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Modeling the Vacuum Filtration of Fine Coal. III. Comparison of Models for Predicting Desaturation Kinetics

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ABSTRACT

Three mathematical models devised by Wakeman, by Baluais, and by Nicolaou have been compared in their ability to predict the desaturation kinetics of fine ($-0.5+0$ mm) coal using vacuum filtration. Although similar in their basic approach and many of their underlying assumptions, the models diverge considerably in the techniques used to solve the equations of air and water flow through a porous filter cake. The models were assessed as a function of vacuum level and cake height, with a deviation of below 1 wt% moisture from the experimental data being deemed a success. All models predicted cake moisture after 300 seconds desaturation time to within 1 wt% moisture, except Baluais, which deviated significantly (by 2.3–3.2 wt% moisture) at the lowest vacuum (40 kPa) and lowest cake height (8–9 mm) tested. At shorter times (up to 50 seconds), the Wakeman model showed the best all-round performance, never deviating more than 1.5 wt% from experiment, and frequently being much closer. The Nicolaou model was particularly good at predicting desaturation kinetics for the thinnest cakes. Taking the data set as a whole, there were no obvious trends for any of the models in systematically under- or overestimating product moisture.

Key Words. Coal; Vacuum filtration; Modeling

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INTRODUCTION

The vacuum filtration of fine (−0.5+0 mm) coal is an important yet poorly understood unit operation within many commercial coal preparation plants. For many coals, up to 25 wt% of mine output can be in the fine size range, which can contain up to 50 wt% of the final product moisture. Improved understanding of vacuum filtration by modeling the kinetics of desaturation is one of the research programs being pursued within CSIRO to identify routes for lowering the level of moisture in fine coal, which is typically between 20 and 25 wt%.

Several models have appeared in the literature for predicting the kinetics of dewatering since the early work of Ruth (1, 2) in the 1930s. Recently, within CSIRO, Condie and Veal (3, 4) have been adapting and applying the model devised by Wakeman (5–7) to the filtration of fine coal. This model has been digitized on a computer spreadsheet and shown to predict very closely the kinetics of desaturation of fine coal filter cakes across a wide range of cake heights and vacuum levels (3). In a subsequent study the model was used to suggest that substantial advances in fine coal filtration are theoretically feasible provided that an appropriate way of conditioning the cake prior to filtration can be identified.

Other models have also been developed and shown promise, in particular those developed by Baluais, Dodds, et al. (8–10), and Nicolaou and Stahl (11, 12). Carleton and Mackay (13) compared the Wakeman and Baluais models (inter alia) and both performed well, providing a good simulation of experimental data on the vacuum filtration of a washed sand (d_{50} 60 μm). However, it was thought that a better test of the relative merits of predictive models would be obtained in using them to simulate the dewatering of a material which is more complex than fine sand. Thus it was decided to simulate the vacuum filtration of fine coal, with its wide size distribution (nominally −0.5 +0 mm but with some material up to 1 mm in size), rough angular and irregular particles, and wide range of surface chemistry depending on the presence of adventitious minerals, either as liberated particles or locked with coal. Thus, a collaborative study was set up between CSIRO and CNRS-ENSIC to produce the required model comparison. The results are summarized in this paper.

SUMMARY OF THE WAKEMAN MODEL

The starting point for Wakeman's model is the capillary pressure curve, determined experimentally by measuring equilibrium moisture values at a series of gradually increasing pressure differentials across the cake. At the start of the experiment, no dewatering occurs until the breakthrough pressure (p_b) is exceeded. The equation of the relationship that is determined between equi-

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librium moisture and pressure differential allows calculation of the pore size distribution index (λ). Wakeman then calculated the kinetics of desaturation by applying Darcy's law to the flow of both water and air through the filter cake in a dimensionless analysis, which expressed the pressure difference as a function of p_b. The resultant equations are

$$v_L^* = -S_R^{(2+3\lambda)/\lambda} \frac{dp_L^*}{d(x/L)} \tag{1}$$

and

$$v_a^* = -(1 - S_R)^2(1 - S_R^{(2+\lambda)/\lambda}) \frac{dp_a^*}{d(x/L)} \tag{2}$$

Wakeman solved them by conceptually dividing the cake into a number of elemental slices and calculating the progress of the air/water interface through the cake. The results were presented in the form of charts from which the values of moisture content and time for a given set of dewatering conditions could be interpolated. In compiling the charts, values of pore size distribution index (λ) and breakthrough pressure constant were assumed to be 5 and 4.6, respectively, which were appropriate for the sand particles of reasonably narrow size distribution to which the model was applied.

Wakeman's charts were digitized into a series of look-up tables within a computer spreadsheet (3). As a result, the model, which was within the same spreadsheet, was entirely software driven.

SUMMARY OF THE BALUAIS MODEL

The Baluais model, like that of Wakeman, is based on the application of Darcy's law for transient, two-phase (air and water) flow through the filter cake. However, in contrast to Wakeman's numerical approach, Baluais et al. proposed an analytical solution to the equations that revealed the two-stage nature of the drainage process.

Like Wakeman, Baluais derived Eqs. (1) and (2), and combined them with Eq. (3) (derived from Darcy's law):

$$f_1 = \frac{1}{1 + \left(\frac{k_a}{k_l}\right)\left(\frac{\eta_l}{\eta_a}\right)} \tag{3}$$

The net result was

$$f_1 = \frac{1}{1 + (1 - S)^2\,(1 - S^{\alpha})/(S^{\alpha+2}\,M)} \tag{4}$$

where S is the cake saturation, $\alpha = (2 + \lambda)/\lambda$, and $M = \eta_a/\eta_w$.

The curve of f_1 against S has an inflection point, and therefore the distribution of the rates of movement of local saturations is bell shaped. In effect, the cake is calculated to have two values of saturation, which is clearly impossible in practice. This problem was overcome by considering the convex envelope of the flow vs saturation curve and drawing a tangent from the initial condition ($S = 1$, $f_1 = 1$), which intersects the curve at a point $S = S_b$, the value of saturation at breakthrough. Between $S = 1$ and $S = S_b$, the tangent corresponds to a "shock" or compressive front whereas between $S = S_b$ and $S = S_{eq}$ (equilibrium saturation) the displacement front is dispersive and reduction of saturation is slow and inefficient.

Thus, air breakthrough represents a discontinuity in the desaturation process and the value of saturation at which this occurs (S_b) is an equilibrium parameter and independent of the kinetics of the process (see Fig. 1). Saturations greater than S_b move through the filter cake at a rate given by the tangent of f_1 vs S at the value of S_b. Saturations below S_b have a rate of movement given by the slope of the f_1 vs S curve (i.e., df_1/dS) at the appropriate value of S. As the rate of movement of each value of saturation is known, then the average saturation is given by integration of the saturation profiles, i.e.,

$$S_{av} = 1/L \int_0^L S\,dx = 1 - (\text{Area A} + \text{Area B})/L.1 \tag{5}$$

Thus, before breakthrough,

$$S_{av} = 1 - \frac{\tau}{L}\left[(1 - S_L)\left(\frac{df_1}{dS}\right)^* + f_1\right] \tag{6}$$

and after breakthrough,

$$S_{av} = S_L - \tau/L f_1(S_L) \tag{7}$$

where τ is the reduced time given by $Q/(\varepsilon AL)t$. In order to use the Baluais

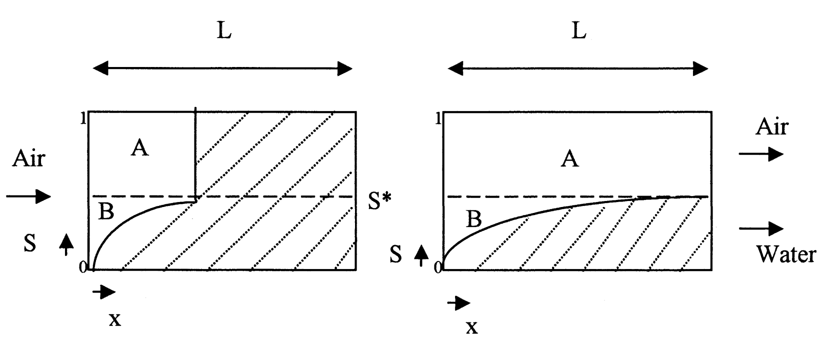

FIG. 1 Schematic representation of two saturation profiles.

model the following additional modifications are required:

- The model was originally developed for dewatering by air pushing water out of a cake. Thus the total flow Q was the same as the air flow (f_a). In vacuum filtration both air and water are flowing, and so $Q = f_a + f_l$. Thus the model was corrected according to the relative permeabilities of the cake to air and water.
- A series of Excel spreadsheets were formulated for solving the equations and producing graphs of moisture reduction against time.

SUMMARY OF THE NICOLAOU MODEL

The model of Nicolaou is a physically based regression procedure that characterizes the filtration properties of a given product with the minimum number of experiments. The equation used to describe desaturation is based on the analytical solution of differential equations that describe the flow of both water and air through the filter cake, based on Darcy's law. The resultant equation is

$$\frac{S - S_{eq}}{1 - S_{eq}} = S_R = [1 + AK^*]^{-B} \qquad (8)$$

A and B are two adaptation parameters and K^* is a dimensionless dewatering time, designated by Nicolaou as the desaturation number, and defined by

$$K^* = \frac{k(\Delta p - p_b)}{\varepsilon \eta_l L^2} t \qquad (9)$$

For a given set of experimental data [i.e., breakthrough pressure (p_b), cake permeability (k), pressure difference (Δp), cake porosity (ε), filtrate viscosity (η_l), cake height (L)], the model was used to derive the values of S_{eq}, A, and B which provided the best fit of Eqs. (8) and (9) to the experimental data. This procedure was then repeated for a complete data set covering a range of cake heights and pressure differences, but with all other conditions kept constant. The model was then used to calculate a capillary pressure curve from this new data set, and from the line of best fit, derive a value of pore size distribution index (λ).

This value of λ was then used by the model to recalculate a single profile of reduced saturation (S_R) against desaturation number (K^*) with a new set of values of equilibrium saturation (designated S_u) and adaptation parameters (designated A_u and B_u) derived by nonlinear regression. This new profile (shown in Fig. 2) represents the best overall fit of the model to the entire data set, with the minimum relative deviation.

The new values of S_u, A_u, and B_u were then used to derive profiles of moisture against time for each individual set of experimental conditions to provide

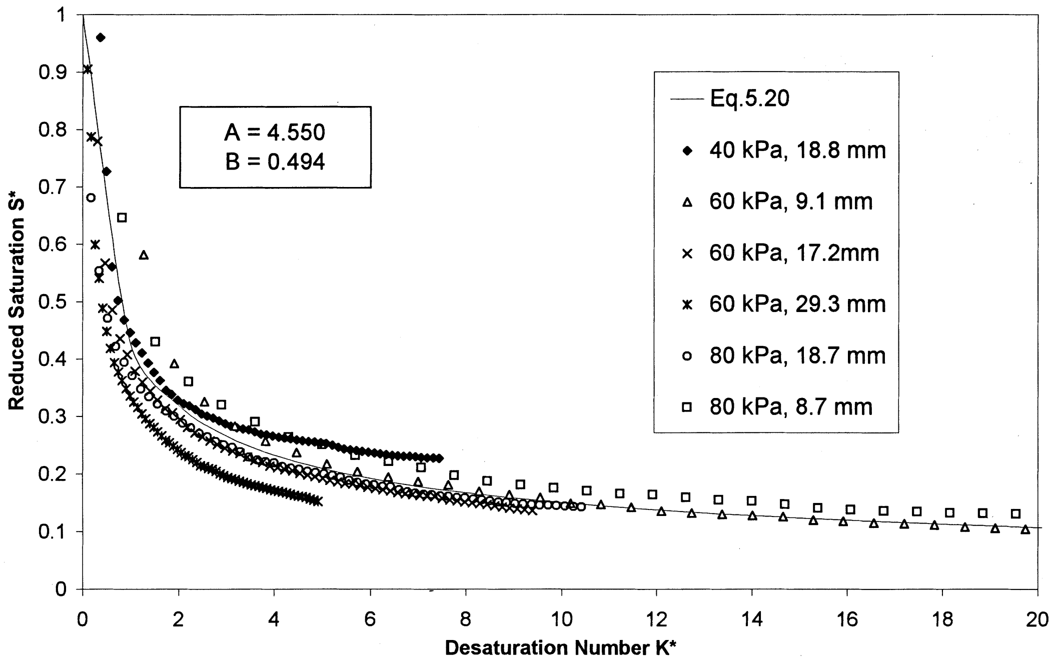

FIG. 2 Nicolaou and Stahl's model. Relation between reduced saturation and desaturation number.

a prediction of desaturation kinetics. The procedure, while containing a high degree of underlying complexity, is in fact simple to use in the computerized version of the model (FILREG) used in this study.

A minimum of three sets of desaturation data is needed to set up the model and derive values of S_u, A_u, and B_u. In this work the six sets of data given in Fig. 2, as well as several others within the envelope of dewatering conditions (not shown for reasons of clarity), were used to ensure as accurate a determination of the adaptation parameters as possible.

UNDERLYING ASSUMPTIONS OF THE MODELS

All three versions of the models used in this work have several common underlying assumptions:

- The filter cake is a porous material containing a capillary structure with capillaries covering a range of different sizes.
- The filter cake is homogeneous, isotropic, incompressible, and contains no cracks.
- Both fluids (air and water) are incompressible and immiscible.
- The capillary pressure gradient is negligible with respect to the applied displacing pressure.

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- Fluid flow is unidirectional and plug type through the capillaries which are large enough to be desaturated by the applied dewatering force.
- All moisture removal is by displacement due to the air, with no evaporation.

For fine (−0.5+0 mm) coal these assumptions are adhered to reasonably well, although great care is needed to ensure that filter cakes are as uniform as possible. In addition, Wakeman used a pore size distribution index (λ) value of 5 in developing his charts. This value, which was derived for sand, is considerably higher than the value derived (see below) for fine coal and used in the calculations of equilibrium saturation.

All of the models required the following input data:

- Cake area (A) and thickness (L).
- Profile of kinetics of cake formation to calculate permeability (k) and medium resistance (R_m) using

$$\frac{t}{V} = \frac{C^* \eta_l}{2A^2 \Delta p k} V + \frac{R_m \eta_l}{A \Delta p} \tag{10}$$

  where C^* is the concentration parameter derived from the mass balance of filtrate flow through the cake and V is the volume of filtrate collected in time t.
- Cake porosity (ε).
- Viscosity of filtrate (η_l).
- Infinite saturation = 0.155 (S_∞).
- Breakthrough pressure (p_b).
- Vacuum (Δp).

When simulating the desaturation kinetics of a given test, the experimental values of permeability, medium resistance, cake height, cake porosity, and pressure difference that were determined during that test were used as input data for the models.

Wakeman and Baluais required a value of the pore size distribution index for calculating the equilibrium saturation. Nicolaou required desaturation profiles for the material under test so that the adaptation parameters and equilibrium saturation could be calculated.

MATERIALS AND EXPERIMENTAL

All experiments were performed on flotation concentrate from a coal preparation plant in New South Wales, nominally −0.5+0 mm. Analytical details of this material together with descriptions of the experimental proce-

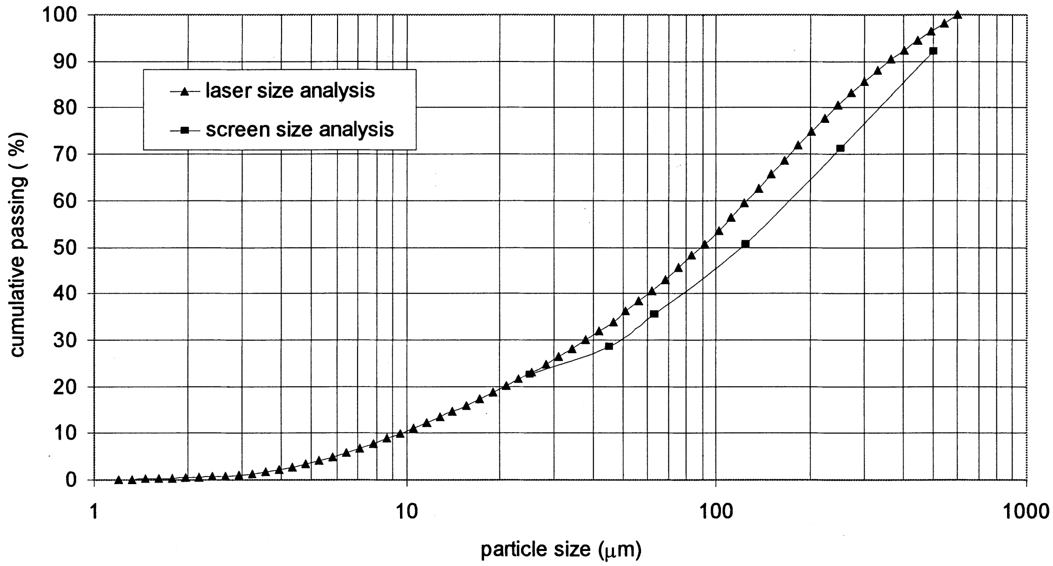

FIG. 3 Size distribution of the feed coal.

dures used are given in Ref. 3. The particle size distribution of the coal is given in Fig. 3.

Determination of the capillary pressure curves yielded values of breakthrough pressure (p_b) of 10 kPa and pore size distribution index (λ) of 0.7.

Throughout this paper, moisture content is designated as the (weight of water)/(weight of water plus the weight of solids).

RESULTS

Filtration Results

Experimental dewatering curves measuring moisture reduction as a function of time were obtained under a range of conditions, varying the pressure difference across the cake between 40 and 80 kPa and the cake height between 9 and 29 mm. Product moisture values were mainly in the 20–25 wt% moisture range for desaturation times of 50 seconds.

The conditions used covered most of those that would typically be encountered in commercial scale plants, and the results, despite the batchwise, bench-scale nature of the tests, were inherently sensible when compared to the typical performance of fine coal vacuum filters.

Several repeat series of experiments were performed to verify the quality of the experimental data. Typical examples are shown in Fig. 4 for two pairs of experiments performed at 40 kPa for cake heights of 27.0 and 29.3 mm, and at 80 kPa for cake heights of 18.1 and 18.7 mm. The small differences in cake height suggested that the desaturation profiles for each level of vacuum should

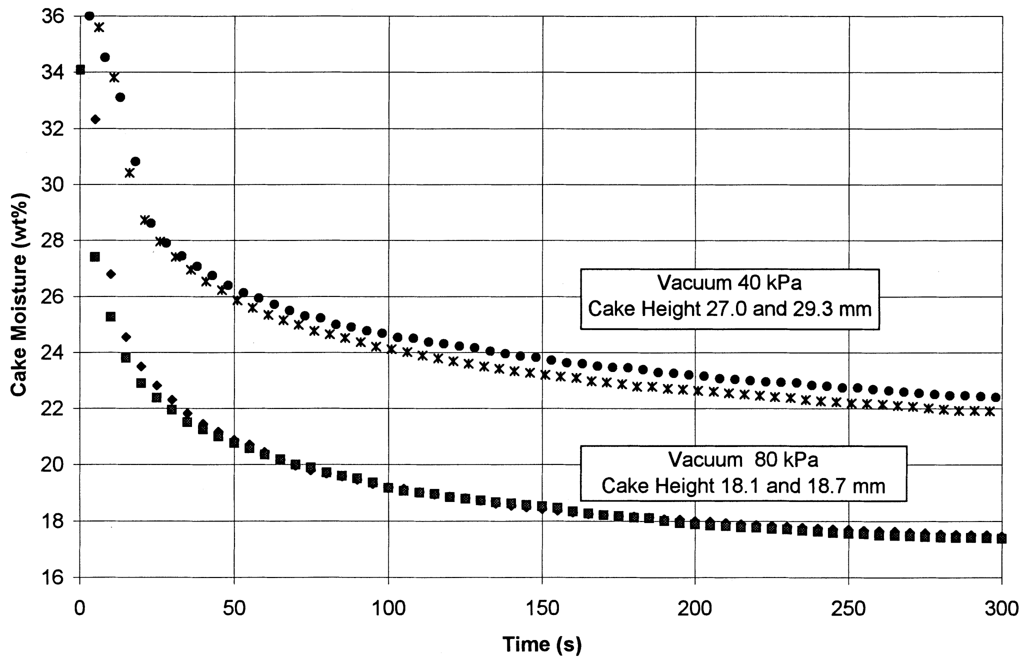

FIG. 4 Examples of experimental repeatability.

be the same, and this is indeed the case. Above a desaturation time of 15 seconds the maximum difference between either pair of curves was 0.75 wt% moisture, with most of the time being <0.3 wt% apart. Only in the very early stages of desaturation (up to 10 seconds), which is very difficult to control, did the gap exceed 1 wt%. However, this was not considered particularly important since such short times are not used in commercial practice.

The results are shown in Figs. 5–11, which compare the experimental moisture reduction kinetics with those predicted by the three models. It was important to identify some criterion by which to judge the predictive capabilities of the models. Thus it was decided that a model was being successful so long as prediction and experiment were within 1 wt% of each other.

Modeling of the Filtration Results—Desaturation Rate as a Function of Pressure Difference

Figures 5, 6, and 7 show the performance of the models in comparison with the experimental data for three levels of vacuum, 40, 60, and 80 kPa, all at the same cake height of ca. 27–29 mm.

The trends in the experimental data were as expected, with product moisture falling with increasing vacuum level at all values of desaturation time. For example, at 50 seconds, product moisture fell from 26.3 to 21.0 wt% as vacuum increased from 40 to 80 kPa. Cake porosity was constant at 0.40 ± 0.1, irrespective of vacuum, indicating that the cakes were noncompressible within

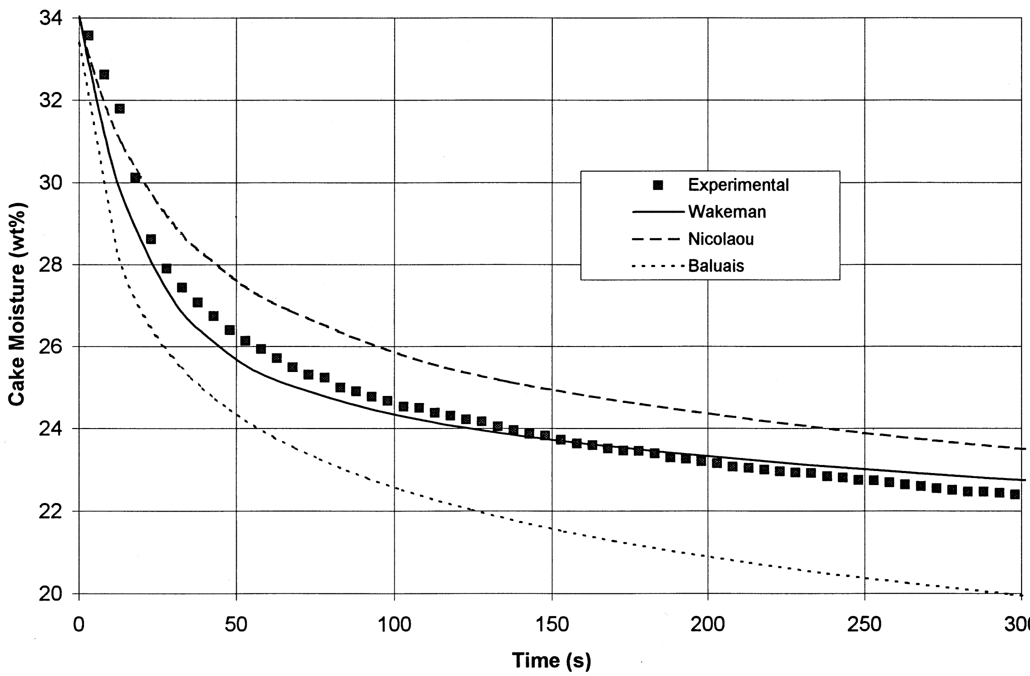

FIG. 5 Comparison of experimental and predicted desaturation kinetics (vacuum 40 kPa, cake height 29.3 mm).

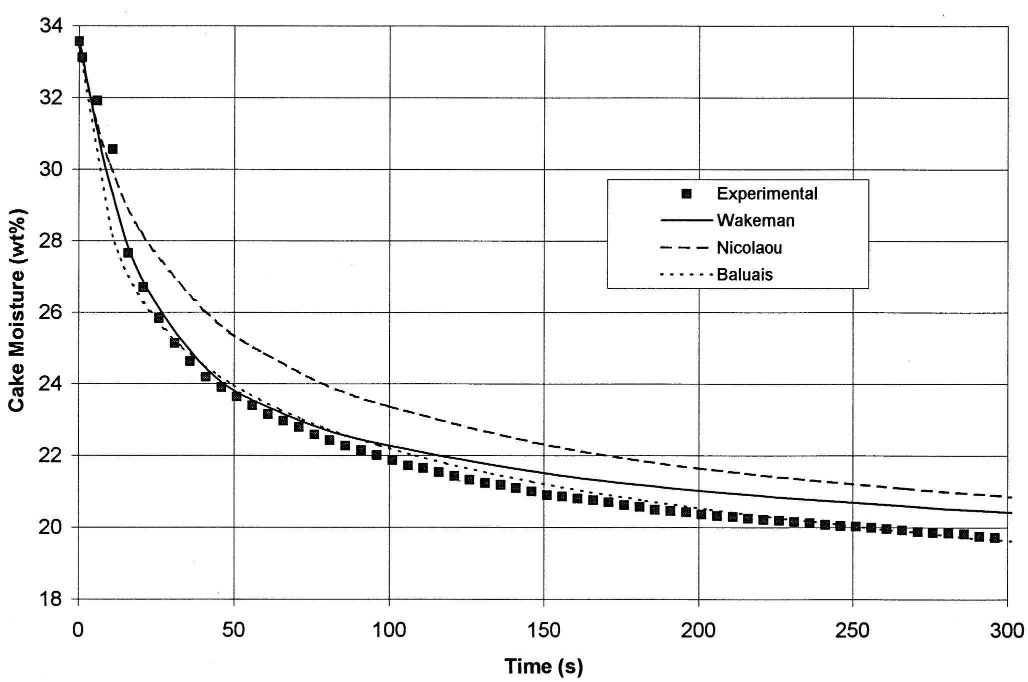

FIG. 6 Comparison of experimental and predicted desaturation kinetics (vacuum 60 kPa, cake height 29.3 mm).

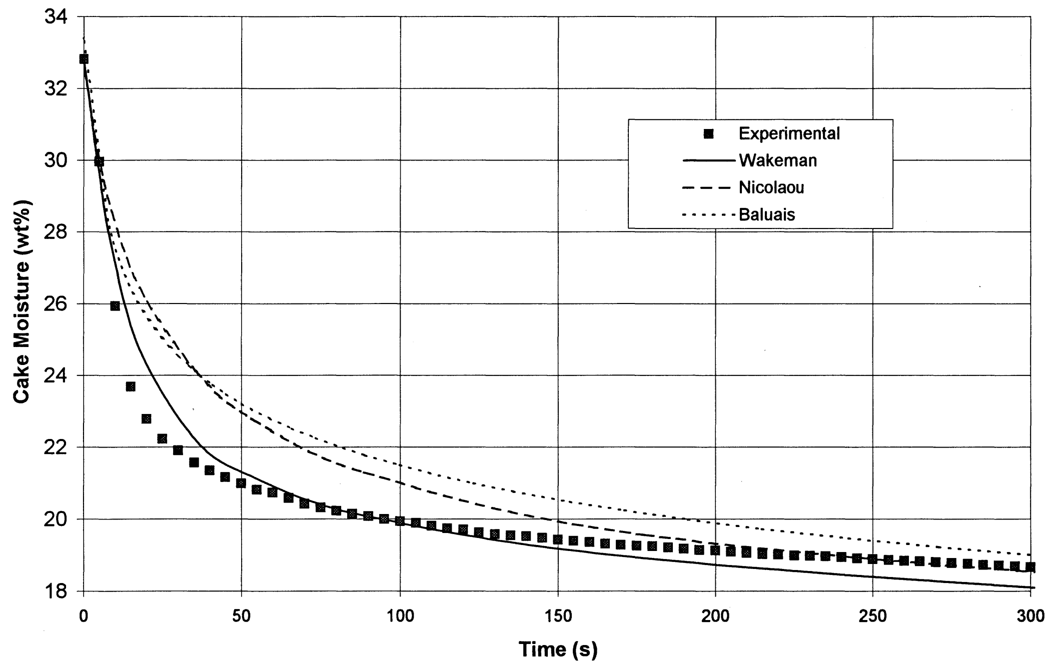

FIG. 7 Comparison of experimental and predicted desaturation kinetics (vacuum 80 kPa, cake height 27.9 mm).

the vacuum range tested. Values of cake permeability were all reasonable, being between 1.0 and 1.5×10^{-13} m^2.

The deviations in product moisture between model and experiment after desaturation times of 25, 50, and 300 seconds are shown in Table 1. A number of trends are apparent from the results:

- All three models simulated accurately the moisture levels of the cakes at prolonged dewatering times, none being more than 1.0 wt% away from the experimental values at 300 seconds desaturation time. The one exception to this was the poor performance of the Baluais model at low (40 kPa) vacuum where the deviation form experiment was 2.3 wt%.

TABLE 1
Deviations between Models (W = Wakeman, N = Nicolaus, B = Baluais) and Experiment as a Function of Vacuum Level

	Δ (Moisture) (wt%)								
	40 kPa			60 kPa			80 kPa		
Time (s)	W	N	B	W	N	B	W	N	B
25	−0.3	+1.5	−1.9	+0.1	+1.5	−0.2	+1.5	+3.2	+2.8
50	−0.6	+1.5	−2.0	+0.1	+1.6	+0.2	+0.3	+2.0	+2.1
300	+0.5	+0.9	−2.3	+0.8	+0.4	−0.1	−0.6	−0.1	+0.3

- In the region of 25–50 seconds desaturation time, none of the models was entirely successful. The Wakeman model performed the best, although at 80 kPa the deviation from experiment was 1.5 wt% after 25 seconds. At all times above 25 seconds, Wakeman's model was within 0.6 wt%.
- The Nicolaou model consistently overestimated cake moisture during the early stages of desaturation at all vacuum levels, the difference between model and experiment being quite high (1.5–3.2 wt%). By contrast, the Baluais model underestimated product moisture at 40 kPa, was virtually on spot at 60 kPa, and overestimated product moisture at 80 kPa. Again, the deviations from experiment were quite large, being up to 2.8 wt%.

Modeling of the Filtration Results—Desaturation Rate as a Function of Cake Height at 80 kPa

Figures 7, 8, and 9 show the performance of the models in comparison with the experimental data for three levels of cake height (27.9, 18.1, and 8.7 mm) for a fixed vacuum of 80 kPa.

The trends in the experimental data were as expected, with product moisture tending to fall with decreasing cake height at all values of desaturation time, although the effects were not large given the large proportional changes

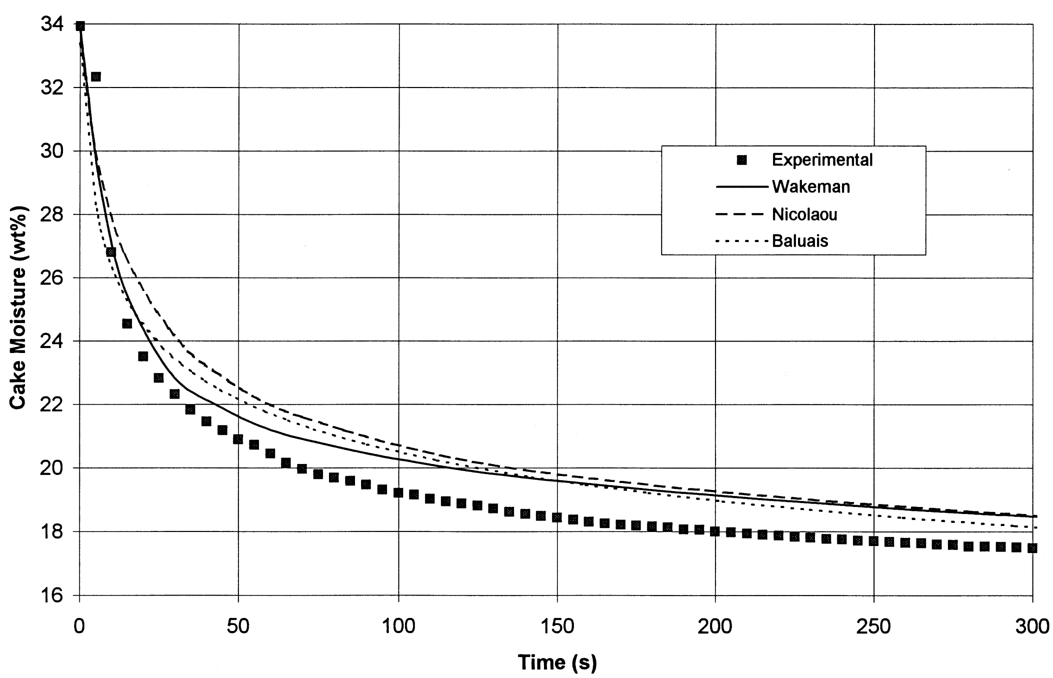

FIG. 8 Comparison of experimental and predicted desaturation kinetics (vacuum 80 kPa, cake height 18.1 mm).

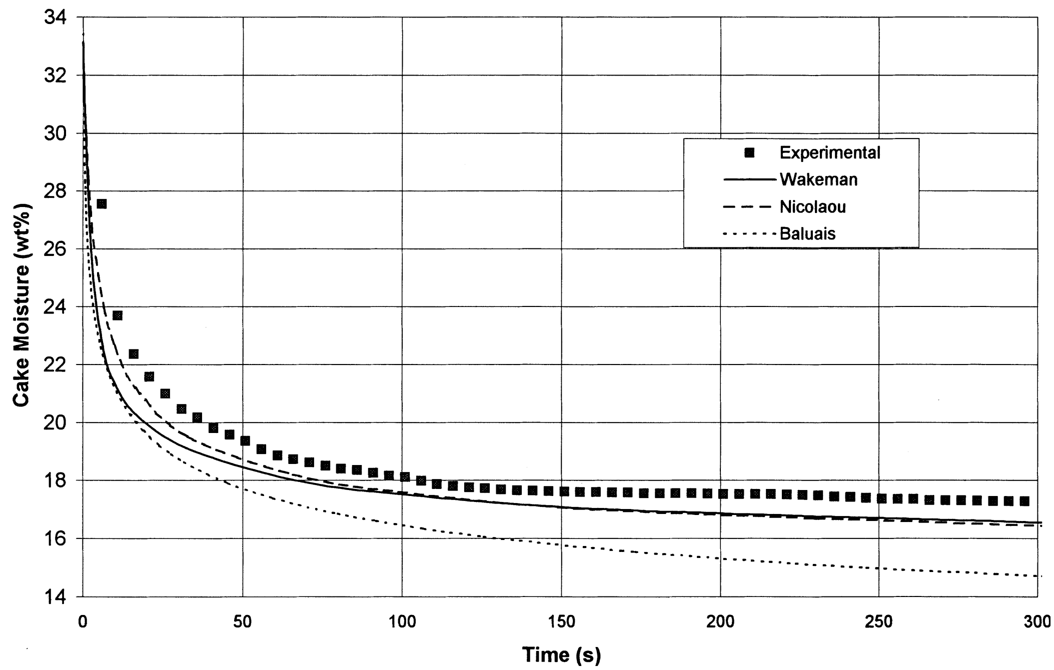

FIG. 9 Comparison of experimental and predicted desaturation kinetics (vacuum 80 kPa, cake height 8.7 mm).

in cake height. For example, at 25 and at 50 seconds, product moisture values for the 27.9 and 18.1 mm cakes were 22.5 ± 0.3 and 21.0 ± 0.1 wt%, respectively. At 25 and 50 seconds the corresponding values for the thinnest cake were slightly lower at 21.1 and 19.4 wt%. At 300 seconds the cake moisture contents fell more regularly, from 18.7 wt% for the 27.9 mm cake down to 17.3 wt% for the thinnest cake.

The reason(s) for the relative insensitivity of experimental desaturation kinetics to cake height are not clear. Cake porosity was constant at 0.40 ± 0.1, irrespective of cake height, and values of cake permeability were all reasonable, being between 0.6 and 1.0×10^{-13} m^2. Experimental error is not thought likely because similar effects were determined at 60 kPa (see later).

The deviations in product moisture between model and experiment after desaturation times of 25, 50, and 300 seconds are shown in Table 2. A number of trends are apparent from the results:

- As with the data at different levels of vacuum, the Wakeman and Nicolaou models simulated accurately the moisture levels of the cakes at prolonged dewatering times, with neither being more than 1.0 wt% away from the experimental values at 300 seconds desaturation time. The one exception was the poor performance of the Baluais model at low cake height (8.7 mm) where the deviation from experiment was 2.6 wt%.

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TABLE 2
Deviations between Models (W = Wakeman, N = Nicolaus, B = Baluais) and Experiment as a Function of Cake Thickness at 80 kPa

	Δ (Moisture) (wt%)								
	27.9 mm			18.1 mm			8.7 mm		
Time (s)	W	N	B	W	N	B	W	N	B
25	+1.5	+3.2	+2.8	+0.8	+2.2	+1.2	−1.4	−0.7	−2.0
50	+0.3	+2.0	+2.1	+0.7	+1.6	+1.3	−0.9	+0.6	−1.7
300	−0.6	−0.1	+0.3	+1.0	+1.0	+0.6	−0.6	−0.7	−2.6

- In the region of 25–50 seconds desaturation time for the two thickest cakes, all three models overestimated cake moisture, with Wakeman being the most successful.
- For the thinnest cake (8.7 mm) at shortest times, the Nicolaou model was very successful, deviating from experiment by <0.7 wt% across the entire length of the profile. Both the Wakeman and Baluais models underestimated product moisture, although the deviations with the Baluais model (1.7–2.0 wt%) were significantly greater.

Modeling of the Filtration Results—Desaturation Rate as a Function of Cake Height at 60 kPa

Figures 6, 10, and 11 show the performance of the models in comparison with the experimental data for three levels of cake height (27.9, 17.2, and 9.1 mm), all at the same vacuum of 60 kPa.

The trends in the experimental data were, again, as expected, with product moisture falling with decreasing cake height. For example, at 50 seconds the product moisture fell from 23.7 to 23.1 and then to 20.7 wt% as cake height decreased from 29.3 through 17.2 to 9.1 mm. As in the previous tests, cake porosity was virtually constant at 0.40 ± 0.1, and values of cake permeability were all reasonable and very similar, being between 0.8 and 1.0×10^{-13} m^2.

The deviations in product moisture between model and experiment after desaturation times of 25, 50, and 300 seconds are shown in Table 3. The trends in the data are very similar to the results for the effect of cake thickness at 80 kPa. In particular:

- The Wakeman and Nicolaou models again simulated accurately the moisture levels of the cakes at prolonged dewatering times, with neither being more than 1.0 wt% away from the experimental values at 300 seconds desaturation time. The one exception to this was the poor performance of the

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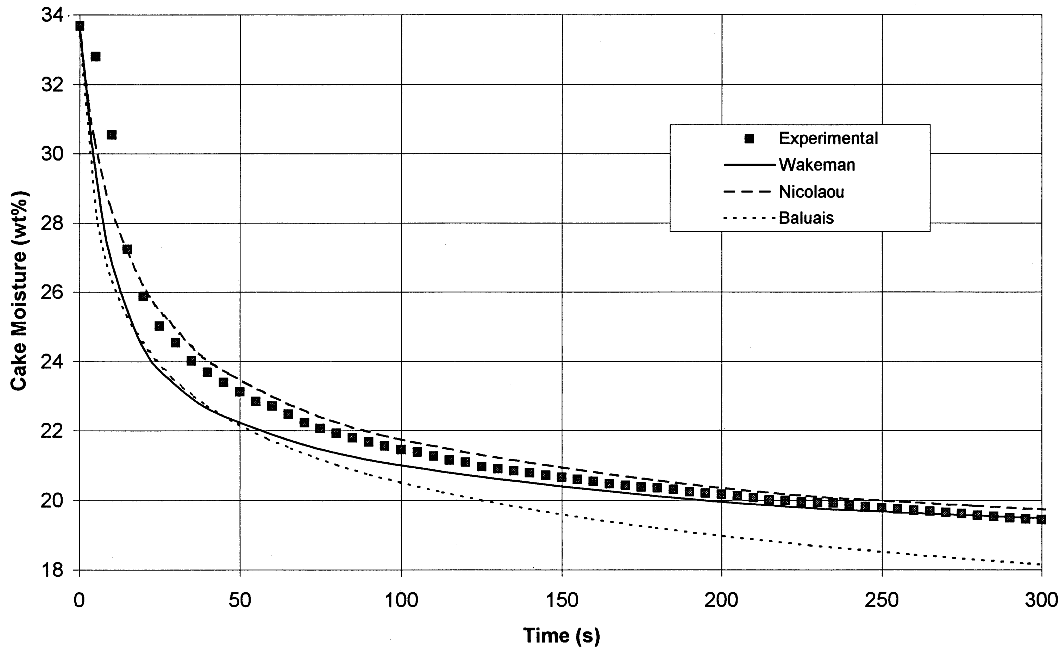

FIG. 10 Comparison of experimental and predicted desaturation kinetics (vacuum 60 kPa, cake height 17.2 mm).

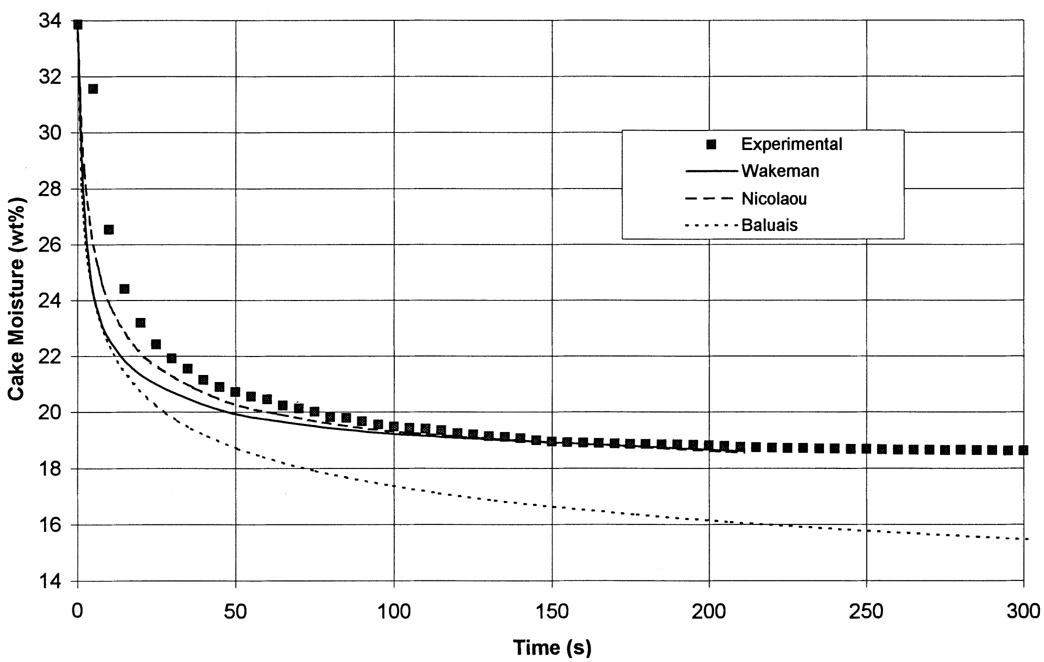

FIG. 11 Comparison of experimental and predicted desaturation kinetics (vacuum 60 kPa, cake height 9.1 mm).

TABLE 3
Deviations between Models (W = Wakeman, N = Nicolaus, B = Baluais) and Experiment as a Function of Cake Height at a Vacuum of 60 kPa

	Δ (Moisture) (wt%)								
	29.3 mm			17.2 mm			9.1 mm		
Time (s)	W	N	B	W	N	B	W	N	B
25	+0.1	+1.5	−0.2	−1.2	+0.7	−1.0	−1.3	−0.6	−2.1
50	+0.1	+1.6	+0.2	−0.9	+0.5	−0.9	−0.8	−0.4	−1.9
300	+0.8	+0.4	−0.1	+0.1	+0.3	−1.3	−0.4	−0.4	−3.2

Baluais model at the two lower cake heights of 17.2 and 9.1 mm, where the deviations from experiment were, respectively, 1.3 and 3.2 wt%.

- For the thinnest cake (9.1 mm) the Nicolaou model was very successful, deviating from experiment by <0.6 wt% across the entire length of the profile. Both the Wakeman and Baluais models underestimated product moisture, although the deviations with the Baluais model (1.9–3.2 wt%) were significantly greater.

However, there were some differences in the trends between 60 and 80 kPa, in particular:

- At 60 kPa, the Baluais model performed well on the thickest cake, but performance deteriorated as cake height fell, with the underestimation of cake moisture increasing progressively with cake height. At 80 kPa, the Baluais model was not good at any cake height, although the same progression toward increasing underestimation of cake moisture was evident.
- The Nicolaou model performed much better with the intermediate cake at 60 kPa than at 80 kPa for all values of desaturation time.

CONCLUSIONS

1. Mathematical models devised by Wakeman, Baluais, and Nicolaou have been compared in their ability to predict the desaturation kinetics of fine (−0.5+0 mm) coal during vacuum filtration.
2. All models were capable of predicting cake moisture after long (300 seconds) desaturation times to within 1 wt% of the experimental values, except the Baluais model which deviated by 2.3–3.3 wt% at the lowest vacuum tested (40 kPa) and the thinnest cakes (8–9 mm)
3. At shorter times (25–50 seconds) the Wakeman model gave the best overall performance, never deviating by more than 1.5 wt% from experiment.

4. The Nicolaou model was best at predicting desaturation kinetics of the thinnest (8–9 mm) cakes.
5. Work is ongoing to explore some of the underlying reasons for the trends observed herein, and to apply the models to fine coal filtered in the presence of polymer flocculants.
6. The model comparison described in this paper pertains only to the feedstock and envelope of filtration conditions used in this work and should not be extrapolated to other systems.

NOMENCLATURE

A	cake area
A_N and B_N	adaptation parameters (Nicolaou)
A_u and B_u	adaptation parameters calculated from nonlinear regression of desaturation curves (Fig. 2) (Nicolaou)
f_l and f_a	fractional flow rate of liquid and air (Baluais)
k	cake permeability
k_l and k_a	relative permeabilities of filter cake to liquid and air
K^*	dimensionless desaturation time (Nicolaou)
Δp	pressure difference
L	cake height
p_b	breakthrough pressure
p_l^* and p_a^*	Dimensionless pressures in the residual liquid and air at the cake surface (Wakeman)
Q	total flux rate of liquid and air (Baluais)
R_m	medium resistance
S	cake saturation
S_R	reduced saturation
S_b	saturation at air breakthrough (Baluais)
S_{eq}	equilibrium saturation
S_{av}	average saturation (Baluais)
S_L	saturation at exit face of cake (Baluais)
S_u	saturation calculated from nonlinear regression of desaturation curves (Fig. 2) (Nicolaou)
S_∞	irreducible saturation (0.155)
t	desaturation time
v_l^* and v_a^*	dimensionless flux densities of liquid and air (Wakeman)
x/L	dimensionless distance into the cake from air entry surface
ε	cake porosity
η_l and η_a	liquid and air viscosities
λ	pore size distribution index
τ	reduced desaturation time

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