Flow Resistance in Filter Cakes Due to Air

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Abstract

The objective of this work is to show that air bubbles can adversely effect the performance of pressure filtrations. The effect of air on liquid flow resistance is measured in a well-characterized filter cake of Lucite particles. Air is introduced into the cake by allowing air bubbles to become entrained with the particles in the slurry at the start of filtration. Filtration with entrained air bubbles is compared to filtration without air bubbles. Experimental measurements show a significant increase in flow resistance due to the presence of air in a pressurized cake filtration. The presence of air bubbles in the filter cake can result in misinterpretation of experimental data. This in turn can increase operating and experimental testing costs and complicate efforts to predict filtration performance.

INTRODUCTION

There are many ways that air or other gases can enter a filter assembly and become trapped in a filter cake. For example, the slurry entering the filter assembly may have air bubbles in it or the liquid may have dissolved air which may degas in a vacuum filter. Another way is for the air to be present in the filter assembly before filtration starts. This latter case can occur if filtration equipment is not completely purged of air before it is run. Filtration equipment such as plate pressure filters typically have vents (1) to remove the air after assembly, or the air is forced out through the medium as the slurry is pumped into the assembly (2, 3). No studies are currently available in the literature on how well air is removed from process scale filtration equipment or on the effect that incomplete removal of air has on the filter performance.

Perry and Dobson (4) showed that the presence of degassed air in a cake performed in a vacuum filter is an important factor in controlling the course of filtration. Their experiments were run on polyvinyl chloride in water slurries, and the presence of the air bubbles was detected by using conductivity electrodes.

Chi et al. (5) examined the effect of entrained air bubbles on the rate of filtration and extent of dewatering of fine-coal filter cakes in vacuum filtration. They used an image analyzer to measure the bubble sizes in relation to the pore size and particle size distributions in the cake.

In this work the presence of air in Lucite filter cakes is detected with conductivity electrodes and local pressure gradients. An air space is introduced at the top of the filter assembly before the start of filtration as shown in Fig. 1. Experimental data show that in a constant pressure filtration, enough air can be entrained to have an adverse effect on filter operation. These data are compared with a filtration when the chamber is completely purged of air at the start of filtration.

THEORETICAL

Current cake filtration theories are based on the two resistance model (1–3) or the volume-averaged continuum theory (6, 7). These two theories are compared in Table 1 in which analogous equations are given for the total resistance to liquid flow through a filter cake. The governing equation for the two resistance model is based on an analogy to Ohm's law in electricity (8). The governing equation for the continuum model is the simplified momentum balance for the fluid phase from volume-averaging theory (6, 7).

A subtle difference between the two approaches is in the definition of the pressure drops that are related to the total resistance to flow. For the two-resistance model the total resistance, μr, is related to the total pressure
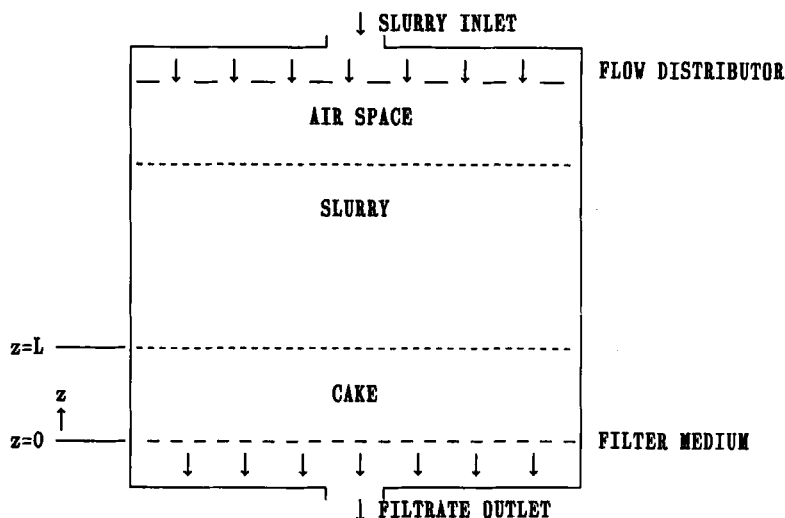

FIG. 1. Filter assembly with air space.

TABLE 1.
Comparison of Filtration Theories

Two-resistance theory (1–3)	Continuum theory (6, 7)
Governing equation:	Governing equation:
$$\frac{\dot{V}}{A} = \frac{\Delta P}{\mu[R_c + R_m]} \qquad (1)$$	$$R'v_z^d = \epsilon_f \frac{\delta P}{\delta z} \qquad (4)$$
Neglect medium resistance and introduce $R_c = rx(V/A)$:	Evaluate the filter medium at $z = 0$:
$$\frac{\dot{V}}{A} = \frac{\Delta P}{\mu[rx(V/A)]} \qquad (2)$$	$$-\frac{R_0^f \dot{V}}{A\epsilon_{fo}} = \epsilon_{fo} \frac{Pc}{L} \qquad (5)$$
Substitute $x = AL/V$ and solve for total resistance:	Solve for total resistance:
$$\mu r = \frac{A\Delta P}{\dot{V}L} \qquad (3)$$	$$-\frac{R_0^f}{\epsilon_{fo}^2 J_0} = \frac{AP_c}{\dot{V}L} \qquad (6)$$

drop across the cake plus the filter medium, ΔP. Conversely, the total resistance in the continuum approach, $-R_0^f/\epsilon_{fo}^2 J_0$, is related to the pressure drop only across the filter cake, P_c.

Filter cakes can be characterized by data on the total resistance to flow. For isothermal one-dimensional filtrations, the two-resistance model characterizes a cake with a constant total resistance as an incompressible cake. If the total resistance increases as the filtration progresses, then the cake is said to be compressible due to the character of the particles that form the cake (1–3). The changing resistance is attributed to the material property dependence on the pressure drop, ΔP. Compressible cakes are normally correlated by the empirical relationship proposed by Almy and Lewis (9):

$$r = r_0 \Delta P^s \qquad (7)$$

in which r_0 is the specific cake resistance at small pressure drops and s is the compressibility factor.

Similarly, the continuum approach interprets a cake with a constant total resistance as nonclogging and one with an increasing resistance as clogging (7). The resistance function, R_0^f, can be shown to be dependent on fluid density, temperature, and local porosity (10). The fluid intrinsic viscosity

can be factored out of the resistance function to relate the resistance to the permeability by

$$R_0^f = \mu \epsilon_{f_o}^2 / K_0 \qquad (8)$$

which in effect separates out the temperature dependence (6, 11). The porosity dependence can be evaluated by introducing a constitutive relation for the solid phase stress (12).

EXPERIMENTAL

To show that air has an adverse effect on filter performance and can cause misinterpretation of experimental data, two experiments were run in the same filter assembly in which the only significant difference between the experiments was the presence or absence of air. In these experiments the local pressures were measured by transducers connected to taps along the assembly wall, the local fluid phase volume fraction was measured by conductivity probes along the wall opposite the pressure taps, the filtrate volume was obtained from the weight of the collected filtrate, the filtrate rate was measured with a magnetic flowmeter, and the cake height was measured visually with a scale.

The experimental conditions are summarized in Table 2. The experimental results are plotted in Fig. 2 through 8.

Figures 2 and 3 are plots of the total flow resistance versus cake height for the cakes without air and with air, respectively. In both figures the solid circles are the resistances calculated for the two-resistance theory, Eq. (3), and the open circles are for the continuum theory, Eq. (6).

TABLE 2
Summary of Experimental Conditions

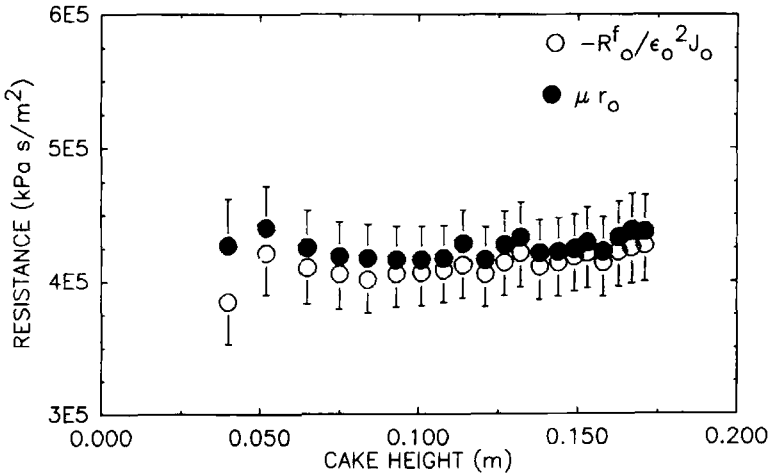|	
Slurry concentration	93% by volume liquid phase
Liquid phase	0.0025 molal solution of KCl in water
Solid phase	Spherical particles of Du Pont Lucite acrylic resin, mean diameter of 70 μm, 70% of the particles fall in the 44 to 148 μm range.
Filter medium	Whatman 4
Controlled cake pressure drop	69 kPa
Filtration area	0.004093 m²
Temperature	21°C
Presence of air	Experiment 1: All air is completely purged from the assembly.
	Experiment 2: At the start of filtration a 2-cm layer of air is trapped at the top of the assembly.

FIG. 2. Total flow resistance for Lucite cake without air.

The relatively constant resistances in Fig. 2 indicate that the cake is incompressible (two-resistance theory) and nonclogging (continuum theory). However, the increasing resistances in Fig. 3 indicate that the cake is compressible and clogging. This shows an inconsistency in the cake material behavior under identical conditions (except for the presence of air).

Figures 4 and 5 are plots of the local porosity (liquid phase volume fraction) for the experiments without and with air. Figure 4 shows a uniform
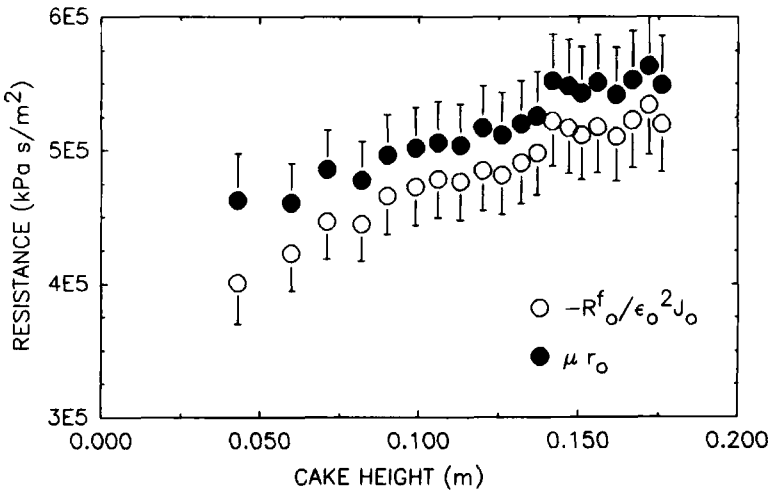

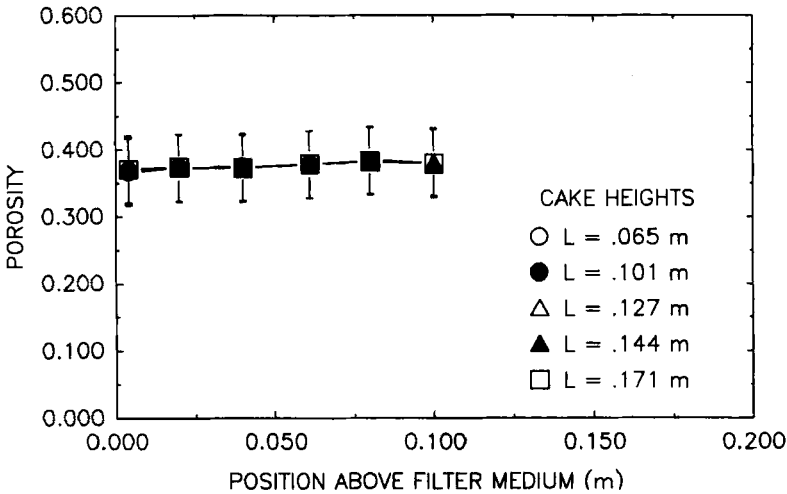FIG. 3. Total flow resistance for Lucite cake with air.

FIG. 4. Local porosity profiles for Lucite cake without air.

porosity profile which is consistent with the incompressible and nonclogging characterization of the cake in Experiment 1. Figure 5 shows a nonuniform porosity profile which is consistent with the compressible and clogging characterization of the cake in Experiment 2.

Similarly, the (almost) linear pressure profiles in Fig. 6 are consistent with the incompressible and nonclogging cake of Experiment 1, and the
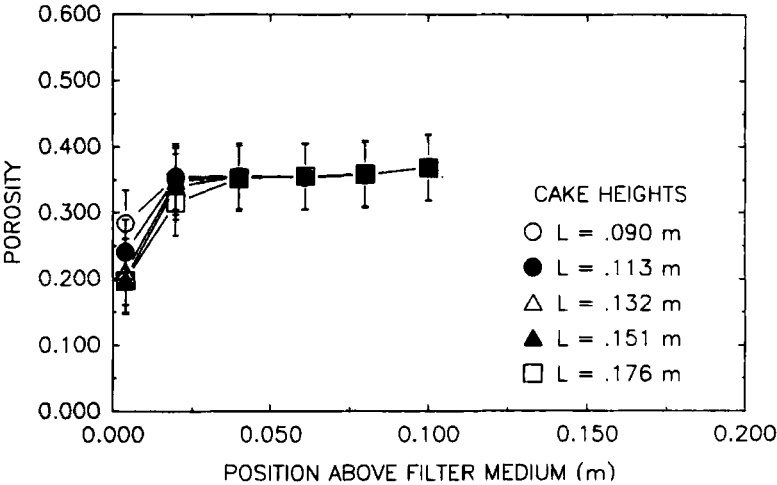
FIG. 5. Local porosity profiles for Lucite cake with air.

FIG. 6. Pressure profiles for Lucite cake without air.

nonlinear pressure profiles of Fig. 7 are consistent with the compressible and clogging cake of Experiment 2. The nonlinearity in the pressure profiles of Fig. 7 occur within the same 0 to 0.04 m above the medium, as does the significant change in porosity in Fig. 5.

The filtrate volume versus cake height data for the two experiments are plotted in Fig. 8. A linear fit of the data shows that the plots have the

FIG. 7. Pressure profiles for Lucite cake with air.

FIG. 8. Comparision of filtrate volume versus cake height for the filtrations with and without air.

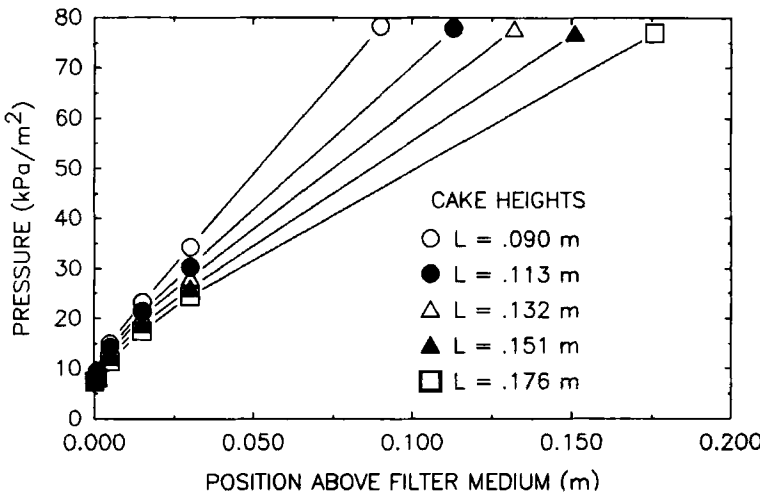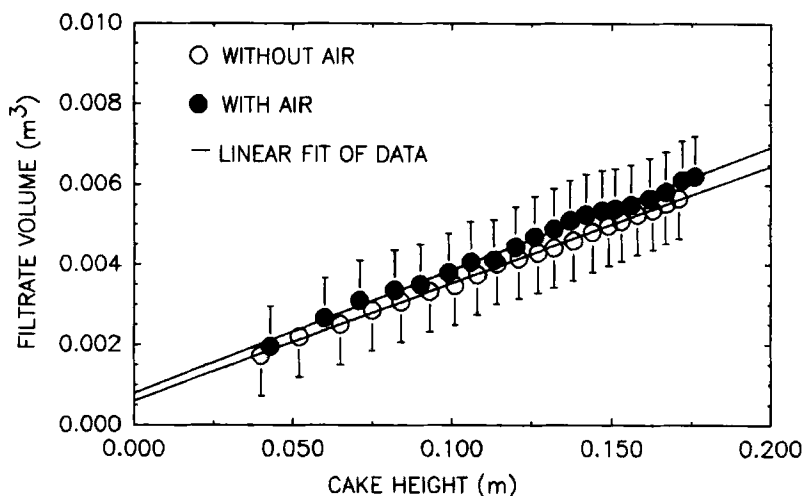same slope within experimental error. This means that the solid phases of the cakes for the two experiments occupy the same volume fraction. If the solid particles in Experiment 2 were migrating or deforming to cause a reduced porosity near the medium as indicated in Fig. 5, then the filtrate volume data for Experiment 2 in Fig. 8 would be nonlinear with a slope greater than that for Experiment 1. The two curves in Fig. 8 do not pass through the origin due to the displacement of particle-free liquid that is in the filter assembly before the start of filtration.

DISCUSSION

The identical slopes of the two plots in Fig. 8 show that the two filter cakes in Experiments 1 and 2 have the same particle packing and that the decrease in the porosity in Fig. 5 near the medium is not due to particle movement or deformation. The most likely cause of the reduced porosity is the presence of air bubbles within the cake in Experiment 2.

Quantitative measurement of the amount of trapped air bubbles within the cake in Experiment 1 is not available. Small bubbles were visually observed through the Plexiglas walls of the filter assembly in the region between 0 and 4 cm above the filter medium. No bubbles were observed in Experiment 2.

It is speculated that in the filtration rate is high enough at the start of filtration that many air bubbles are entrained with the particles in the slurry when air is present at the top of the filter assembly. As particles start

formimg the cake, they trap bubbles inside the cake. As the cake grows, the flow rate slows enough so that the air bubbles in the slurry can move counter to the flow and not get trapped in the succeeding layers forming the cake. This accounts for the shape of the porosity profile in Fig. 5 and our visual observation that air bubbles are trapped only near the medium in the initial layers of the cake.

As the cake depth increases, the local pressure at a given point in a cake decreases. When a cake has trapped air bubbles, the decrease in pressure allows the bubbles to expand. The expanding bubbles cannot move the solid phase, so they displace the liquid phase. This constricts the void space available for liquid flow through the cake near the medium, and it causes an increase in the pressure gradient as observed in Fig. 7.

The plot in Fig. 3 shows an increase of about 20% in the total resistance to flow. For some equipment this may be within experimental error. However, this increase occurred with air bubbles trapped in only a small portion of the cake. Much higher flow rates could be achieved with industrial equipment, which would result in trapped bubbles throughout the cake. Chi et al. (5) showed that when bubbles are trapped throughout a cake, total resistance can increase by as much as 300%.

A common technique in industry is to start filtration with a gradual increase in the pressure drop (13). This is done to allow the particles in the initial layers of a cake to form with more open packing and lower resistance to flow. The experimental data here suggest that another reason would be to minimize the entrainment of air in the cake.

CONCLUSIONS

The experimental data show that air in a filter assembly can be entrained with the slurry and trapped in a filter cake. Trapped air bubbles cause the resistance to flow to increase, and they can make an otherwise incompressible or nonclogging cake appear to be compressible or clogging. This inconsistency can make experimental analysis of filter cakes more difficult. To obtain consistent results, air must be completely purged from filter assemblies before starting filtration.

NOMENCLATURE

A filtration area
J_0 dimensionless pressure gradient at the medium, at $z = 0$
K_0 permeability of the cake at medium, at $z = 0$
L cake height
P_c pressure drop across the filter cake
ΔP pressure drop across the cake plus the filter medium

R_c resistance of the cake to flow, two-resistance theory
R_m resistance of the medium to flow, two-resistance theory
R^f resistance function, continuum theory
R_0^f resistance function evaluated at the medium
r specific volumetric cake resistance, two-resistance theory
r_0 specific volumetric cake resistance at small pressure drop
s cake compressibility factor
$\dot{V}$ filtrate volumetric flow rate
V filtrate volume
v_z^d velocity difference between the solid and fluid phases
x ratio of cake volume to filtrate volume
ϵ_f porosity or void fraction of the liquid phase
ϵ_{f_o} porosity of the cake at the medium, at $z = 0$
μ fluid phase intrinsic viscosity

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