal, and the nonwoven felt is a GORE-TEX membrane from W. L. Gore & Associates, Inc.

The experimental setup is shown in Fig. 2. Water is pumped from a tank, through the filter assembly, through a flowmeter, and back into the source tank. The filter cake is formed in layers by filling a loading tube with slurry and diverting the water flow through the loading tube and into the filter assembly. In this way the cake is formed in layers, and the pressure drop across the cake and medium can be measured for different cake thicknesses and flow rates.

The pressure drop across the filter medium is determined from pressure measurements immediately above the medium and below the plate where the pressure drop across the plate is assumed negligible. The pressure drop across the cake is made in a similar way. Local pressures could also be made within the cake, but they are not needed for this work.

Each layer of the cake is loaded under slow flow rate conditions. After the layer is loaded, then the flow rate is incremented from low to high rates. Measurements are recorded when the flow rate and pressures have reached a steady value. The flow rate is reduced to a low value again when the next layer is loaded.

The experimental procedures and setup used here is a compromise be-

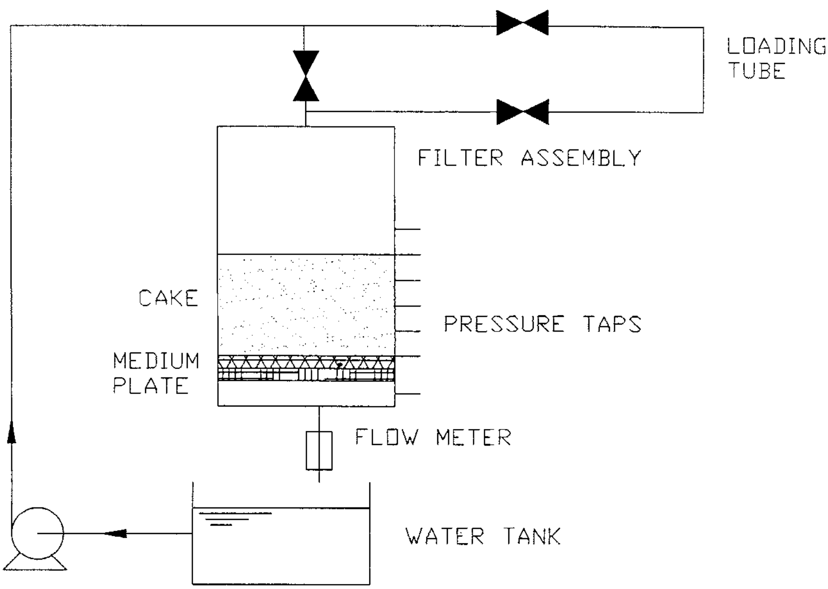

FIG. 2 Experimental setup.

tween an idealized continuous cake filtration and the pragmatic challenge of acquiring these measurements with the same cake and same cake thickness for different flow rates. Since the formation of the filter cake is not continuous, the build up of layers to form the cake may have an influence on the experimental results. However, the authors believe that this influence will be small compared to the overall effect on the medium resistance.

If anything, by taking the measurements when the flow rate and pressure drop are steady should produce data after the particles within the cake or medium have been given sufficient time to move and adjust their positions. In a continuous filtration the particles may still be moving when the cake is at a particular height, and so the effect of the cake on the medium resistance would be somewhat less than that determined here.

EXPERIMENTAL RESULTS

The experimental results are shown in Figs. 3–11. At the top of each figure is a box that lists the cake material, the type of filter medium, and the three cake heights corresponding to the experimental data. The experimental data are in the three plots in each figure: the pressure drop across the cake, the pressure drop across the filter medium, and the relative medium resistance as defined by Eq. (8).

The plots of the medium pressure drop also show the medium pressure drop for the clean medium without cake present. This datum is determined just prior to loading the first layer of cake.

In all cases the relative medium resistance is greater than unity, which means that the medium resistance is greater when the cake is present. In nearly all of the experiments, the relative resistance increases with cake height. This increase with height could be due to particle migration into the medium over time. Since measurements are recorded when the flow and pressure measurements are at a steady value, this suggests that the cake may be pressing particles into the pores of the medium at the cake–medium boundary, or the medium itself is compressing.

Of the three media, the cake height has the least effect on the nonwoven felt filter medium (Figs. 5, 8, and 11). The paper and woven cloth media have an increased resistance by a factor of 1.5 to 2.5 times. The Geon and paper medium have the greatest increase in medium resistance of about 3.5 times for a cake height of 81 mm and slow flow rates.

The results here are specific to the materials and filter media. Other media or particles could display a greater or lesser effect on the relative medium resistance. Also, the relative resistance plots are obtained from the raw pressure drop data. If smoothed curves from the pressure drop data were used, the resistance plots would show smooth monotonically

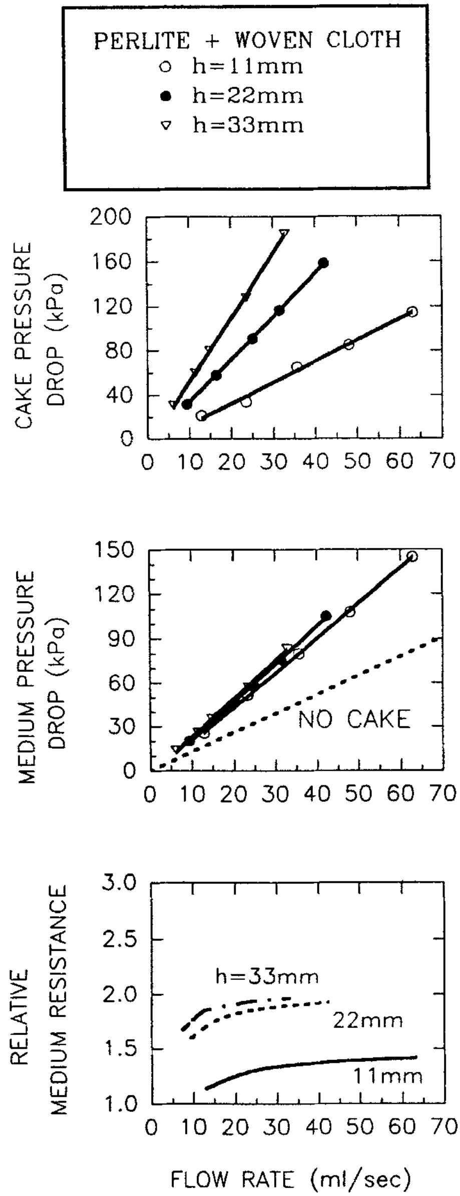

FIG. 3 Experimental data for perlite and the woven cloth medium.

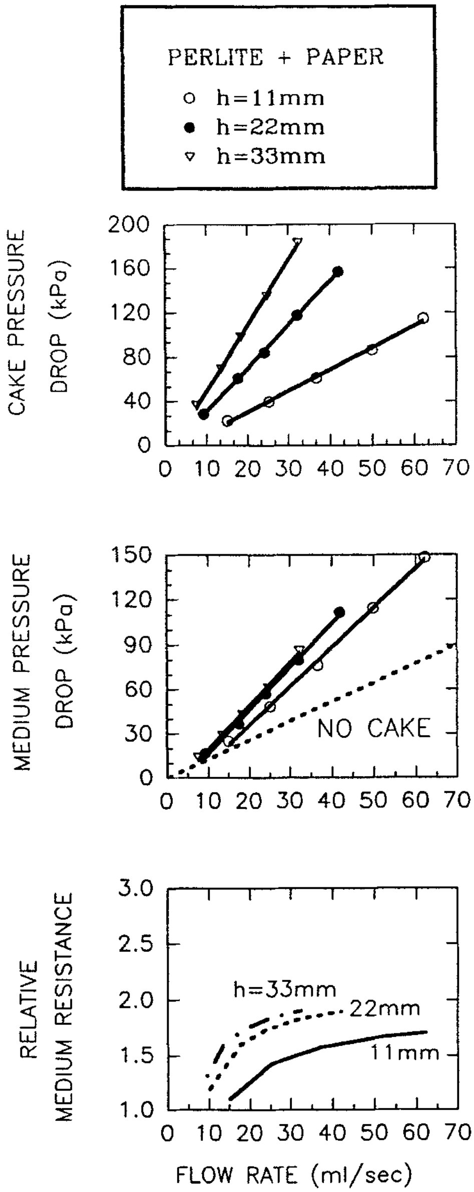

FIG. 4 Experimental data for perlite and the paper medium.

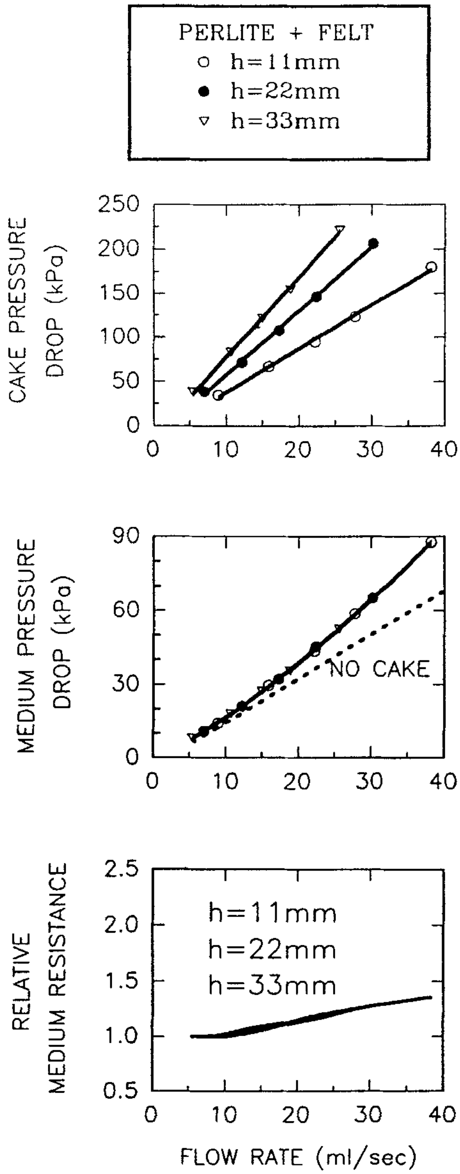

FIG. 5 Experimental data for perlite and the nonwoven felt medium.

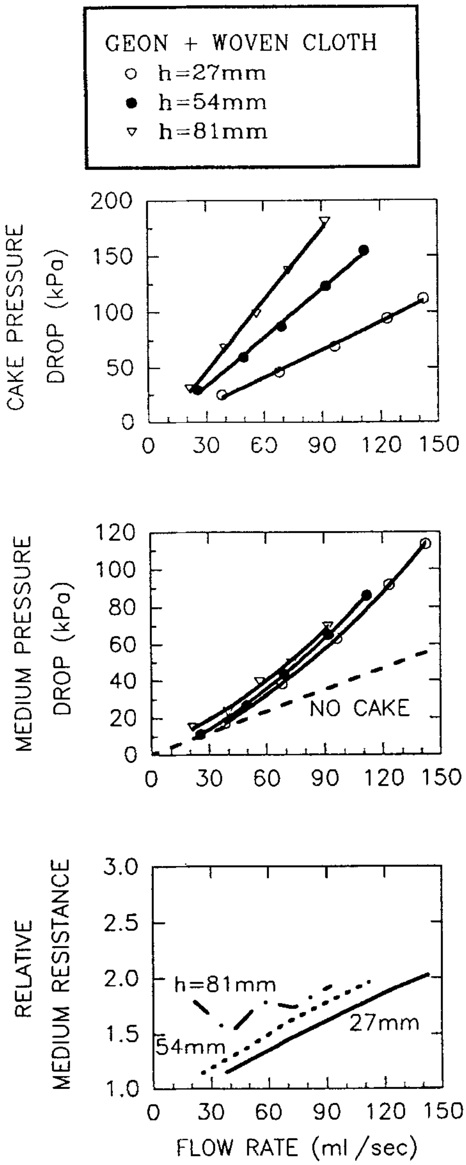

FIG. 6 Experimental data for Geon and the woven cloth medium.

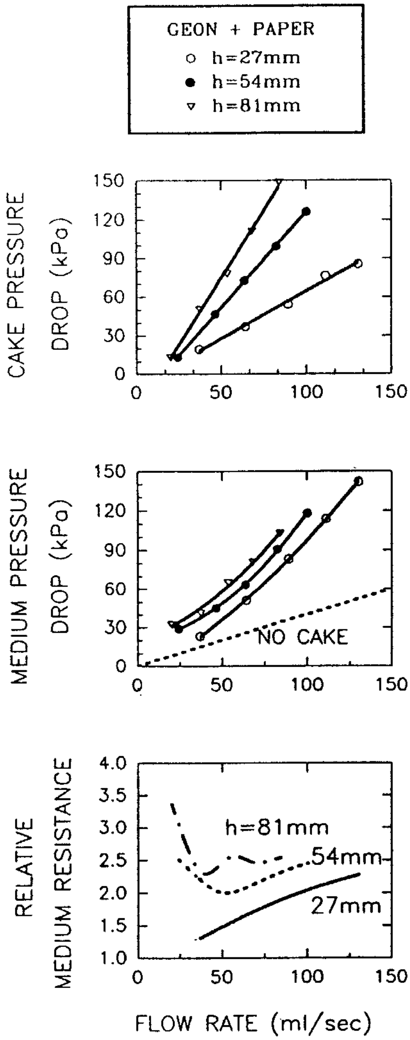

FIG. 7 Experimental data for Geon and the paper medium.

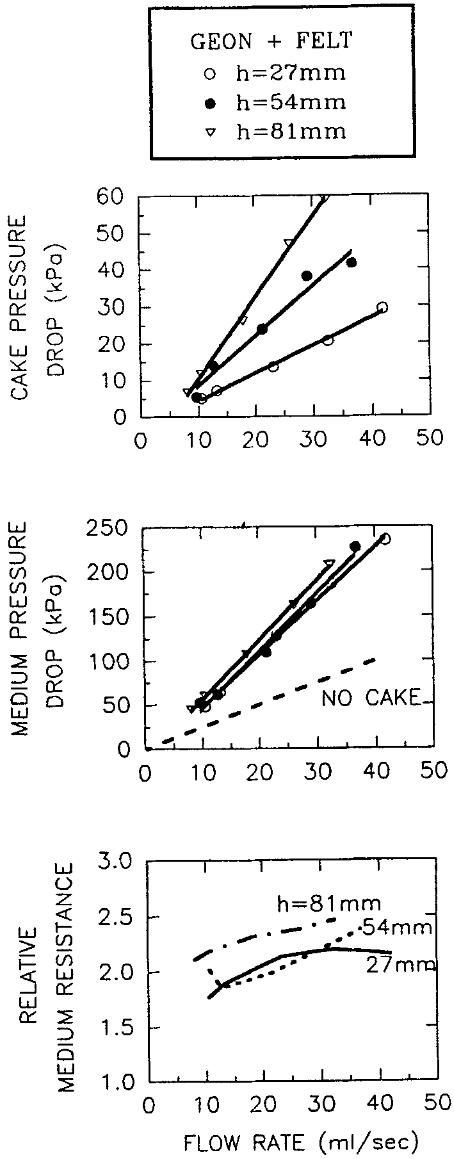

FIG. 8 Experimental data for Geon and the nonwoven felt medium.

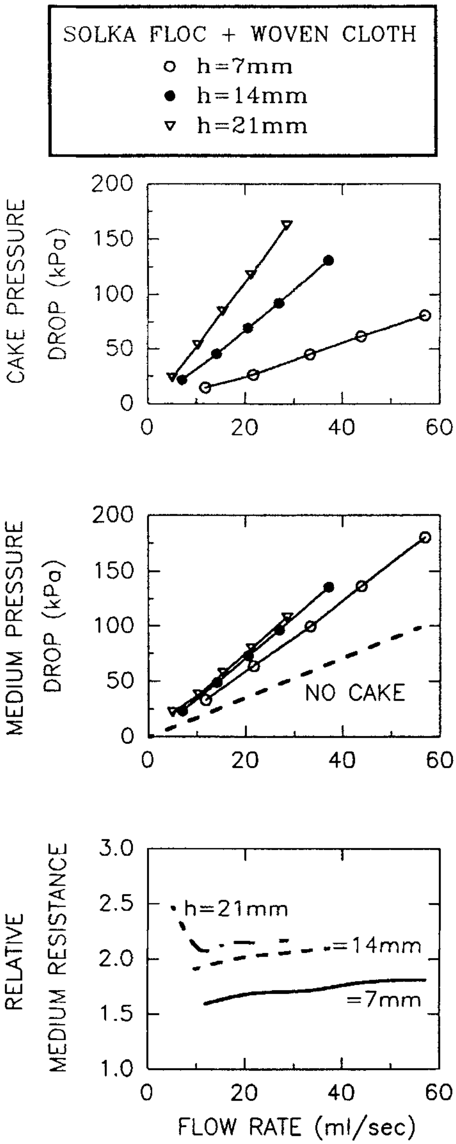

FIG. 9 Experimental data for Solka Floc and the woven cloth medium.

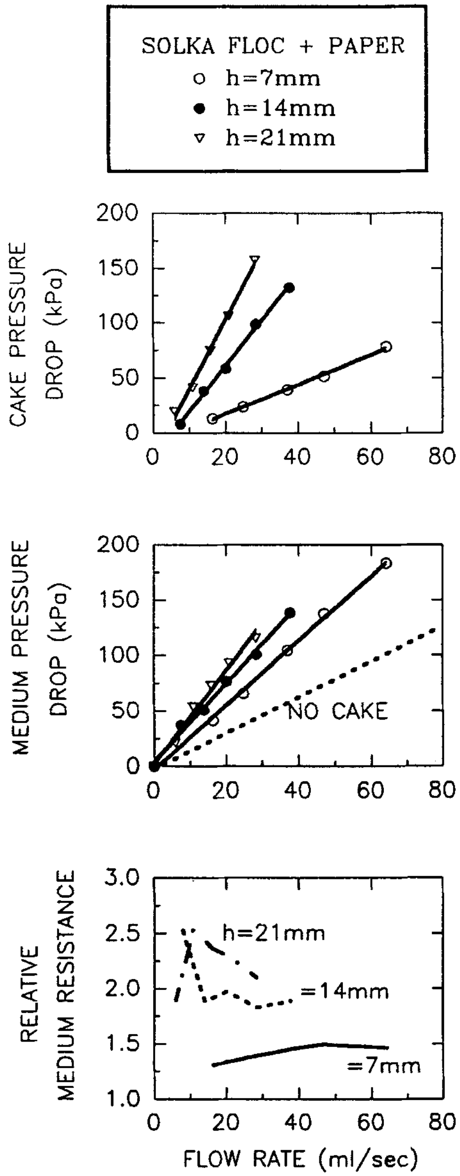

FIG. 10 Experimental data for Solka Floc and the paper medium.

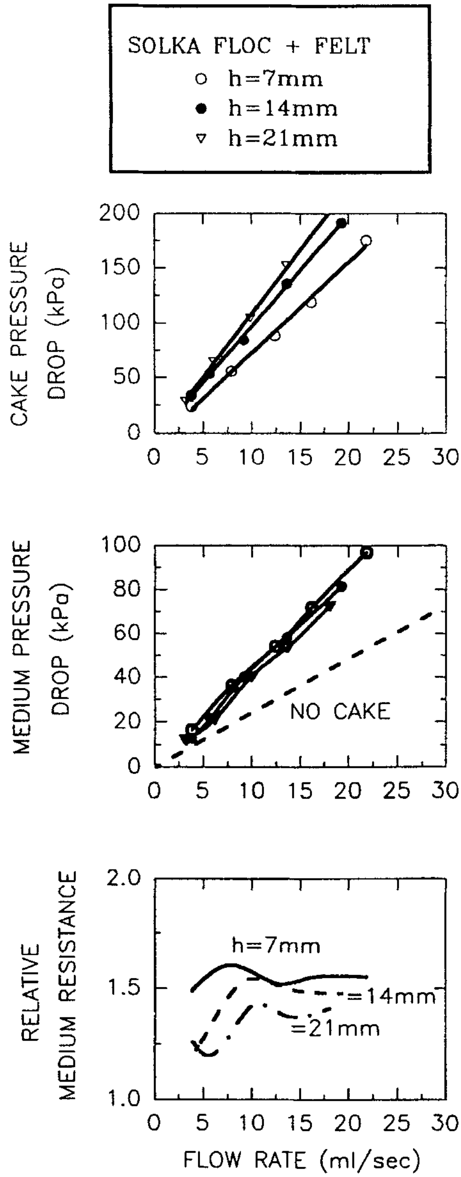

FIG. 11 Experimental data for Solka Floc and the nonwoven felt medium.

increasing resistance functions with flow rate and cake height in most cases.

Determination of the specific mechanisms responsible for the increase in resistances for each material and each type of medium would require a detailed analysis of the penetration of particles into the media, blocking of pores, or the compression of the filter medium. This additional analysis is beyond the scope of the present work.

CONCLUSIONS

Experiments were conducted on three cake materials and three different media that show that the medium resistance increases when the cake is present and that, in general, the resistance increases with the cake height. Continuum analysis provided a set of continuum and macroscopic scale equations and boundary conditions for describing the behavior of the several multiphase regions of the cake filtration. Local measurements cannot be made within the thin filter media; hence, a model is needed to correlate the macroscopic data. A model is not developed in this work, but a relative medium resistance is defined which may be useful in model development in future work.

NOTATION

A	cross-sectional area of filter assembly
F_z^d	drag force between phases
K	Darcian permeability
L_c	z-position at slurry–cake boundary
L_m	z-position at cake–medium boundary
L_p	z-position at medium–plate boundary
P	piezometric pressure
ΔP	pressure drop across a multiphase region
Q	volumetric flow rate
R	relative medium resistance defined by Eq. (8)
R^f	resistance to flow, Eq. (3)
v_z^α	α-phase average velocity
z	axial position as measured from the plate–filtrate boundary
ϵ^α	α-phase volume fraction
$\epsilon^{\alpha*}$	region average α-phase volume fraction
ρ^α	α-phase intrinsic density

Superscripts/Subscripts

α, f, s	α-phase, fluid-phase, solid-phase quantity
z	z-component of a vector or tensor
MEDIUM	quantity evaluated in the medium region
z=L	quantity evaluated at boundary at $z = L$

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