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THE APPLICABILITY OF DAVIS TUBE TESTS TO ORE SEPARATION BY DRUM MAGNETIC SEPARATORS

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The current practice of assessing the efficiency of recovery of magnetite and ferrosilicon by drum magnetic separators is to conduct Davis tube tests at a magnetic induction equal to that on the surface of the drum. It is, however, the magnetic force or the force index, and not the magnetic field strength, that are decisive in the operation of a magnetic separator. Since the magnetic field gradients generated by Davis tube and drum magnetic separators are generally different, it is unlikely that the above practice would yield correct information. This article analyses the patterns of the force index generated by drum magnetic separators and a Davis tube operated at different field strengths. It is shown that in order to obtain a correct assessment of the efficiency of separation by a ferrite drum magnetic separator, a Davis tube should be operated at the field of about 0.1 T, which is lower than the current practice suggests. For a rare-earth drum separator the Davis tube operating field should be at least 0.3 T.

Keywords: Davis tube; Magnetic separation; Drum magnetic separator; Force index; Magnetic field

INTRODUCTION

A Davis tube (DT) is a laboratory instrument designed to separate small samples of magnetic ores into strongly magnetic and weakly magnetic fractions. It has become standard laboratory equipment used for the assessment of the separability of magnetic ores by low-intensity magnetic separators [1,2]. Schulz [1] suggested that a magnetic induction of 0.4 T or greater between the magnet poles should be used. On the other hand, Steinert and Boehm [3] claim that current practice is to conduct the Davis tube tests at a magnetic induction equal to that on the surface of the drum of the magnetic separator.

Justification for such a practice appears to be rather questionable for two reasons. Firstly, the efficiency of separation is not determined by the magnetic field strength

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but rather by the product of the magnetic induction B and the field gradient ∇B, usually called the force index FI:

$$FI = B\nabla B \tag{1}$$

It is obvious that the magnetic field gradients of a Davis tube and that of a drum magnetic separator are not necessarily the same and thus the force index of a Davis tube and a drum separator will most likely be different.

The second reason is that for the efficient recovery of a magnetic material, the drum separator must generate the required force index at a sufficient distance from the surface of the drum. It is still common practice to specify the field strength at a distance of 50 mm (2″), although this distance has little to do with the separation function. The distance between the drum and the bottom of the tank in applications such as heavy media recovery or beneficiation of magnetic ores, is usually set close to 25 mm (e.g. [4,5]). The standard operating gap actually depends on the drum diameter and ranges from 14 mm for a 610 mm drum to 40 mm for a 1200 mm diameter drum. It is well known that the force index decreases rapidly with increasing distance from the surface of the drum. It thus becomes obvious that information obtained from the Davis tube tests conducted according to the practice mentioned in [3] may not be directly applicable to low-intensity drum magnetic separators (LIMS).

In order to assess the applicability of the Davis tube tests to production-scale LIMS, modelling of the distribution of the magnetic field and of the force index was performed for a Davis tube electromagnet and for several types of drum magnetic separators.

MODELLING OF THE DAVIS TUBE ELECTROMAGNET

The modelling of the Davis tube electromagnet (DT) was performed using Vector Fields PC-Opera software. Figure 1 shows a 3D distribution of the magnetic field in a typical Davis tube.

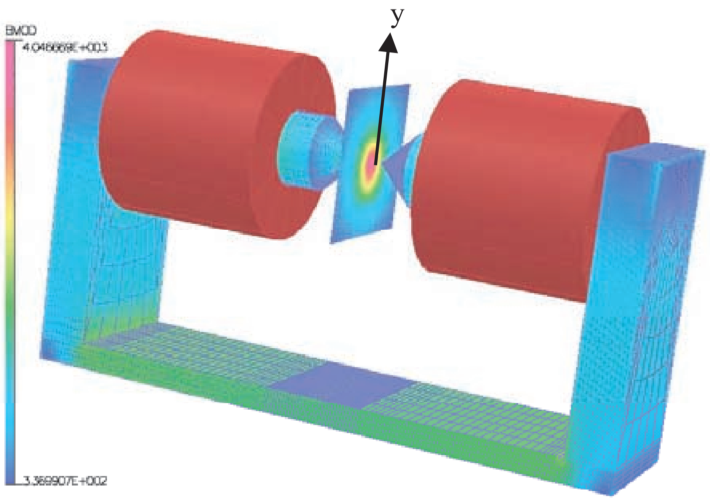

FIGURE 1 A 3D model of the Davis tube electromagnet.

The electromagnet of the Eriez DT, model EDT/723352, consists of an iron yoke (620 × 310 × 150 mm) and a pair of coils, the outer diameter of the coils being 185 mm. The maximum diameter of the conical iron pole-tips is 76 mm and the electromagnet gap is 22 mm.

The magnetic field pattern in the plane situated at the centre of the gap is shown in Fig. 2.

It can be seen that the magnetic field decreases from 0.4 T in the middle of the gap to 0.04 T at 15 cm off-centre along the vertical. This means that the average magnetic field gradient is approximately 2.4 T/m. The variation of the *FI* along a vertical line in the plane situated in the middle of the DT gap is plotted in Fig. 3.

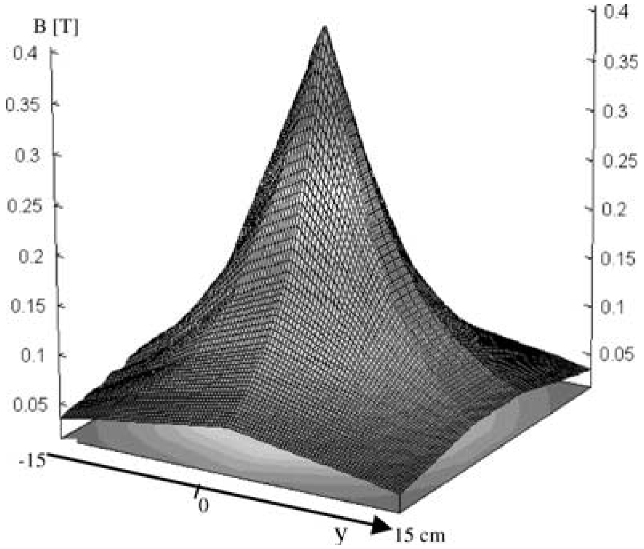

FIGURE 2 The values of the magnetic field in the central plane of the DT gap.

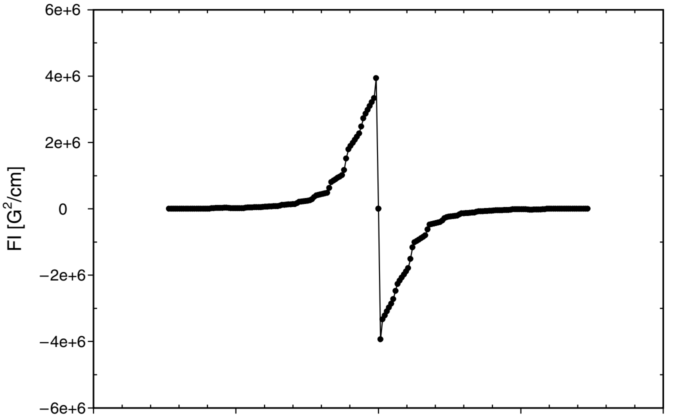

FIGURE 3 The variation of the force index along the vertical line at the centre of the DT gap.

TABLE I The values of B, ∇B and FI at the centre of the DT gap and 5 cm off-centre along the vertical

Distance from the centre of the DT gap (cm)	B (T)	∇B (T/m)	FI (T^2/m)
0	0.4	10	3.93
5	0.1	2.4	0.24
0	0.5	11.8	5.54
5	0.13	3.0	0.39
0	0.6	12.85	7.71
5	0.16	3.94	0.63
0	0.2	5.7	1.14
5	0.045	1.06	0.048
0	0.1	3.4	0.34
5	0.022	0.5	0.011

It can be observed that the force index FI has a maximum value of $4\,\mathrm{T}^2$/m or $4\times10^6\,\mathrm{G}^2$/cm at the centre of the gap, and decreases rapidly to zero at about 6 cm off-centre. The characteristic values of B, ∇B and FI, at the centre of the gap and at 5 cm off-centre, are summarised in Table I.

MODELLING OF DRUM MAGNETIC SEPARATORS

In order to compare a distribution of the magnetic field and of the force index of a DT with drum magnetic separators, several types of drum separators were considered.

A conventional drum separator consists of a rotary drum (shell) made of a non-magnetic material. The magnetic system consists of five to eight stationary magnets of alternating polarity. Adjacent magnets are separated by air, by additional perpendicularly orientated permanent magnets or by steel (Fig. 4). The variables used to design a drum are: a, the thickness of either steel or permanent magnet spacers, or of the air gap between adjacent magnets at the surface of the drum (the pole pitch); b, the width of the magnet at the surface of the drum; c, the depth of the magnet block; $D=2R$, the diameter of the drum; s, the thickness of the shell; s', the width of the gap between magnets and shell.

Four different configurations of the magnetic circuit of a drum separator were modelled in this investigation and the following parameters were kept constant:

$$D=2R=600\,\mathrm{mm},\ c=100\,\mathrm{mm},\ s=2.5\,\mathrm{mm}\ \text{and}\ s'=1.5\,\mathrm{mm}.$$

Drum A

The first permanent magnet drum consisted of six BaFe permanent magnet blocks of width $b=100$ mm, separated by an air gap of $a=50$ mm. The pattern of the magnetic field in this drum is shown in Fig. 5. The orientation of the magnetisation of the magnetic blocks can be also seen.

Drum B

The second drum was similar to the first one, the only difference being that the pole pitch a was equal to 30 mm. The magnetic field pattern around the drum B is shown in Fig. 6.

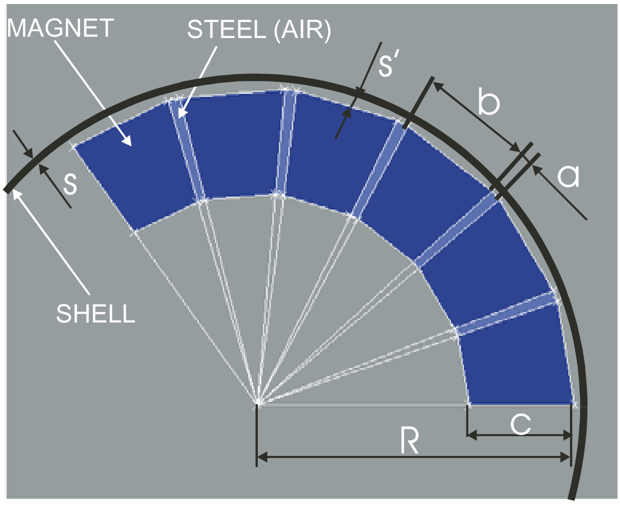

FIGURE 4 Design of the drum and the variables involved in the design.

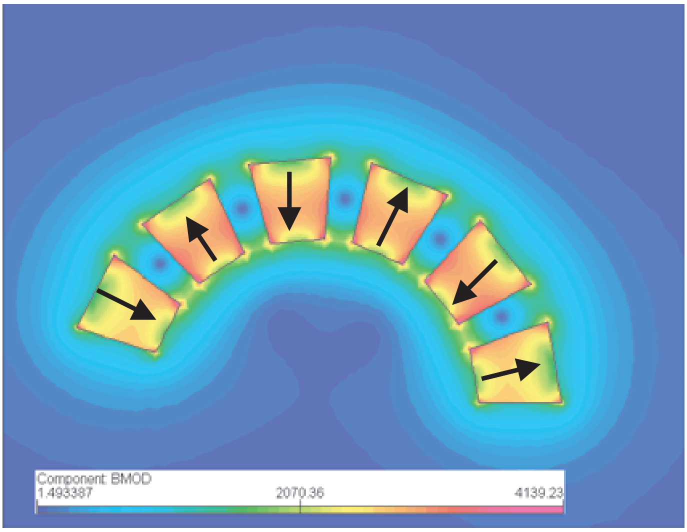

FIGURE 5 The magnetic field pattern generated by drum A.

Drum C

While the geometry of the third drum was also similar to the first one ($a = 50$ mm, $b = 100$ mm), the air gap between two adjacent magnetic blocks was filled with a permanent magnet of depth equal to one half of that of the original blocks. The magnetic field pattern and the orientation of the magnetisation of the permanent magnets is depicted in Fig. 7.

Drum D

Drum D consisted of NdFeB permanent magnet blocks of width $b = 60$ mm and an air gap $a = 10$ mm. The magnetic field pattern in this configuration is shown in Fig. 8.

FIGURE 6 The magnetic field pattern generated by drum B.

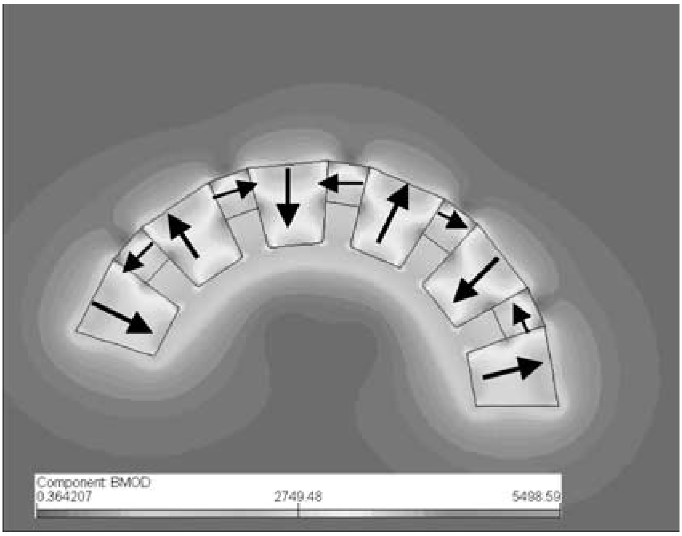

FIGURE 7 Magnetic field pattern generated by drum C.

It can be seen that drum D creates a much greater magnetic field compared to the previous three drums, as a result of a much higher magnetic energy product of the rare earth magnets.

COMPARISON OF A DT AND THE DRUM SEPARATORS

The non-uniformity of distribution of the magnetic field and of the magnetic force can be expressed by the maximum and minimum values of B, ∇B and FI. Such non-uniformity

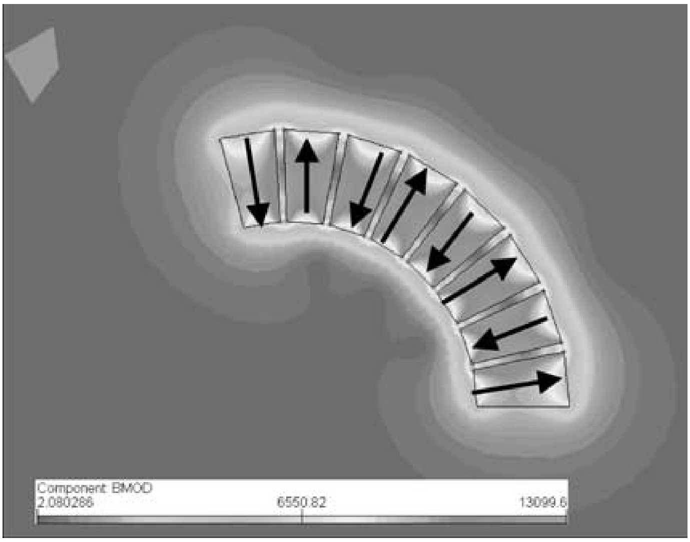

FIGURE 8 Magnetic field pattern generated by drum D.

indices can be defined as:

$$R_1 = \frac{B_{\max}}{B_{\min}} \tag{2}$$

$$R_2 = \frac{FI_{\max}}{FI_{\min}} \tag{3}$$

The maximum values of the magnetic field and of the force index at the surface of the drum, at a distance of 14, 25 and 50 mm from the surface, for all four drums, are summarised in Table II. The non-uniformity indices defined by Eqs. (2) and (3) are also presented in Table II.

The variation of $B_{\max}$ and $FI_{\max}$ with distance from the drum surface is plotted in Fig. 9 for all four drums. Figure 10 depicts the variation of R_1 and R_2 with distance from the drum surface. In Fig. 9, the horizontal lines outline the range of values obtained for a DT.

The BaFe magnetic drums (drums A, B and C) create a magnetic field at the surface of the drum that is lower than the magnetic field generated by a DT, when operated at the standard magnetic field of 0.4 T. On the other hand, the NdFeB magnetic drum generates a magnetic field that is more intense.

It can be seen in Fig. 9 that the maximum values of the force index at the surface of the BaFe drums are close to the values of the force index of a DT operated at 0.4 T. This agreement could have been the reason for the standard practice of operating a Davis tube at 0.4 T. The NdFeB drum generates a considerably greater force index at the surface compared to a DT.

While drum C with interpole magnets creates a slightly lower magnetic field than drums A and B, its maximum force index at the drum surface is very close to the

TABLE II The maximum and minimum values of *B* and *FI*, and their ratios at different distances from the surface of the drum

Drum type	*Distance from the surface* (mm)	$B_{\min}$ (T)	$B_{\max}$ (T)	$(FI)_{\min}$ (T^2/m)	$(FI)_{\max}$ (T^2/m)	R_1 ($B_{\max}/B_{\min}$)	R_2 ($FI_{\max}/FI_{\min}$)
Drum A	0	0.120	0.206	0.182	2.613	1.72	14.36
	14	0.094	0.113	0.170	0.469	1.20	2.76
	25	0.076	0.090	0.108	0.204	1.18	1.89
	50	0.046	0.054	0.041	0.061	1.17	1.49
Drum B	0	0.123	0.215	0.287	4.723	1.75	16.46
	14	0.094	0.121	0.189	0.514	1.29	2.72
	25	0.074	0.095	0.128	0.257	1.28	2.00
	50	0.042	0.053	0.039	0.066	1.26	1.69
Drum C	0	0.018	0.134	0.026	3.842	7.44	147.77
	14	0.018	0.064	0.009	0.183	3.55	19.40
	25	0.019	0.046	0.004	0.076	2.42	19.00
	50	0.015	0.026	0.004	0.022	1.73	5.5
Drum D	0	0.466	0.728	7.535	33.400	1.56	4.43
	14	0.270	0.355	3.021	5.428	1.31	1.80
	25	0.165	0.225	1.134	1.965	1.36	1.73
	50	0.048	0.097	0.108	0.315	2.02	2.91

force index generated by a DT, operated at 0.4 T. However, with increasing distance from the drum, the force index decreases rather rapidly, which indicates that drum C is of a short-reach design.

It can be seen in Fig. 9, that at distances of 14, 25 and 50 mm from the surface, drums A, B and C generate a magnetic field and a force index that are considerably lower than those generated by a Davis tube operated at 0.4 T.

As stated in [3], current practice is to conduct DT tests at a field equal to that on the drum surface. For the BaFe drum this field is about 0.2 T. Figure 9 shows that, under this condition, the force index of a DT and of the BaFe drum is the same as at a distance of about 10 mm from the drum surface. This distance is still too short to cover the separation depth of most drum magnetic separators. However, if the DT test is conducted at a magnetic field of 0.1 T, then drums A and B create similar force indices at about 20 mm from the drum surface. This distance corresponds rather well to real conditions, under which most low-intensity drum magnetic separators are operated. As a result of its low reach, drum C only generates a force index equivalent to that of a DT operated at 0.1 T at a distance of about 10 mm.

In contrast to ferrite magnetic separators, drum D creates a very high magnetic field and force index at the surface, when compared to drums A, B and C and to a DT. The average value of the force index at 14 mm from the surface is very close to the corresponding value for a DT operated at 0.4 T. For a typical operating gap of 25 mm between the NdFeB drum and the tank, the DT tests should thus be carried out at the magnetic field of 0.3 T or more. This will take into account ever improving capabilities of rare earth permanent magnets and an increasing level of sophistication of magnetic system design.

Table II and Fig.10 also show that drums A, B and D have the same value for the field non-uniformity index $R_1 = B_{\max}/B_{\min}$ at their surface. This value only slowly decreases with increasing distance from the surface. At large distances from the surface

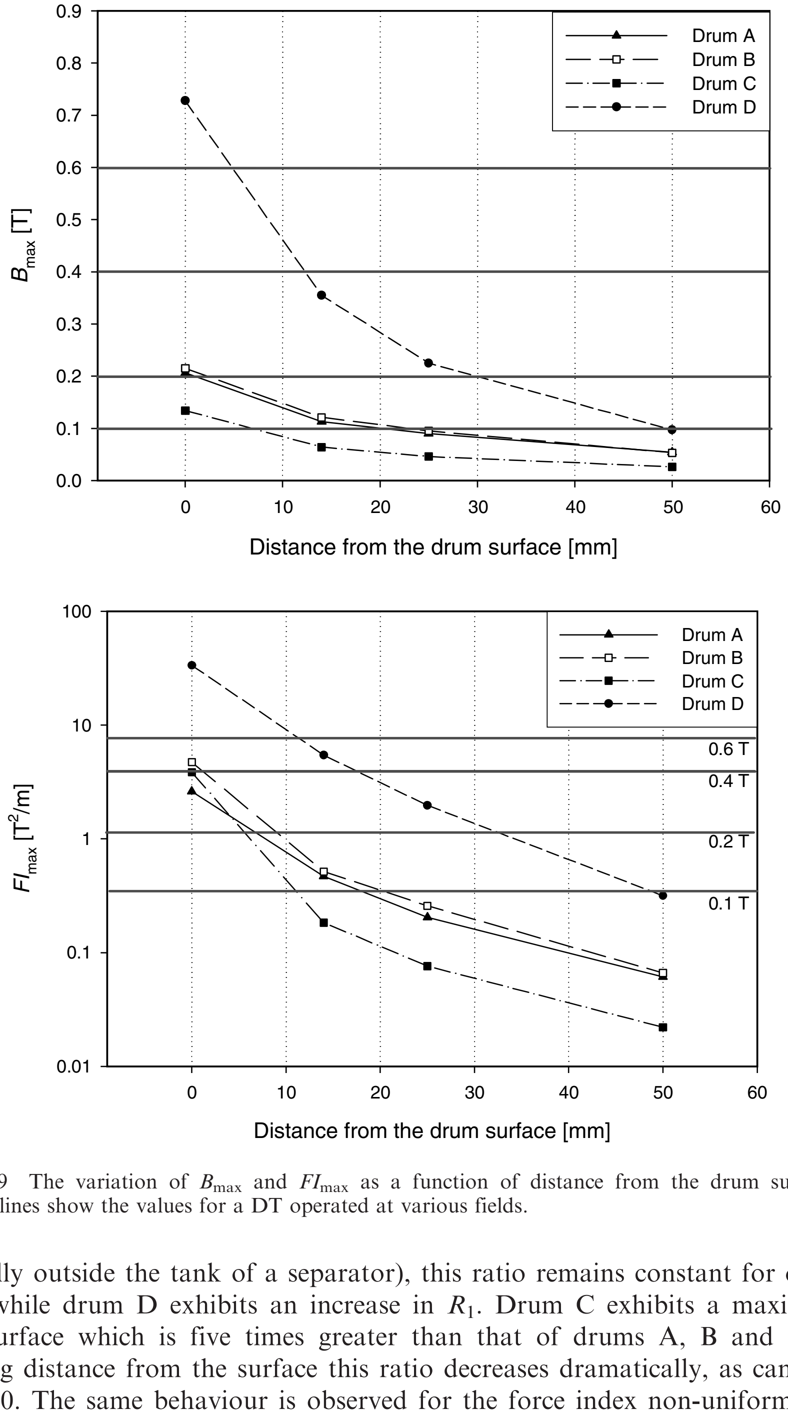

FIGURE 9 The variation of B_{max} and FI_{max} as a function of distance from the drum surface. The horizontal lines show the values for a DT operated at various fields.

(essentially outside the tank of a separator), this ratio remains constant for drums A and B, while drum D exhibits an increase in R_1. Drum C exhibits a maximum R_1 at the surface which is five times greater than that of drums A, B and D. With increasing distance from the surface this ratio decreases dramatically, as can be seen in Fig. 10. The same behaviour is observed for the force index non-uniformity ratio $R_2 = FI_{max}/FI_{min}$. This observation confirms the fact that the design of drum C allows efficient operation close to the surface of the drum. With increasing distance from the drum the operating parameters deteriorate rapidly as a result of its low-reach design.

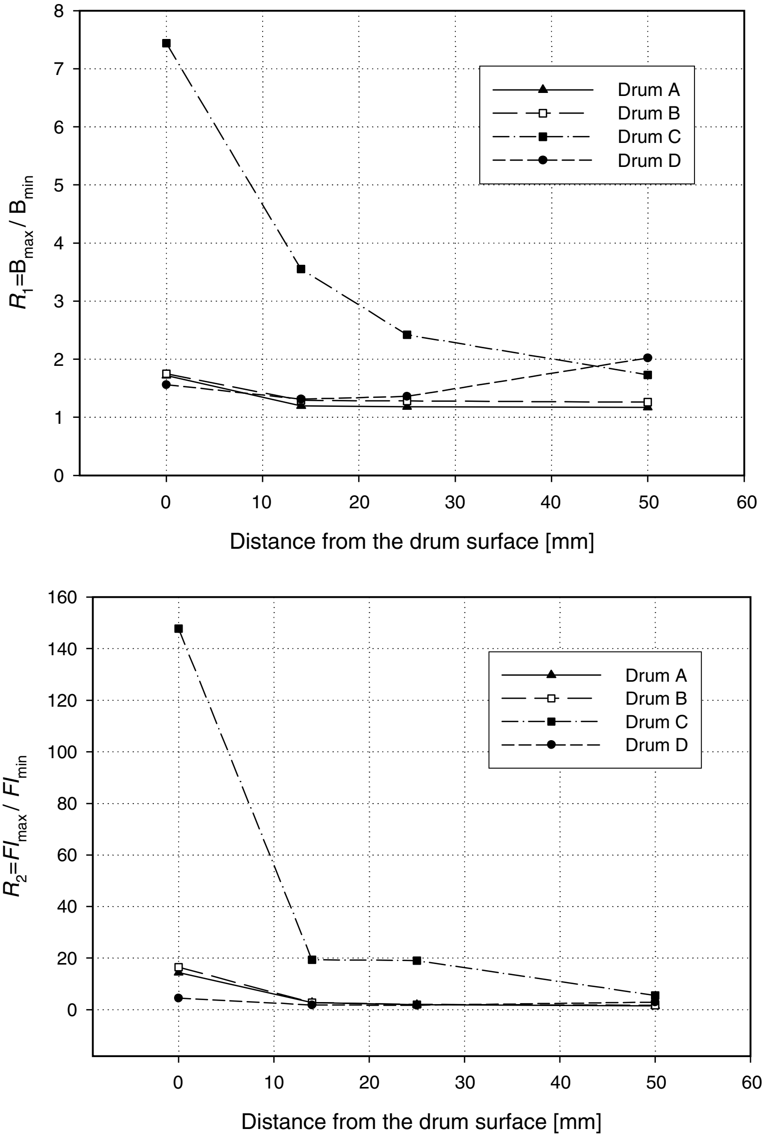

FIGURE 10 The variation of R_1 and R_2 as a function of distance from the drum surface.

CONCLUSIONS

It transpires from a theoretical comparison of the magnetic field and force index patterns of a Davis tube and several designs of a drum magnetic separator that:

- The force index, and thus the magnetic force experienced by particles in the Davis tube operated at the standard magnetic field strength of 0.4 T, is approximately equal to the magnetic force on the surface of conventional BaFe drum magnetic separators. However, at a working distance from the drum, e.g. at 25 mm, the force index in the drum separator is at least an order of magnitude smaller than that of the DT. It is thus clear that DT tests conducted on magnetite at a magnetic field of 0.4 T will seriously overestimate the separation results that would be obtained using BaFe drum separators.

- If the Davis tube is operated at a magnetic field similar to that generated by a drum separator on its surface (i.e. 0.2 T), as recommended in [3], the distance from the drum surface at which these force indices are equal, is approximately 10 mm. This distance is still too short for realistic evaluation of the performance of a drum magnetic separator based on DT data. On the other hand, if a DT is operated at a magnetic field of 0.1 T, its force index agrees well with the force index at the distance of 25 mm from the surface of a magnetic drum.
- In the case of an NdFeB magnetic drum, the value of the force index on the drum surface is an order of magnitude greater than that of a DT operated at 0.4 T. At the distance of 18 mm from the surface, this drum creates a force index that is very close to the force index obtained in a DT operated at 0.4 T. In order to get correct information on the force index at the standard distance of 25 mm, a DT should be operated at 0.3 T or higher.

It has thus been shown that in the case of conventional ferrite drum separators, with the standard gap of 25 mm between the drum and the tank, Davis tube tests should be conducted at a magnetic field strength of about 0.1 T. On the other hand, correct assessment of performance of a rare-earth drum can be obtained by operating a DT at about 0.3 T or higher, depending on the design of the magnetic system.

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