A validation study of the King stratification model

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Synopsis

This paper presents a study on the ability of the King stratification model to describe density stratification patterns that are achieved under idealized conditions. Tests were conducted in a batch jig using artificial particles in seven density classes. All particles in a density class had essentially the same density, size, and shape. Tests were conducted for particle systems involving from two to seven components. Good agreement was obtained between measured and modelled data to an extent that gave strong endorsement of the mathematical appropriateness of the core equation in the King model. Somewhat ambiguous results were found with regard to claims about the independencies of the single experimentally-determined parameter required by the model.

Keywords

mineral jigs, jigging, batch jigging, stratification, mineral beneficiation.

Introduction

Several mineral beneficiation processes are based on stratifying particles in a bed according to their density. Although this approach to separating minerals has a long history, it has proved quite difficult to develop reliable models that can describe or predict density stratification in a satisfactory way. Mehrotra and Mishra (1997) provide an excellent review of the different modelling approaches that have been used.

One of the most promising models of stratification currently available is that due to King (King, 1987; Tavares and King, 1995; King, 2001). The model has been shown to give very good agreement with experimental data for systems of PVC cubes, simple coal systems, and coal and marble mixtures (Vetter, 1987; King, 1987), and reasonable agreement for stratification of an iron ore (King, 1987). In each case the systems were binary in nature. Tavares and King (1995) extended the range of experimental validation by showing good fits of the model with Vetter's (1987) data for ternary systems of PVC cubes, and of coal-marble mixtures. They also reported additional validation work that involved multi-component coal systems and continuous jigging. That work focused on testing a model of continuous jigging based on the King stratification model combined with models for the splitting efficiency and for flow patterns in a jig. Although that work constituted a test of the model of continuous jigging, as opposed to a test of the stratification model, it is significant that good fits of the experimental data were obtained – a result that provides further support for the veracity of King's stratification model.

Since the model was first published in 1987 and then extended in 1995 it has received little attention in the literature. This is rather surprising given, firstly, the considerable potential which the abovementioned validation work demonstrates, and secondly, that the model has some inherent restrictions which suggest that further development is worthwhile given its demonstrated potential. This paper makes a contribution in this regard by presenting additional validation work. It begins with a summary of the model and thereafter presents the findings from a validation study based on stratification in a batch jig.

The King stratification model: a summary

The King model envisages that density stratification of particles in a bed is the result of a dynamic equilibrium between two vertically opposing fluxes of particles – a stratification flux and a diffusive flux. The stratification flux is driven by the reduction in potential energy that occurs when particles of different densities stratify (Mayer, 1964). The diffusive flux is driven by 'random walk' diffusion processes that are considered to be Fickian in nature. When particle motion has reached a state of dynamic equilibrium, the two opposing fluxes are equal and the concentration profiles

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 ISSN 2225-6253. Paper received Jul. 2014; revised paper received Sep. 2014.

of particles of different density stabilize. King developed expressions for the two fluxes in a bed of mono-sized spheres. Equating expressions for the two fluxes leads to the differential equation (Equation [1]) (Tavares and King, 1995, King, 2001), which is at the heart of the King model.

$$\frac{dC_j(h)}{dh} = -\alpha\, C_j(h)[\rho_j - \bar{\rho}(h)] \qquad [1]$$

In this equation, $C_j(h)$ is the volumetric concentration of particles having a density ρ_j in the very thin horizontal layer in the bed located at a relative height h to $h+dh$ from the bottom of the bed, *i.e.* $h=H/H_{bed}$ where H is the actual height of the bottom of the thin layer and H_{bed} is the height of the bed. The variation of $C_j(h)$ with h is termed the concentration profile.

In Equation [1], $\bar{\rho}(h)$ is the average density of the particles in the thin layer at h and can be calculated from Equation [2]

$$\bar{\rho} = \sum_{all\, j} C(j)\, \rho_j \qquad [2]$$

The *stratification parameter*, α, is a composite parameter which, as Equation [3] indicates, takes into account the nature of the diffusive flux as described by the diffusion coefficient, D, and the nature of the stratification flux as described by the 'specific penetration velocity' $\bar{u}$. The other terms in α are the gravitational acceleration, g, the volume of each particle, v, and the depth of the bed, H_{bed}. The stratification constant has the units of inverse density and, significantly, is not a function of particle density or of the composition of the feed to the jig.

$$\alpha = \bar{u}\, g\, v\, H_{bed} / D \qquad [3]$$

To determine the concentration profile, Equation [1] must be integrated to give Equation [4]. (Note that in this equation, k is used to represent the relative height instead of h within the integral, *i.e.* $\int_0^h \bar{\rho}(k)\, dk$)

$$C_j(h) = C_j^o \exp(-\alpha\rho_j h + \alpha \int_0^h \bar{\rho}\,(k)\, dk) \qquad [4]$$

C_j^0 is the concentration of component j at the bottom of the bed (*i.e.* $h = 0$) and is related, through Equation [5], to C_j^f, the concentration of component j in the feed to the jig.

$$C_j^o = C_j^f / \left[\int_0^1 \left\{\exp(-\alpha\rho_j h + \alpha \int_0^h \bar{\rho}\, dk)\right\} dh\right] \qquad [5]$$

Equation [4] can be solved analytically for binary systems (King, 1987; 2001) but a numerical procedure is required for multicomponent systems involving more than two components (Tavares and King, 1995; King, 2001). They suggest an iterative procedure beginning with an estimate of $\bar{\rho}(u)$, integrating numerically, and normalizing successive estimates of C_j^0 to satisfy the constraint that $\sum_{all\, j} C_j^0 = 1$.

Application to batch jigging

In batch jigging, a density separation is performed by splitting the stratified bed horizontally at some height h_{split} to form two layers – the upper layer consisting predominantly of less dense particles and the lower layer consisting predominantly of denser particles. However, for the purposes of experimentation and parameter estimation of parameter the bed can be split into a number of slices, where any slice i consists of the particles found between $h=b_i$ and $h=t_i$. Here b_i and t_i are respectively the relative height of the bottom and top of slice i. The concentrations of the various components in each slice can be determined experimentally and the value of the stratification parameter that leads to the best fit of the experimental data can be established by an appropriate regression procedure. In such a procedure, the experimental data can be expressed in several forms: namely as C_j^i, the concentration of component j in slice i; or as $\overrightarrow{C}_j$, the cumulative concentration of component j up to h (*i.e.* the concentration of j in the lower part of the bed from h=0 to h= h_{split}); or as $\overleftarrow{C}_j$, the cumulative concentration down to h (*i.e.* the concentration of j in the upper part of the bed from h=1 to h=h_{split}); or as $\overrightarrow{R}_j^i$ or $\overleftarrow{R}_j^i$, the recovery of the component j to the lower or upper layers respectively. The corresponding model values relating to the upper and lower layers in the bed can be calculated from the concentration profile, C_j, using Equation [6] or [7] and appropriate values for b_i and t_i.

$$C_j^i = \frac{1}{t_i - b_i} \int_{b_i}^{t_i} C(j)\, dh \qquad [6]$$

$$R_j^i = \frac{1}{C_j^f} \int_{b_i}^{t_i} C(j)\, dh \qquad [7]$$

An investigation into the veracity of the King model

The rationale behind the study reported in this paper is that, at very least, the model should be able to describe stratification behaviour under ideal conditions. Accordingly, tests were conducted in a batch jig in which reproducible and tightly controlled conditions could be maintained. A pilot-scale jig was kindly made available by Mintek in Johannesburg. Wall effects were minimized by using a reasonably large, cylindrical jigging chamber. The diameter of the chamber was 300 mm, which was well over 17 times the diameter of the particles used in the study. In addition, the particles selected for the study were ideal in nature in that they were all essentially the same size and the particles in each density class all had essentially the same density, as indicated in Table I. The particles used were colour-coded 'density tracers' which had been manufactured for conducting investigations on the performance of DMS separators in the coal industry. Although the particles were not the ideal spherical shape assumed by the King model, all particles had the same shape. As shown in Figure 2, this shape was essentially that of a squat cylinder with a domed top surface and an indented bottom surface. The diameter of the particles was 17 mm and the height between 7 and 8.5 mm. The small degree of variation in the density and the dimensions of the tracers is shown in Table I.

Experimental details

As shown in Figure 1, the jig chamber was made up of rings that were 25 mm in height and had an internal diameter of 300 mm. The rings were mounted on top of each other on the jig support screen to make up a cylindrical jigging chamber about 0.3 m high. After the rings had been clamped together, the sample to be tested was poured into the chamber, which

Table I

Specific gravities and dimensions of the density tracers

Tracer colour	Orange	Yellow	Green	Pink	Blue	Red	Woody
Code	**O**	**Y**	**G**	**P**	**B**	**R**	**W**
No. of tracers measured	6	6	5	5	4	5	5
Specific gravity (SG)							
Nominal SG	**2.1**	**1.9**	**1.7**	**1.6**	**1.5**	**1.4**	**1.3**
Measured SG	**2.130**	**1.916**	**1.714**	**1.579**	**1.520**	**1.417**	*
Std deviation	0.0039	0.0332	0.0014	0.0013	0.0021	0.0107	*
% std deviation	0.18	1.73	0.08	0.08	0.14	0.76	*
Tracer volume							
Average (ml)	**1.854**	**1.809**	**1.693**	**1.687**	**1.605**	**1.807**	**1.416**
Std deviation (ml)	0.0291	0.0468	0.0296	0.0247	0.0196	0.0529	0.0196
% std deviation	1.57	2.59	1.75	1.47	1.22	2.93	1.36
Tracer dimensions (mm)							
Diameter	17	17	17	17	17	17	16
Average height	8.2	8.0	7.5	7.4	7.1	8.0	7.3

*The woody tracers were smaller than the other tracers and so were used only when a seven-component system was needed. There was uncertainty about their effective density because they were porous. Accordingly, the nominal value of 1.3 was taken as their SG

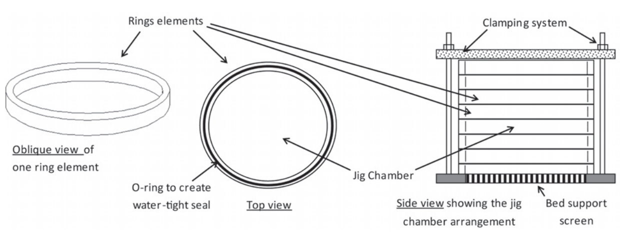

Figure 1—Details of construction of the jig chamber

was then flooded with water and subjected to the jigging cycle shown in Figure 2. The jig cycle was generated pneumatically and was controlled by a PLC so that the jigging conditions in every test were identical. In each test, a hutch water flow of 500 ml/min was maintained. The duration of each test was 20 minutes, which had been shown to be well in excess of the time required for the concentration profiles in the bed to reach a state of equilibrium. After each test the bed height was measured, the rings were unclamped, and slices were removed progressively from the top of the bed by inserting a slicing device between the rings. Except for the top slice, each slice constituted a layer of the bed 25 mm thick.

Six tests were undertaken to investigate how well the model fitted the experimental data for particle systems involving from two to seven components. About 3000 particles were used for each test which amounted to between 7 and 11 kg per sample, depending on the density of the particles. Preliminary tests had indicated that this was sufficient to produce a bed height of around 100 to 150 mm, which would allow the bed to be sliced horizontally into 4–6 fractions. This had been shown to give a satisfactory definition of the concentration profiles within the constraints of the experimental conditions, namely that the bed could be sliced only in 25 mm increments, that the particles were relatively large (*i.e.* around 8×17 mm), and that tests involving only the seven densities indicated in Table I could be undertaken.

The compositions of the particle systems tested are shown in Table II. In most cases the proportions of each component were approximately similar, but arbitrary adjustments were made to obtain round numbers. This approach was violated for the two-component system because insufficient red tracers were available to make up a 50:50 mixture of the required bed volume. The woody coloured tracers were used only when the seven-component system was investigated because they were slightly smaller than the other tracers and because, being slightly porous, their effective density in a jigging environment was uncertain; measured SGs varied between 1.28 when measured dry and 1.35 after they had been soaked in water. The SG value used for this component in the analysis of the seven-component system was 1.3, the nominal value given by the manufacturers of the tracers. The shape of the tracers is shown in Figure 3.

Results

Stratification patterns in the jig

The experimental data obtained, together with the best model fits to that data, is shown in Figures 4 to 10. Plots of component recoveries as a function of split height are the most compact way to present the data, and these are presented first (Figure 4). The plots show $\overleftarrow{R}_j^{\,i}$, the component recoveries to the top (lighter) fraction when the bed is split at a relative height h. The curves in the plots represent the

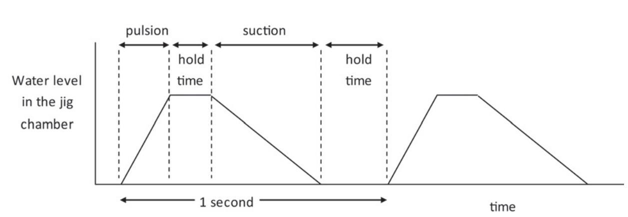

Figure 2—The jig cycle used in the tests

Table II

Compositions of the six particle systems investigated

	Volumetric composition (%)						
Tracer SG	**2.130**	**1.916**	**1.714**	**1.579**	**1.520**	**1.417**	**1.3**
Tracer colour*	Orange	Yellow	Green	Pink	Blue	Red	Woody
2 components (BR)					70	30	
3 components (OYG)	38	25	37				
4 components (OYBR)	25	25			25	25	
5 components (OYGBR)	21	18	20		20	21	
6 components (OYGPBR)	15	12	17	11	30	14	
7 components (OYGBPBRW)	15	13	11	12	14	14	21

* The particle systems tested are identified by a code that uses the initial letter of the tracer colour to indicate which components made up that system

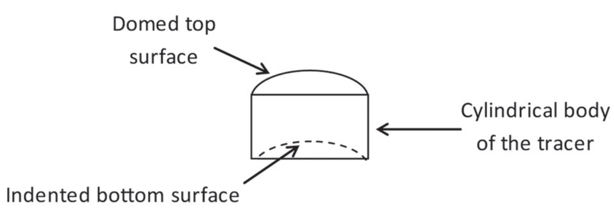

Figure 3—Shape of the density tracers

recoveries calculated using the model while the points represent the experimental data. It should be noted that for each particle system, only a single experimentally determined parameter value (for α) was used to generate the recovery curves for each component in that system. The actual values of the parameters for the different systems are presented and discussed in the following section. If the model provides a good description of the stratification patterns achieved, then the experimentally determined recoveries and the model values should coincide. As can be seen from Figure 4, the level of agreement between the model and experimental values is remarkably good.

Figure 5 to 10 compare experimentally determined concentrations in the jig bed with the data generated by the model. In each figure, the right-hand column of plots shows the variation of the cumulative concentrations, $\overleftarrow{C}_j$, of the upper layer of the bed as a function of h. Each curve indicates what the model predicts the concentration of component j would be in the top (lighter) fraction of the bed if it were to be split at a relative height $h_{split}=h$. The filled circles represent experimental points. These should fall on the relevant curve if the model is providing an accurate description of stratification behaviour. As can be seen, the alignment of the experimental and modelled values is remarkably good. Only with two points in the four-component system is there some substantive misalignment, and even there the experimental and modelled values differ by no more than 5%.

The left-hand columns of the plots in Figures 5 to 10 compare the measured component concentrations in each slice, C_j^i, shown as filled circles, with the model-predicted values shown as unfilled circles. To provide perspective when comparing these values, the concentration profile, C_j, for each component is shown as a dotted curve. This curve refers to the concentration of component j in the very thin layer at h, whereas the filled and unfilled points refer to the much thicker slices removed experimentally from the particle bed, the vertical centres of these slices being located at h. Accordingly, at the relevant value of h, the C_j^i points for the thick slices should have a value somewhere near the value of C_j (for very thin layers), but these values should not necessarily coincide, because they refer to layers of different thicknesses.

As can be seen from the figures, there is a generally good agreement between the experimentally measured and modelled values and, in most cases, these values are close to the curve. However, the agreement is not always as good as is the case with the cumulative concentrations (the right-

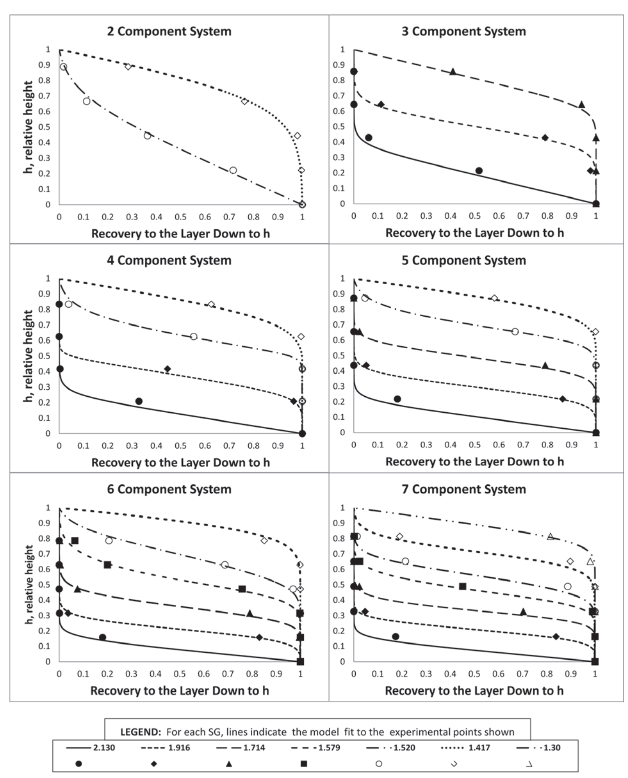

Figure 4—Component recoveries to the upper layer of the stratified bed

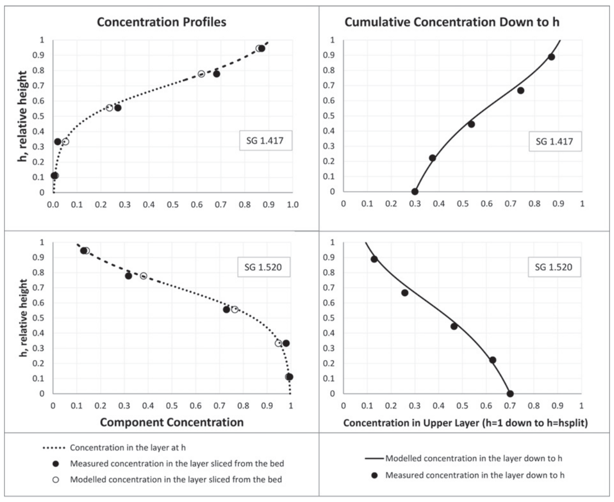

Figure 5—Concentration plots for the two-component system shown in Figure 4

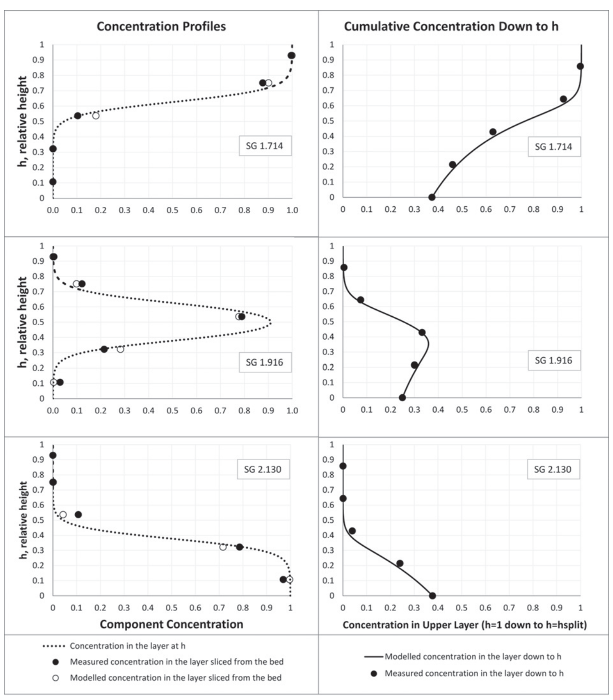

Figure 6—Concentration plots for the three-component system shown in Figure 4

hand plots in the figures) and some significant differences occur; in eight cases, the difference is as large as 10% and in two cases it is 16%.

It is to be expected that the coincidence of measured and modelled data for the concentration profiles would not be as good as with the cumulative concentration data because the former is inherently more sensitive to experimental error. When slicing the particle bed, the slicer is forced through the bed and particles that lie in the path of the slicer are forced upwards or downwards into the layer above or below the slicer. In this process, particles can be misplaced to the wrong layer. In addition, because the particles are relatively large, misplacement errors can also occur because the particle

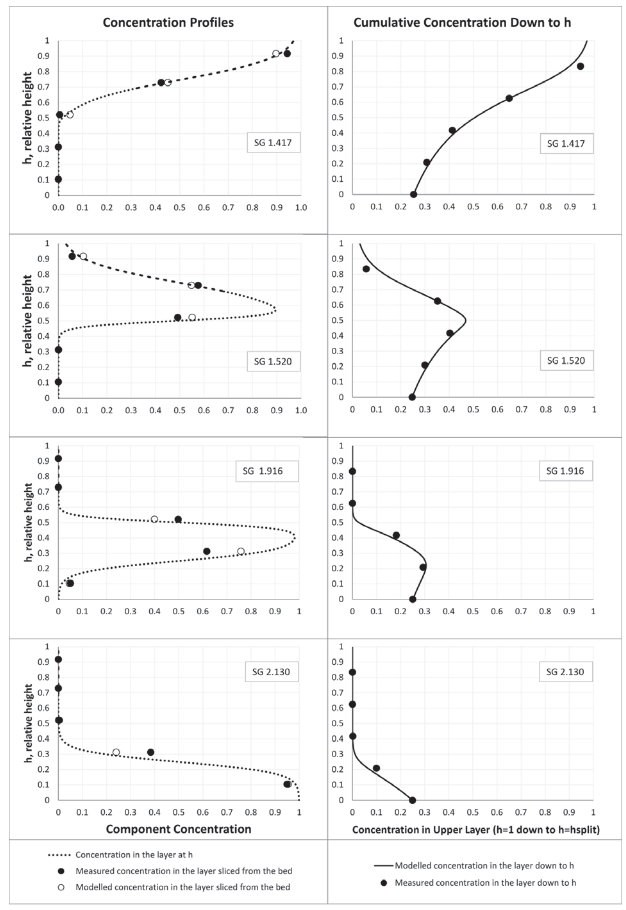

Figure 7—Concentration plots for the four-component system shown in Figure 4

displacement disturbs adjacent particles and, in some cases, may scour out adjacent particles to the upper or lower layer. While such misplacement errors are associated with all the data in the study, the error is doubled when determining the concentrations of slices removed from the bed. This is because the slicing error occurs at both the top and bottom of the slice. When the data is cumulated from the top of the bed, the error is associated only with the bottom of the slice and the effect of the error diminishes as the data is cumulated downwards through the bed. The situation is similar when cumulating from the bottom of the bed.

Considering all results taken together, it can be concluded that the model was able to give reasonable to good descriptions of the concentrations of slices taken from the bed, and remarkably good descriptions of the cumulative concentrations and recoveries associated with the upper fraction of the bed when it is split at any particular height h. With regard to the lower fractions split from the bed, a similar positive conclusion is reached both by implication and by examining the relevant plots (not shown in this paper). The implication of these conclusions is that given the feed composition to a batch jig, the density of each component in the feed, and a single experimentally determined parameter, α, the model is able to give reliable descriptions of the stratification that would be achieved in a batch jig under equilibrium conditions.

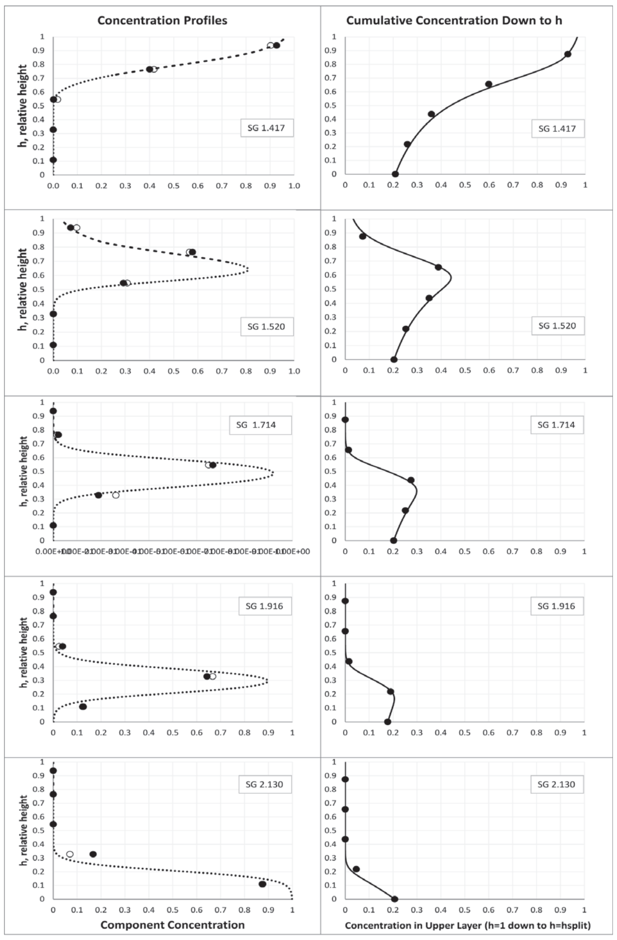

Figure 8—Concentration plots for the five-component system shown in Figure 4

The value of the stratification parameter

A significant feature of the King stratification model is its claim that the value of the stratification parameter, α, is independent of feed composition and the densities of the components in the feed. According to Equation [3], α is a function only of particle volume, the height of the bed, H_{bed}, and the stratification dynamics in the bed represented by $\bar{u}$ and D. Bed height varied in the different tests so the value of α is not expected to be the same for each test. However, the ratio α/H_{bed} should be the same if the model claim is valid. To test this claim, Table III presents the values of α that give the best fits for each set of experimental data, as well as the associated values of H_{bed} and α/H_{bed}.

As can be seen from the table, the value of $\boldsymbol{\alpha}$ increases steadily as the particle systems become more complex; the highest value is 2.5 times greater than the smallest value. When bed height is taken into account – by calculating α/H_{bed} – it is evident that the trend persists to some extent; *i.e.* there is, with two exceptions, an increase in the value of α/H_{bed} as the particle systems involve more components. The implication of this is that the model's assumptions about the independencies of the stratification parameter are not supported by our data. However, this implication is not conclusive because it turns out that the model predictions are relatively insensitive to the value of α over the range of

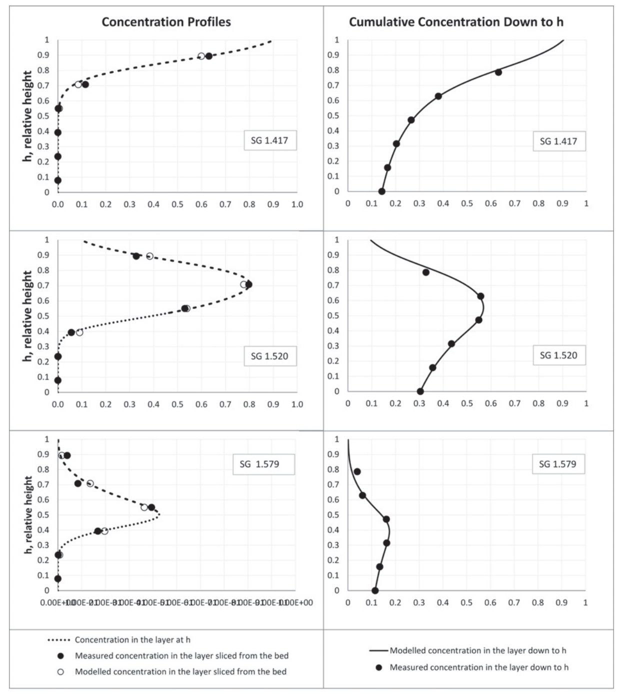

Figure 9a—Concentration plots for the six-component system shown in Figure 4 (plots for components 1 to 3)

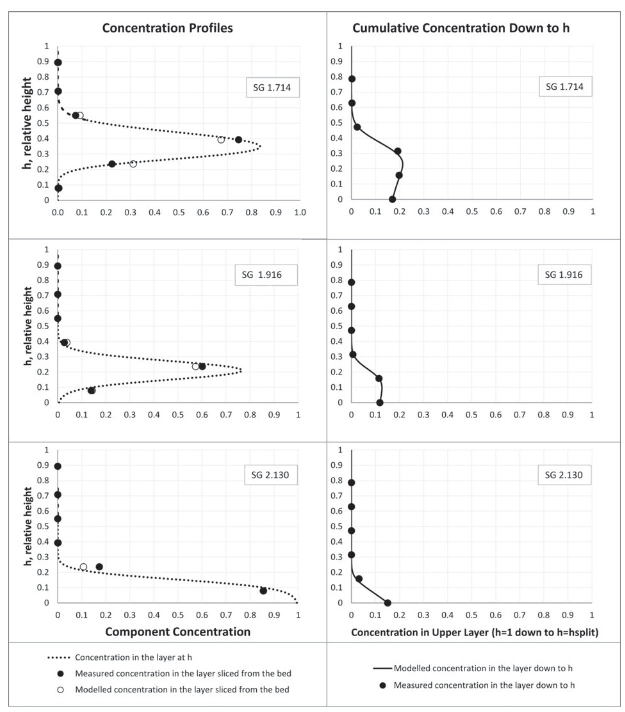

Figure 9b—Concentration plots for the six-component system shown in Figure 4 (plots for components 4 to 6)

values measured in the test; therefore the trend noted may, to some degree, be spurious. This insensitivity is demonstrated most easily by comparing the plots of recoveries and cumulative concentrations derived using 'best-fit' values of $\boldsymbol{\alpha}$ with the plots derived assuming that α/H_{bed} was indeed

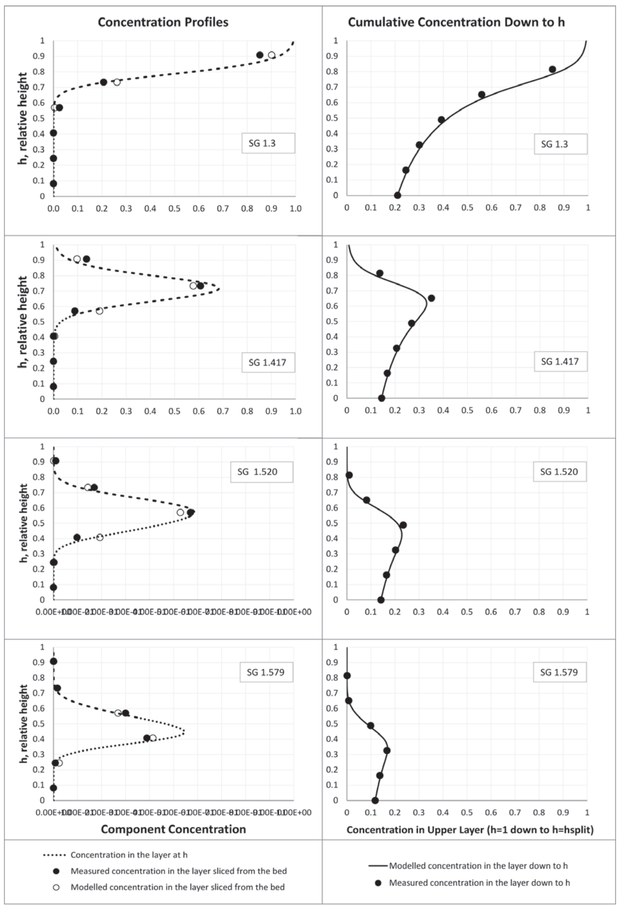

Figure 10a—Concentration plots for the seven-component system shown in Figure 4 (plots for components 1 to 4)

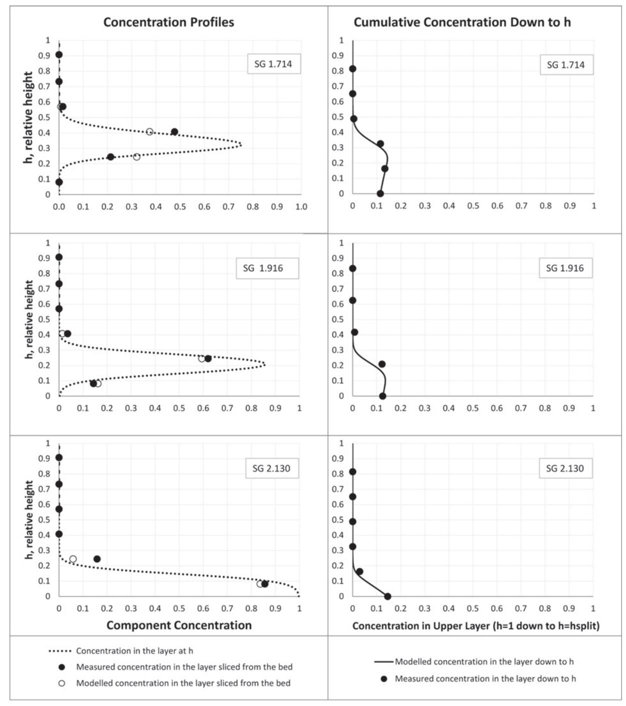

Figure 10b—Concentration plots for the seven-component system shown in Figure 4 (plots for components 5 to 7)

invariate for the conditions that prevailed in the tests. Table III shows what the corresponding values of α would be; these 'averaged' values of α were calculated for each data-set using the average value of α/H_{bed} (1.051 L/kg.mm) and the bed height α/H_{bed} for each test. Figures 11 and 12 compare the plots derived using 'best-fit' values of $\boldsymbol{\alpha}$ with those derived using these 'averaged' values.

In the recovery plots shown in Figure 11, it can be seen that, with one exception, the plots obtained using the 'averaged' values deviate hardly at all from those obtained using the 'best-fit' values. The exception is with the two-component system. Here the 'averaged' value of α is 54% larger than the 'best-fit' value. There is also some deviation in the plots for the heavy and light components in the five-component system, but the deviation is marginal. In this case the 'averaged' $\boldsymbol{\alpha}$ is 23% larger than the 'best-fit' value.

The deviations are more marked when the cumulative concentration plots are considered (Figure 12) but again, it was only with the two- and five-component data that any substantial deviation between the plots obtained using 'best-fit' and 'averaged' values of α was evident. The figure also shows plots for some of the components in the seven-component system. In these, the deviation is so small that the 'best-fit' curves fit the experimental data only slightly better than the curves derived from the 'averaged' α. With this data-set the 'averaged' value of α is 15% smaller than the best-fit value. For all the other systems, the differences between the 'best-fit' and 'averaged' values of α are less than 15% and no discernible deviation between the two sets of plots is evident. Accordingly, these plots have not been included in Figure 12.

Table III

Effect of the number of components on the stratification parameter

No. of components	2	3	4	5	6	7	Average values
Particle system	BR	OYG	OYBR	OYGBR	OYGPBR	OYGPBRW	
Stratification parameter, $\boldsymbol{\alpha}$ (L/kg) ('best-fit' values)	76.9	108.7	132.6	155.6	156.3	190.4	
Bed height, H_{bed} (mm)	112.5	116.5	119.5	114.4	159	153.4	
α/H_{bed} (L/kg.mm)	0.684	0.933	1.106	1.36	0.983	1.242	1.051
'Averaged' α (L/kg)*	118.3	122.5	126.0	120.3	167.1	161.2	
% Difference in α (averaged-best)/best × 100%	54%	13%	-5%	-23%	7%	-15%	

* 'Averaged' α = average value [α/Hbed] × Hbed for the relevant data-set

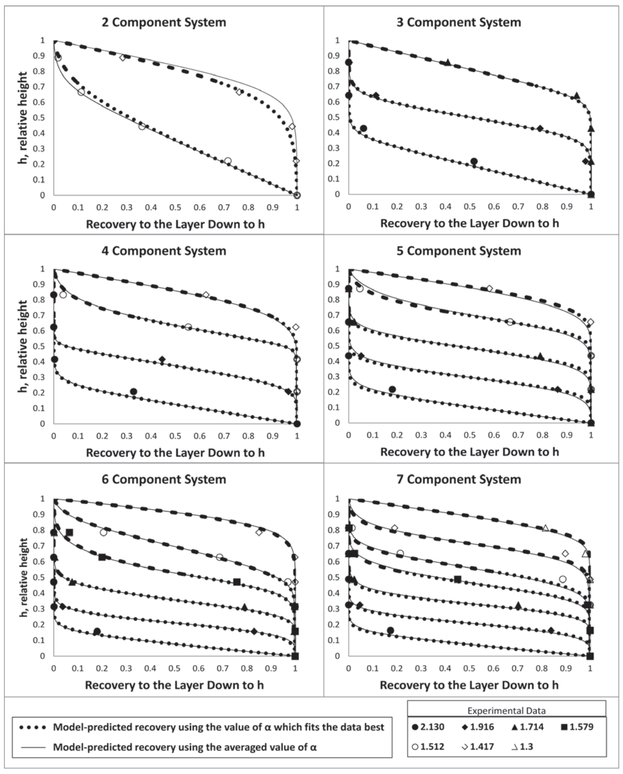

Figure 11—Component recoveries calculated using the 'best-fit' values of α compared with recoveries calculated using the 'averaged' value

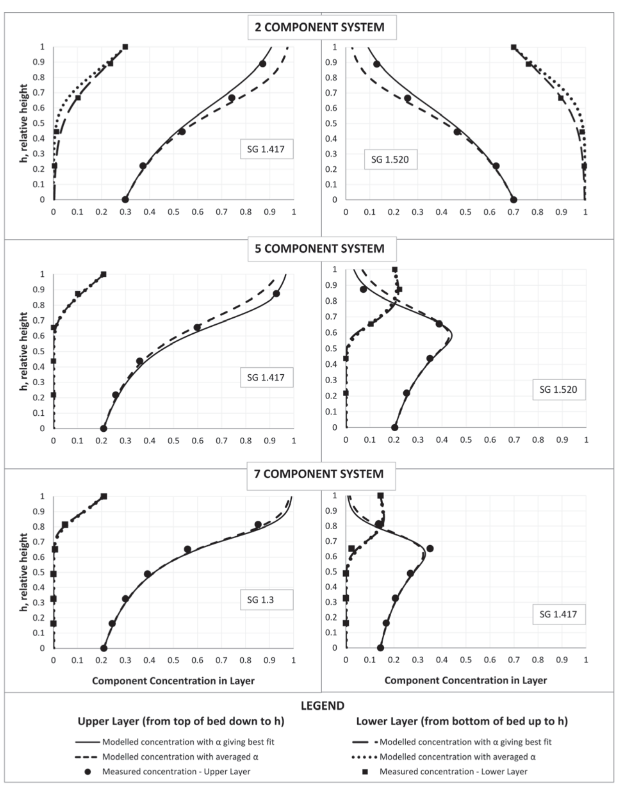

Figure 12 – Comparison of component concentrations in upper and lower layers obtained using the 'best-fit' value of α or the 'averaged' value

What these results suggest is that the model predictions are relatively insensitive to the value of α over the range of values measured in the test. Only when the 'averaged' value differed from the 'best-fit' value by more than about 20% did the model predictions using the two different values deviate discernibly from one another. The implication of these results is that the trend noted earlier may be an artefact of experimental errors and the regression procedure, *i.e.* that in the regression procedure the response surfaces in the regions around the 'best-fit' values of α were very flat, so that equally good fits of the experimental data could be obtained for α values that were within 20% of the 'best-fit' value.

Conclusions

It is clear from the results of the validation study reported in this paper that the mathematical form of the model equation – Equation [1] – is appropriate for describing stratification in a batch jig under the ideal conditions that prevailed in the tests. For each of the six particle systems tested, this model achieved very satisfactory fits to the experimentally determined recoveries and grades of jig products that would be produced if the bed height were to be split at any particular level in the bed. The concentration profiles in the bed are inherently more sensitive to experimental error than the recovery and grade data, and here there was greater divergence between the model fits and the experimental data. However, the fits obtained were reasonable to very good in all cases. Given that a wide range of particle systems were tested – *i.e.* systems involving from two to seven components – the overall quality of the model fits gives very strong support to the veracity of the King model, at very least with respect to the mathematical form of its core equation. The model allows the calculation of the concentration profiles in a stratified bed as well as the recoveries and grades obtained when the bed is split. It does this requiring only the feed composition, the densities of each component in the bed, and a single experimentally determined stratification parameter, and assumes that particles are all the same shape and that size and size distribution effects can be ignored. Interestingly, the results of the study imply that the exact nature of the particle shape is not important as long as all the particles have the same shape. This can be argued from the fact that the derivation of the model assumed all particles were spheres, yet good fits were obtained for particle shapes that were all essentially squat cylinders.

While the finding about the mathematical appropriateness of the model equation appears to be quite conclusive, the finding with regard to model claims about the dependencies of the stratification parameter is less certain. On the one hand, some variation was found in the ratio of the stratification parameter to bed height (α/H_{bed}) which, according to the model, should not happen if the particle volume and stratification dynamics are the same (which is the case in all the tests conducted). On the other hand, it was found that the model fits were relatively insensitive to the value of the stratification parameter over the range found in the tests, to the extent that the observed variation in α/H_{bed} may have been a direct consequence of this insensitivity. However, given that the range of particle systems tested was considerably wider and more divergent than the range likely to prevail in practical situations, it may be that for practical purposes the value of the stratification parameter may be assumed to be independent of the feed composition in an industrially operating stratification device, as the King model claims. Such a conclusion is only tentative, however, and further research is required to verify it. This and related issues are currently being investigated and will be reported in a future publication.

Acknowledgements

The generous support of Mintek in Johannesburg in making their pilot jig and associated facilities available for this work is acknowledged with thanks.

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