Assessing the effects of the cone force ratio on the performance of hydrocyclones

by D. Lusinga*, J. Angombe*, and A.N. Mainza*

Paper written on project work carried out in partial fulfilment of B.Sc. (Chem. Eng.)

Synopsis

Hydrocyclones are a common feature in almost all mining operations in the world, serving mainly as classifiers. Some of their advantages include low capital costs, low space requirements and their ability to reduce residence time in closed circuit grinding processes. Although an extensive body of literature exists for hydrocyclones, these devices are still inherently inefficient, and more research is currently being undertaken, particularly in the field of modelling. In the vast body of hydrocyclone literature published so far, there has been little or no effort devoted to analysing the effect of the cone force ratio on the performance of hydrocyclones. The cone force ratio is defined as the ratio of the spigot to the vortex finder diameter (Shah, 2005).

In this study a total of 44 tests was carried out in a custom-built rig at the University of Cape Town. These tests were aimed at evaluating the effect of the cone force ratio on the performance of a small diameter hydrocyclone. The cut size and water split were used as the criterion for evaluating the performance of the hydrocyclone.

Results from the tests showed that the cut size decreased with an increase in the cone force ratio. The cut size also appeared to decrease as the calculated locus of zero vertical velocity (LZVV) shifted inwards. The water recovery to the underflow appeared to increase with an increase in the cone force ratio. The effect on the cut size of adjusting the cone force ratio was found to be higher for a coarser feed than it was for a finer feed.

Introduction

Hydrocyclones are widely used in industry for separating solids from liquids, liquids from liquids and gases from liquids. They have found extensive use in the pulp and paper, mining, coal, food, petroleum (Bradley, 1965) and more recently, in the environmental and biotechnology industries (Neese *et al*., 2006).

While there are other possible clarifiers such as solid bowl centrifuges, bowl classifiers, cylindrical tank classifiers and cone classifiers, hydrocyclones have, amongst others, the added advantages of requiring low capital, low operating and maintenance costs, small area utilization, and simplicity in construction (Asomah, 1996).

The fluid flow within a hydrocyclone is illustrated in Figure 1. When the fluid is injected tangentially into the hydrocyclone, there is relative separation of the particles due to the action of centrifugal forces. Consequently, there is a profiling of particles, with the coarsest near the wall of the hydrocyclone and the finest near the air core which occupies the central axis of the hydrocyclone. The fluid flows in such a way that two spiral patterns are created, one in the upward direction carrying fine particles and the other in the downward direction carrying predominantly coarse particles.

Since there is both upward and downward flow within the hydrocyclone, there exists a dividing line, where it is assumed that particles that lie on it have zero vertical velocity and have an equal chance of reporting either to the underflow or to the overflow. This dividing line is known as the locus of zero vertical velocity and the particles that lie on it have the particle size corresponding to the cut size (Svarovsky, 2000).

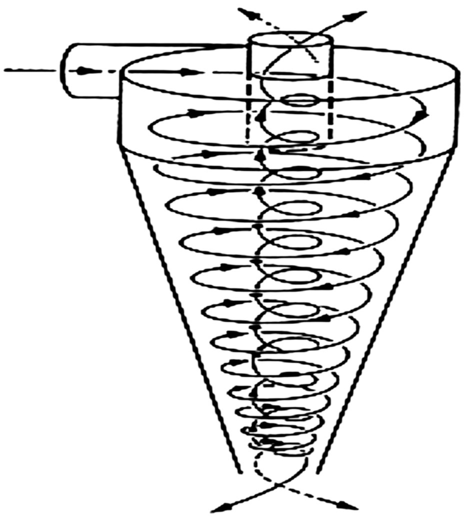

Figure 1—A representation of the fluid flow in a hydrocyclone (Bradley 1965)

* Centre for Minerals Research, University of Cape Town, Rondebosch, South Africa.

 SA ISSN 0038–223X/3.00 + 0.00. Paper received Feb. 2008; revised paper received Mar. 2008

In all operations that employ a non-transparent hydrocyclone and a coloured slurry, it is difficult to locate the position of the LZVV; however, Bradley (1965) proposed an estimation for the position of its base given below as:

$$R_{LZVV} = R_c \times \frac{R_o}{R_o + R_u} \qquad [1]$$

where R_o - the vortex finder radius
R_c - the cyclone radius
R_u - the spigot radius

The objectives of this study were to:

- Assess the effect of the cone force ratio on the performance a 100 mm diameter hydrocyclone
- Investigate the effect of the feed particle size distribution and the feed solids concentration at different cone force ratios on the performance of a 100 mm diameter hydrocyclone
- Analyse the effect of varying the cone force ratio on the water split to the underflow stream.

Experimental set-up

The test rig

All the experimental tests were carried out using a custom-built rig at the University of Cape Town.

The test rig consisted of a 0.7m^3 sump that was equipped with a Weir variable speed pump that could be operated at a range of pressures. A 100 mm diameter hydrocyclone, connected to a pressure gauge, was installed at the feed inlet, as shown in Figure 2. The specifications of the hydrocyclone are given in Table I.

Silica sand from Consol was used as the test material. This material was chosen because it has a consistent density, making the analysis and interpretation of results easy.

Experimental procedure

The test work consisted of water only tests as well as silica sand tests at 20% and 40% solids concentrations. Samples and test data were collected after ensuring that the hydrocyclone had a correct underflow discharge pattern. The underflow discharge pattern was assumed correct if it had a shape in the form of a hollow cone with a 20–30° angle, as illustrated in Figure 3.

When the operation of the hydrocyclone was deemed stable the test data was obtained. The mass flow rates were obtained by using the bucket and stop watch method and samples of the overflow, underflow and feed were collected every 5 minutes. Standard sample preparation and processing techniques, which involved filtering, weighing and screening, were employed.

Typical size distribution curves for the feed, underflow and overflow streams obtained from the test work are presented in Figure 4.

The size distribution data and the mass flow rates were used to obtain partition numbers for the partition curves. The cut size information used in the analysis was then obtained from the partition curves. Figure 5 shows the corresponding corrected partition curve obtained from the size distributions in Figure 4.

Results and discussion

Silica tests at 20% and 40% solids concentration

The results of the tests performed with silica at a solids

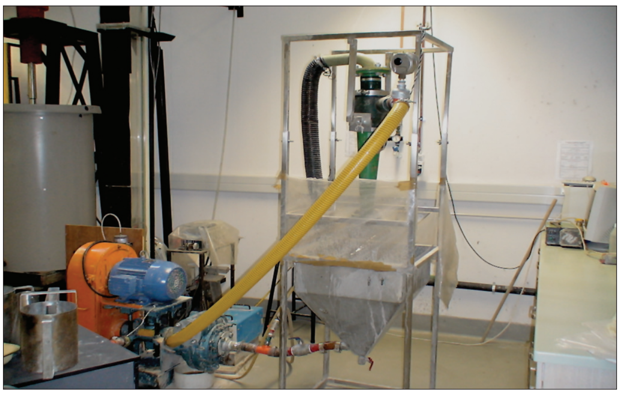

Figure 2—The hydrocyclone test rig used for the experiments

Table I

The specifications of the hydrocyclone used during the experiments

Cylinder diameter (mm)	100
Cylinder length (mm)	200
Cone angle (°)	15
Cone length (mm)	480
Vortex finder diameters (mm)	26, 34
Spigot diameters (mm)	12,16, 18, 20, 23

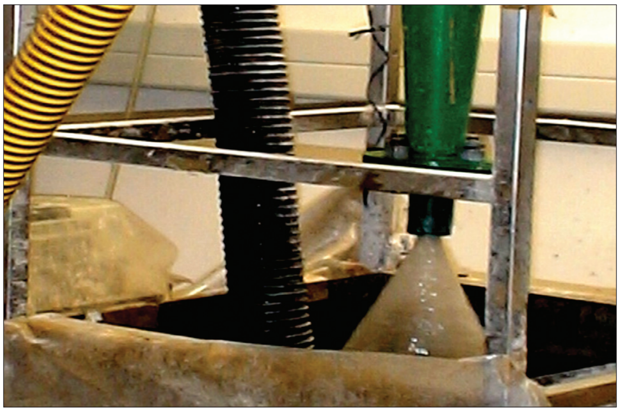

Figure 3—The hydrocyclone used, under correct operation (i.e. the underflow was in the form of a hollow cone of angle 20–30°)

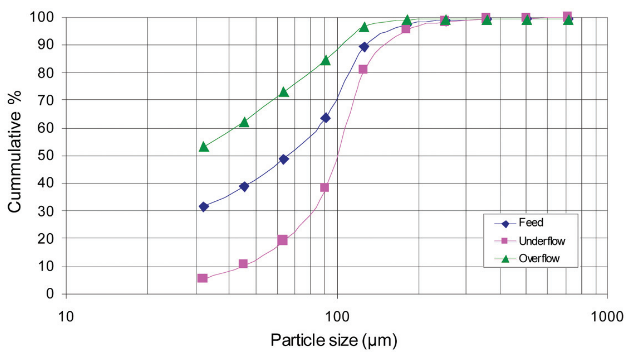

Figure 4—Typical feed, underflow and overflow particle size distributions, for the fine feed at a cone force ratio = 0.53 and a 34 mm VF

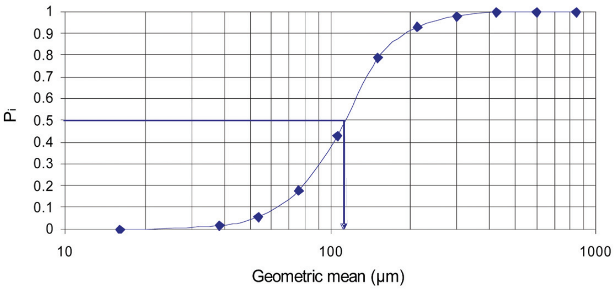

Figure 5—A typical corrected partition curve, obtained during operation with a fine feed and a 34 mm VF

concentration of 20% by weight are presented and discussed in this section.

Figures 6 and 7 show the relationship between the cone force ratio and corrected cut size for relatively fine and coarse feed size distributions, using the 26 mm and 34 mm vortex finders respectively.

It can be seen in both cases that the cut size decreased linearly with an increase in the cone force ratio. The decrease in the cut size, observed when there is an increase in the cone force ratio, can be explained by the inward shift of the locus of zero vertical velocity (LZVV). It can be seen from Equation [1], proposed by Bradley (1965) for estimating the radius of the base of the LZVV, that the position of the LZVV depends on the radii of the hydrocyclone, spigot and vortex finder. Therefore the LZVV is related to the cone force ratio since the cone force ratio is the ratio of the spigot to vortex finder diameters.

According to elements of the Equilibrium Orbit Theory, the cut size is the particle size whose equilibrium orbit radius lies on the LZVV (Svarovsky, 2000). Since there is a profiling of particles in the hydrocyclone with the coarsest near the wall of the hydrocyclone and the finest near the axis, the cut size changes as the LZVV shifts. From Equation [1], it can be seen that as the spigot diameter increases, thereby increasing the cone force ratio, the LZVV moves inwards away from the coarse particles at the hydrocyclone's wall towards the fine particles at the hydrocyclone's axis. Eventually the LZVV lies in the region where fine particles are in their equilibrium orbits and as a result, a smaller cut size is obtained.

It can be seen from Figures 6 and 7 that the coarser feed has a wider range of cut size values as compared to the finer feed for the same cone force ratio range. Figure 8 shows the effect of the vortex finders on the cut size.

The results shown in Figure 8 appear to suggest that the cut size increases with a decrease in the vortex finder diameter. However, this contradicts the observations made by other authors (Fujimoto, 1958; Napier-Munn, 1996 and Lim *et al.*, 2003). These authors reported that the cut size increased with an increase in the vortex finder diameter.

A possible reason for the aforementioned contradiction and the observed cut size increase in Figure 8 is short circuit flow. Short circuit flow occurs when the fluid that enters the hydrocyclone moves directly across the roof of the hydrocyclone onto the walls of the vortex finder and exits directly through the overflow stream.

Kelsal (1952) found this to be a source of inefficiency since the relatively coarser particles ended up in the stream that should be carrying only fine particles. Coarse particles misplaced to the fine product cause the partition curve to behave in an irregular manner.

Bradley (1965) and other researchers (De Kok, 1956; Haas, 1956; Moder and Dahlstrom, 1952) found optimum vortex finder diameters below or above which the cyclone efficiency starts to decrease. They found the maximum diameter as that which approaches the diameter of the locus of zero vertical velocity (LZVV). The optimum vortex finder diameters recommended include Dc/3 to Dc/7(De Kok, 1956), Dc/4 to Dc/6 (Moder and Dahlstrom, 1952). The dimensions of the two vortex finders used in this experiment were Dc/3 and Dc/4. Figure 9 shows the effect of the locus of zero vertical velocity on the cut size for the fine feed distribution. It can be seen from the graph that there is a decrease in the cut size as the locus of zero vertical velocity moves inwards.

The same tests as those performed at a solids concen-

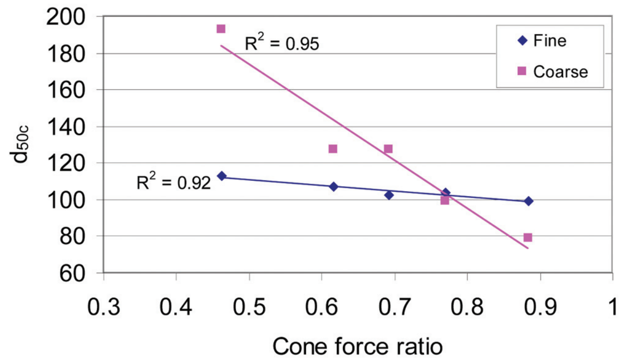

Figure 6—The effect of the cone force ratio on the cut size for the 26 mm vortex finder

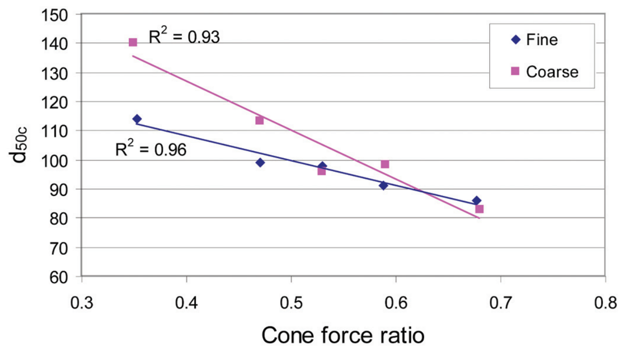

Figure 7—The effect of the cone force ratio on the cut size for the 34 mm vortex finder

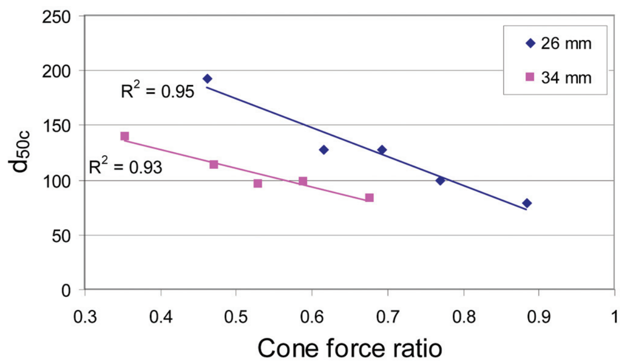

Figure 8—The effect of the vortex finders (26 mm and 34 mm) on the cut size for the coarse feed

tration of 20% were carried out at a solids concentration of 40% in order to analyse the effect of concentration on the performance of the hydrocyclone. However, for all the runs carried out at this solids concentration, an extremely dense roping discharge was observed in the hydrocyclone underflow. Figure 10 shows the discharge pattern observed. This discharge pattern indicated improper operation of the hydrocyclone at high solids concentration. Visual observations made during these tests showed that the hydrocyclone performed more like a thickener instead of a classifier. The roping discharge pattern was observed for all the cone force ratios tested at this concentration, with the exception of the combination of the largest spigot and vortex finder (Refer to Table I). No meaningful data could be obtained from these test runs.

The water only tests

Water split is one of the key indicators of hydrocyclone performance. This is especially important for the hydrocyclone used to classify particles for further processing before the valuable minerals are recovered. The effect of a very high water recovery to the underflow is a decrease in the efficiency of the hydrocyclone since the relatively finer particles become entrained in the underflow fluid. Figure 11 illustrates the relationship between the water recovery to the underflow and the spigot diameter for two different vortex finder diameters. The results in Figure 11 are for the water only tests.

It can be seen that the water recovery to the underflow increases linearly with an increase in the spigot diameter and decreases with an increase in the vortex finder diameter. These observations agree with what has been observed in practice. The effect on the water recovery to the underflow of changing the vortex finder was found to be higher as the spigot diameter was increased.

The error analysis indicates that the results obtained among the repeats were fairly consistent and that confidence in the results should be high. The high R^2 values shown in Figure 11 indicate that the linear correlation between the spigot diameter and the water recovery to the underflow is strong.

The effect of the cone force ratio on the water split

Figure 12 illustrates the relationship of the cone force ratio and the water recovery to the underflow for the water only tests. The water recovery to the underflow increased linearly with the cone force ratio regardless of the combinations of vortex finders or spigots used.

The water recoveries to the underflow for the fine and coarse feeds are shown in Figure 13. It appears that the water recovery to the underflow is greater for a relatively fine feed as compared to a coarser feed.

As a result, it is highly likely that the sharpness of separation for a feed dominated by relatively finer particles is lower than the sharpness of separation for a feed dominated by coarser particles since there are more fines displaced to the underflow when the water split is high. Although consistent trends were observed between the spigot diameter and the water recovery to the underflow, no attempts were made to develop a mathematical model in this study. Table II shows the effect of increasing the concentration of solids on the water recovery to the underflow.

The water recovery to the underflow decreased as the feed concentration was increased. This is because solids cause obstruction at the spigot and therefore reduce the free flow of water in that region, forcing the liquid to exit through the vortex finder. For the purpose of classification, it is desired that less water be removed in the underflow since water entrains the relatively finer particles. The entrainment of fine particles in the underflow decreases the efficiency of the hydrocyclone.

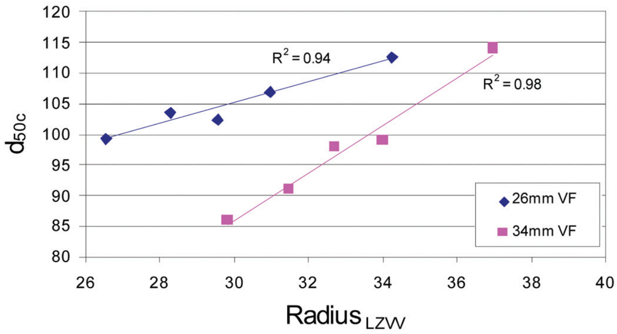

Figure 9—An illustration of the relationship between the position of the base of the LZVV and the cut size (d_{50}) for the relatively finer particles

Figure 10—Roping discharge observed at 40% solids concentration, indicating improper use of the hydrocyclone at high solids concentrations

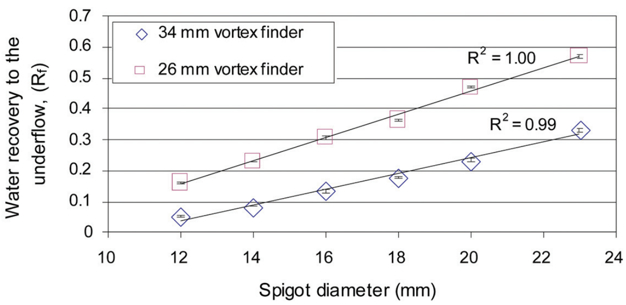

Figure 11—The water recovery to the underflow as the spigot diameter is varied for two different vortex finder diameters

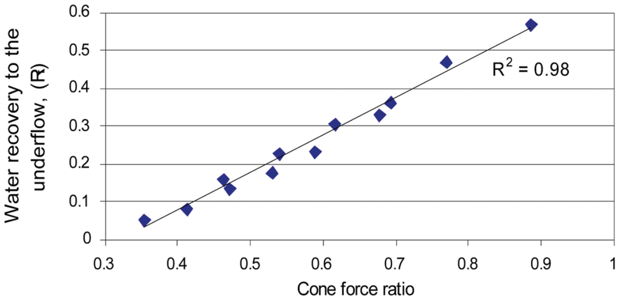

Figure 12—The effect of the cone force ratio on the underflow water recovery

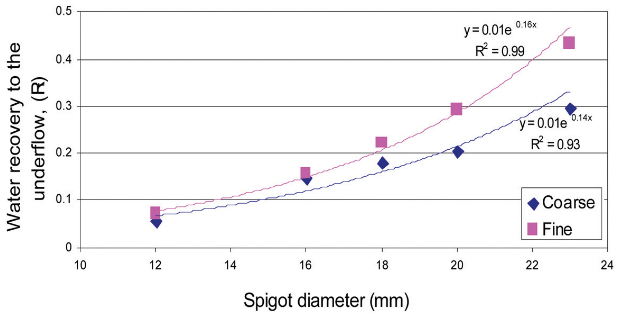

Figure 13—The effect of feed size distribution on the water recovery to the underflow

Conclusions

A total of 44 tests was carried out at the University of Cape Town in order to:

- ➤ Analyse the effect of the cone force ratio on the performance of a 100 mm diameter hydrocyclone
- ➤ Investigate the effect of the feed particle size distribution and the feed solids concentration at different cone force ratios on the performance of a 100 mm diameter hydrocyclone
- ➤ Analyse the effect of varying the cone force ratio on the water split to the underflow stream.

Based on the outcomes of the tests carried out with slurry the following conclusions were drawn:

- ➤ When the cone force ratio was increased, the calculated locus of zero vertical velocity shifted inwards causing a decrease in the cut size.
- ➤ The cut size (d_{50c}) decreased linearly with an increase in the cone force ratio for a particular vortex finder.
- ➤ The effect on the cut size of adjusting the cone force ratio was higher for the relatively coarser particles than it was for the finer particles.
- ➤ The water recovery to the underflow increased as the feed became finer.
- ➤ The water recovery to the underflow increased exponentially when the diameter of the spigot was increased.

From the results of the tests carried out on the hydrocyclone to analyse the effect of varying the spigot and vortex finder diameters on the water split in a hydrocyclone using water only, the following conclusions were drawn:

- ➤ Both the vortex finder and the spigot had an effect on the water split.

Table II

The effect of the solids concentration on the water recovery to the underflow

Spigot diameter (mm)	Water only R_f	20% solids R_f
12	0.16	0.07
16	0.31	0.15
18	0.36	0.21
20	0.47	0.29
23	0.57	0.43

- ➤ The water recovery to the underflow increased with an increase in spigot diameter and a decrease in vortex finder diameter.
- ➤ The water recovery to the underflow varied linearly with the spigot diameter.
- ➤ The water recovery to the underflow increased linearly with the cone force ratio regardless of the combinations of vortex finders and spigots used.

Acknowledgements

The authors would like to thank Dr Aubrey Mainza who was our project supervisor for his tireless and willing supervision throughout the course of the project. Mr Jason Waters is also thanked for his help in setting up the rig as well as ensuring that all the supplies needed were available. The authors would also like to thank the University of Cape Town for allowing us to use their equipment and facilities.

References

Asomah, I. Thesis: Improved Models of Hydrocyclones Julius Kruttschnitt Mineral Research Centre, University of Queensland Australia, 1966.

Bradley, D. *The hydrocyclone*, 1st edition., Pergamon Press, Oxford.

De Kok, S.K. *J Chem. Met & Min Soc.*, South Africa, vol. 56, no. 281, 1965. pp. 1956.

Fujimoto, T. The performance of the Hydrocyclone as a classifier, retrieved September 20, 2008 from the World Wide Web: http://www.journalarchive.jst.go.jp/jnlpdf.php?cdjournal=jsme1958&cdvol=1&noissue=3&startpage=321&lang=en&from=jnlabstract. 1958.

Haas, P.A. *Chem Engng.Progr.*, vol. 53, no. 203, 1957.

Kellsall, D.F. A study of the motion of solid particles in a hydraulic cyclone, retrieved September 29, 2008 from the World Wide Web:http://archive.icheme.org/cgibin/somsid.cgi?session=711809B&page=30ap0087&type=framedpdf. 1952.

Lim,K.S., Kim, H.S., and Lee, K.W. Characteristics of the collection efficiency for a cyclone with different vortex finder shapes, retrieved September 20, 2008 from the World Wide Web: http://www.sciencedirect.com, 2003.

Moder,S.J. and Dahlstrom, D.A. *Chem.Engng.Progr.*, vol. 48, no. 75, 1952.

Napier–Munn, T.J., Murell, S., Morrison, R.D., and Kojovic, T. *Mineral Communtion circuits—Their Operation and Optimisation*. JKMRC Monograph Series in Mineral Processing 2.JKMRC, University of Queenslad, Australia, 1996.

Neesse, T., and Dueck, J. Dynamic modelling of the hydrocyclone, retrieved September 24, 2008 from the World Wide Web: http://www.sciencedirect.com, 2006.

Shah, H., Majumder, A.K., and Barnwal, J.P. Development of water split model for a 76 mm hydrocyclone, 2005.

Svarovsky, L. Solid—*Liquid Separation*, 4th edition, Butterworths, London, 2000. ◆