

# **CHAPTER 2.**

# **LITERATURE**

# **REVIEW**

This review aims to discuss and evaluate the current knowledge on the spigot loading and overloading of cyclones. The loading and overloading behaviour of both classification and dense medium cyclones are considered. In order to characterise the spigot overloading behaviour of the cyclone better, classification and dense medium cyclones are considered separately. This way the similarities and differences in behaviour between the two cyclonic devices can easily be identified. The logic followed here is that we first need to characterise and understand the spigot loading and overloading behaviour of the cyclone before investigating (and quantifying) the effects of the various variables on the spigot capacity.

## **2.1. CLASSIFICATION HYDROCYCLONES**

Classification cyclones separate solid particles according to their differences in size. The operation principles for classification cyclones are similar to those of dense medium cyclones, although there are differences in terms of the angle of inclination and cyclone geometry. Classification cyclones make use of water as the separating medium, while a mixture of water and magnetite/ferrosilicon is employed in dense medium cyclones.

### **2.1.1. Characterisation of Overloading at the Underflow**

In tackling this problem it is important to first define what exactly is the maximum spigot capacity, and establish what determines it. Jull (1972), and Mular and Jull (1978) suggested that the spigot capacity of a hydrocyclone was reached at the onset of rope discharge at the underflow. The association of the spigot capacity with roping flow has also been suggested/implied by others, including: Dahlstrom (1949); Fahlstrom (1963); Abbot (1967a); Plitt (1976); Flintoff et al. (1987); Plitt et al. (1987) and Heiskanen (2000). Under the normal operating conditions of the cyclone a 'cone-shaped' discharge is prevalent at the spigot, and is referred to as spray discharge. During spray discharge the air core extends across the entire length of the cyclone from the overflow through to the underflow (Fig. 2.1). However, when a rope discharge commences at the spigot the air core in this part of the cyclone collapses. Consequently, the flow at the underflow changes from a 'cone-shaped' discharge with an air core in the middle to a 'rope-shaped' flow in which the slurry occupies the entire cross-section of the spigot (with no air core at the underflow).

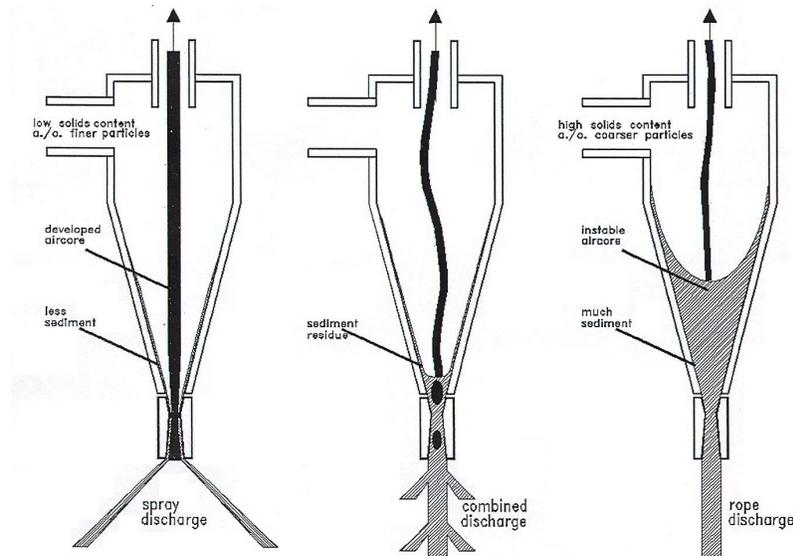


Figure 2.1. Schematic diagram showing spray, semi-rope and rope discharges at the underflow of a hydrocyclone. (Neesse et al., 2004a)

### (a) Air Core and Roping

Plitt et al. (1987) proposed, “Roping is initiated by the formation of a bed of solids in the apex (spigot) region of the cyclone. When the viscosity of the slurry increases to the point where the frictional drag of the cyclone wall stops the rotary motion, roping is initiated”. Dyakowski and Williams (1995) also proposed that the collapse of the air core during the onset of roping was a consequence of excessive ‘fluid’ viscosity, which decays the tangential velocity and, consequently, the rotational motion at the underflow.

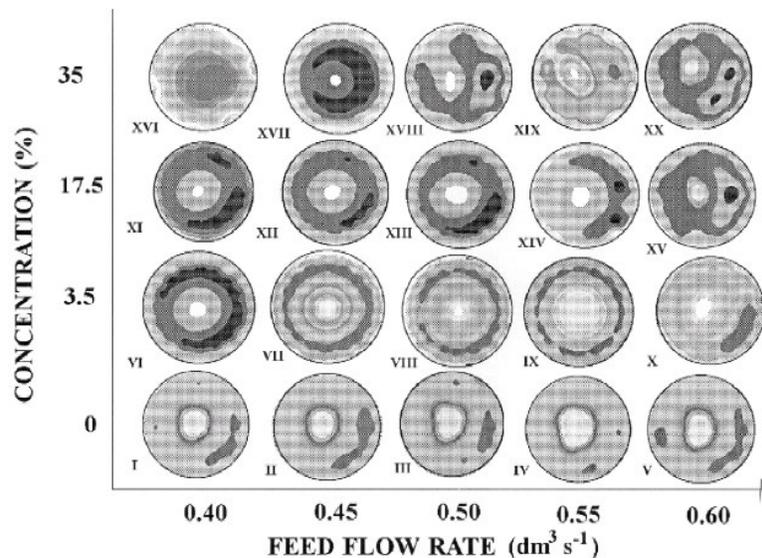


Figure 2.2. Resistivity images showing the air core below the feed inlet of a 44mm diameter hydrocyclone. (Gutiérrez et al. 2000)

Gutiérrez et al. (2000) illustrated the above-mentioned behaviour with their work on the use of electrical impedance tomography to control the underflow discharge of a hydrocyclone (Fig. 2.2). These resistivity images were taken in a single horizontal plane near the feed inlet, and the circular white shapes in the middle of the images represent the air core. The presence of an air core at the underflow can clearly be seen in all images except for image XVI in which rope discharge was obtained at the underflow.

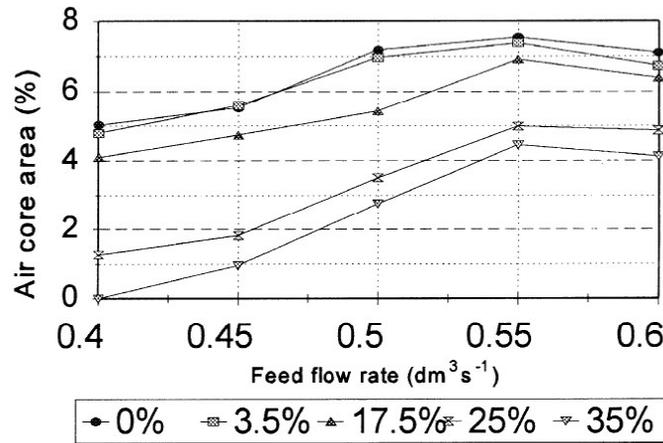


Figure 2.3. The influence of feed solids' concentration on the air core size. (Gutiérrez et al., 2000)

Furthermore, Gutiérrez et al. (2000) studied the effect of the feed flow rate and feed solids concentration on the air core size at the underflow, as shown in Fig. 2.3. The air core size was observed to increase with increasing feed flow-rate up to a certain maximum at various feed solids concentrations. Fig. 2.2 and 2.3 illustrate clearly that the lowest air core sizes were encountered at the highest feed concentration of 35%, and the highest air core sizes were observed at the lowest feed concentration of 0%. Thus, an increase in the feed solids concentration consistently brings about a decrease in the air core size. And the decrease in the air core size with increasing solids concentration is a consequence of increased slurry viscosity, which increases with solids concentration as shown in Fig. 2.5. And once a certain critical underflow solids concentration (and slurry viscosity) is reached the rotational motion of the slurry in the cyclone can no longer be sustained, and as a result the air core collapses and roping commences. This is in agreement with the behaviour postulated by Plitt et al. (1987) as previously mentioned. The critical underflow solids concentration at which roping commences will be discussed in more detail in later parts of this chapter.

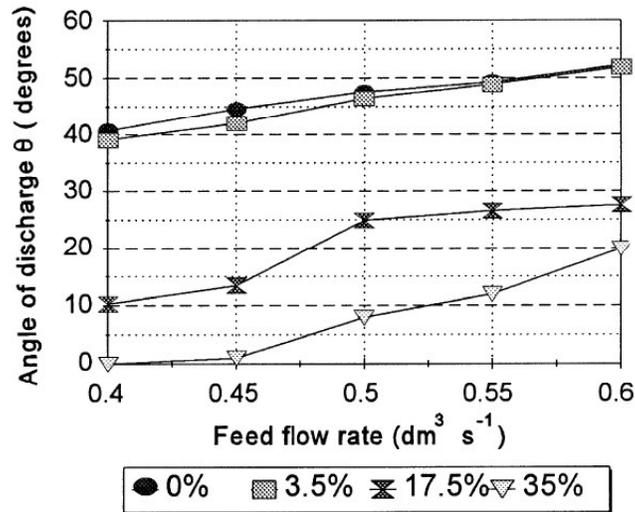


Figure 2.4. Angle of discharge for the underflow slurry with changing feed flow-rate and solids concentration. (Gutiérrez et al., 2000)

The air core area within the hydrocyclone and the angle of discharge at the underflow are shown in Fig. 2.3 and 2.4, respectively. These two figures illustrate clearly that during roping, when the angle of discharge is zero (Fig. 2.4), the air core at the underflow collapsed (Fig. 2.3).

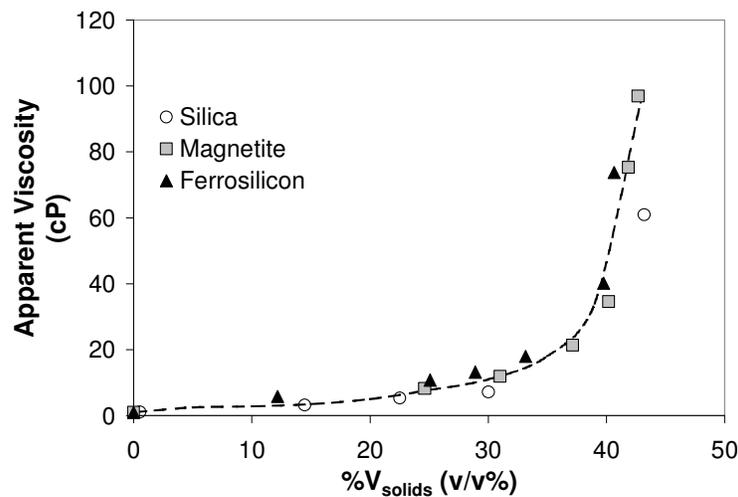


Figure 2.5. The influence of solids concentration on the apparent viscosity of the pulp. Particle size range: -75+50 $\mu$ m. (Aplan, 1985)

The particle size range of the solids used in plotting Fig. 2.5 was -75+50 $\mu$ m for all three material types. It is interesting to note that particle density does not seem to influence the relationship between volumetric solids concentration and apparent viscosity. The abrupt rise

in viscosity with increasing solids concentration was observed to occur at the same concentration of around 37-40% for all three particles types.

### (b) Underflow Solids Concentration

According to Neesse et al. (1984) and Neesse et al. (2004a) a ‘sediment layer’ with high solids concentration forms at the underflow during roping, as illustrated in Fig. 2.1, in which the coarse particles accumulated in the conical section of the cyclone.

As mentioned previously, Plitt et al. (1987) postulated that the collapse of the air core at the underflow during the onset of roping was a consequence of the prevalent high solids concentrations; once a certain critical solids concentration at the underflow is exceeded roping commences. In support of this notion a number of authors established that there is a critical underflow solids concentration beyond which roping flow occurs. These include Dahlstrom (1949), Fahlstrom (1964), Abbot (1967a), Mular and Jull (1978), Plitt et al. (1987), and Heiskanen (2000), amongst others. Thus, the onset of rope discharge could be anticipated/predicted by studying the behaviour of the underflow solids concentration. As a result, some of the authors proposed mathematical expressions that attempted to predict the onset of rope discharge at the underflow. Plitt et al. (1987) refers to the *SPOC* model which makes use of the following expression to predict the onset of roping flow:

$$\%V_{MSU} = \%V_{SU20} + 0.2(\%V_{SF} - 20) \quad (2.1)$$

where  $\%V_{MSU}$  is the %solids by volume in the underflow at which roping is initiated for a feed concentration of  $\%V_{SF}$ ,  $\%V_{SF}$  is the volumetric percentage solids in the feed, and  $\%V_{SU20}$  is the user defined value for the limiting %solids by volume in the underflow at a feed solids concentration of 20% by volume (default is 56%). Heiskanen (2000) modified the above expression to obtain the following:

$$\%V_{MSU} = 33.8 + \%V_{SF}^{0.098} \quad (2.2)$$

According to the above-mentioned expressions the critical underflow concentration is dependent only on the feed concentration. It is, however, expected that  $\%V_{MSU}$  should not be dependent on  $\%V_{SF}$ , but rather on the concentration of solids particles in the feed that eventually exit at the underflow. If for instance we have two cyclones (A and B) with same dimensions, operating under the same conditions and at the same  $\%V_{SF}$ , but say cyclone A has a high proportion of its feed exiting through the underflow and cyclone B has a much smaller proportion of its feed going to the underflow. In such a scenario it is possible for

cyclone A to be roping and for cyclone B to be operating under a spray discharge, even though both cyclone may have the same  $\%V_{SF}$ . Cyclone B will require a much higher  $\%V_{SF}$  than cyclone A in order to exceed  $\%V_{MSU}$ , assuming that  $\%V_{MSU}$  is the same for both cyclones.

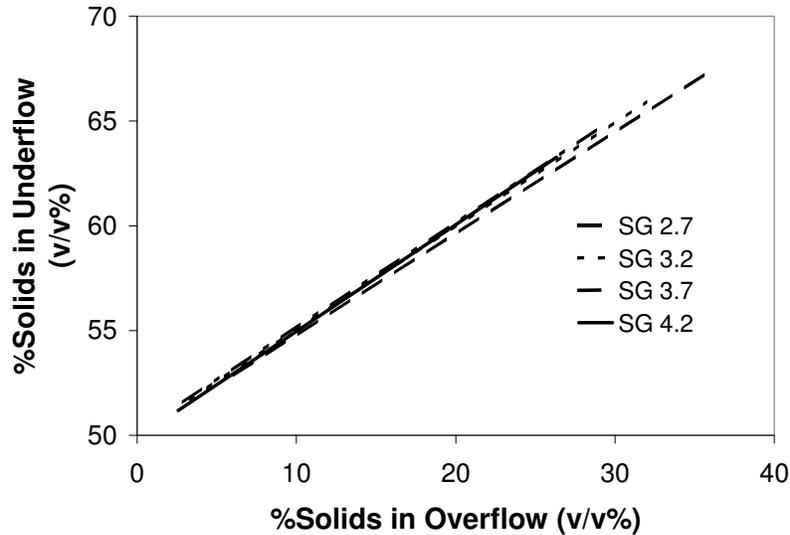


Figure 2.6. The underflow solids concentration at which roping was initiated for ores of different densities. (From Mular and Jull, 1978 adapted in Heiskanen, 2000)

According to Mular and Jull (1978),  $\%V_{MSU}$  increased with increasing overflow solids concentration (Fig. 2.6). This behaviour is actually similar to equations (2.1) and (2.2) because the overflow solids concentration increase in accordance with the increase in feed solids concentration. Mular and Jull (1978) attributed the increase in  $\%V_{MSU}$  with increasing overflow solids concentration to “filling up of the void space between coarse underflow particles with fine slurry of high percent solids”. Thus,  $\%V_{MSU}$  increased with increasing overflow solids concentration due to increased short-circuiting of fines to the underflow. In support of this view, Lynch and Rao (1975), and Asomah and Napier-Munn (1997) determined the following relationship between water split to underflow ( $R_f$ ) and volumetric fraction of solids in the feed slurry ( $\%V_{SF}$ ):

$$R_f \propto \frac{100}{(100 - \%V_{SF})^n}$$

with  $n = 1.0$  according to Lynch and Rao (1975) and  $n = 0.825$  according to Asomah and Napier-Munn (1997). These relationships were determined under normal, spray discharge conditions at the underflow, while Fig. 2.6 was determined under roping conditions. It is assumed that this trend should not change with the discharge type at the underflow.

Plitt et al. (1987), on the other hand, reported that once roping flow had commenced the underflow solids concentrations remained constant with further addition of solids into the cyclone (Fig. 2.7). The dotted line in Fig. 2.7 is a plot of equation 2.1. Abbot (1967a), Heiskanen (2000) and Neesse et al. (2004) also reported the same behaviour.

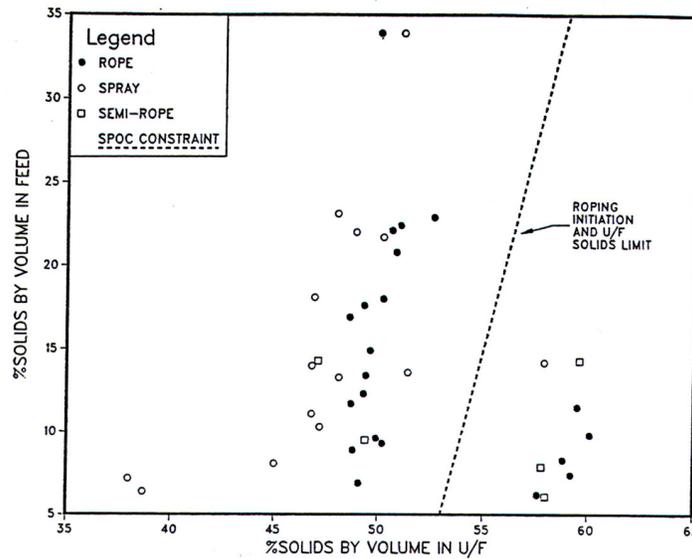


Figure 2.7. Influence of feed solids on roping. (Plitt et al., 1987)

Fahlstrom (1963) also observed  $\%V_{MSU}$  to be constant once roping commenced at the underflow; this is shown in Fig. 2.8 (a) and (b). Curves 1, 2 and 3 in Fig. 2.8(a) correspond to volumetric feed concentrations of 19.6, 8.4 and 3.9%, respectively. And curves 6, 7 and 8 in Fig. 2.8(b) correspond to volumetric feed concentrations of 15.1, 21.7 and 37.4%, respectively.

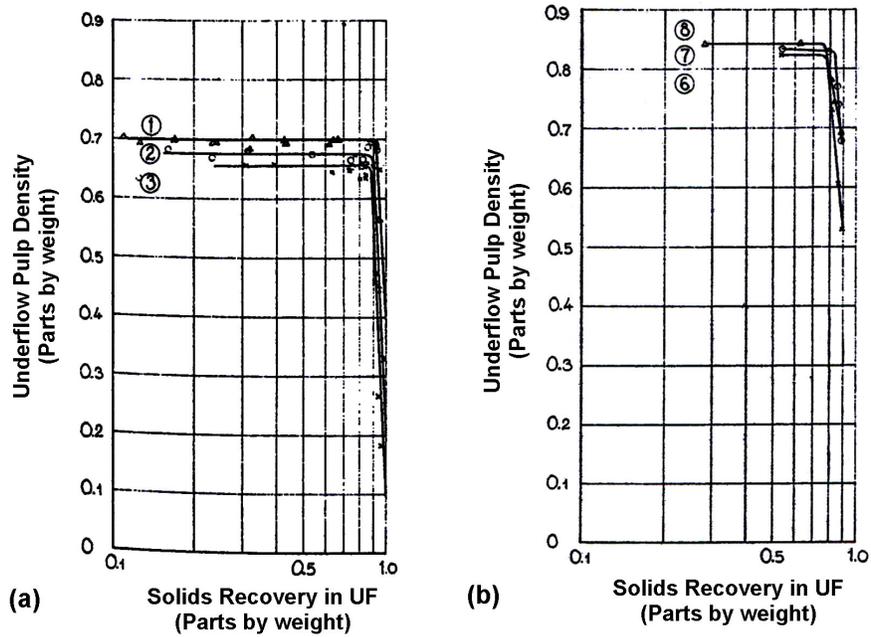


Figure 2.8. Underflow solids concentration during the transition from spray to rope discharge for (a) a 69mm test cyclone and (b) a 300mm plant cyclone. (Adapted from Fahlstrom, 1963).

Fahlstrom (1963) reported the solids recovery in the underflow ( $g_u$ ) to be a function of  $C_i^+$ , the percentage weight of solids in the feed coarser than the separation size (Fig. 2.9).  $g_u$  increased with increasing  $C_i^+$  as shown in Fig. 2.9. Obviously the feed solids concentration at which roping commences decreases with increasing  $C_i^+$ .

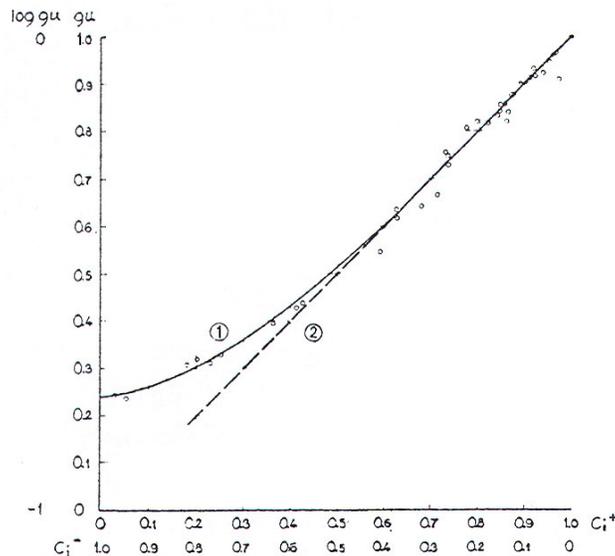


Figure 2.9. Solids recovery in the underflow as a function of material coarser than the separation size in the feed for a 69mm test cyclone. Fahlstrom (1963). Curve 1:  $\%V_{SF} = 3.9, 8.4$  and  $19.6\%$ . Curve 2:

$$g_u = C_i^+.$$

Table 2.1 shows %V<sub>MSU</sub> obtained from various sources in which hydrocyclones of different sizes and configurations, and ores of different densities and sizes were used. It is shown clearly in Table 2.1 that %V<sub>MSU</sub> is generally around 50% solids (by volume) for most hydrocyclones; a minimum of 39% and a maximum of 68% have been reported.

Table 2.1. Various %V<sub>MSU</sub> obtained by different workers.

Source	%V <sub>MSU</sub> (v/v%)	Material Treated	Particle Size (µm)	D (mm)
Abbot (1967)	48	Coal	-	-
Concha et al. (1996)	49-60	-	-	-
Dahlstrom (1949)	~56 <sup>a</sup>	Coal	-	356
Fahlstrom (1963)	41-47	Flotation tails	150 <sup>b</sup>	69
Fahlstrom (1963)	54-57	Sulphide ore	1500 <sup>b</sup>	300
Heiskanen (2000)	39-46	Limestone	95-212 <sup>d</sup>	-
Mular and Jull (1978)	51-68	Various	-	Various
Neesse et al. (2004b)	52	Quartz	1000 <sup>b</sup>	150
Plitt et al. (1987)	49-60	Sand	53-151 <sup>c</sup>	146
Plitt (1983) <sup>*</sup>	53-62	-	-	150
Yianatos et al. (2002)	56-59	-	-	-

\*As reported in Flintoff *et al.* (1987).

<sup>a</sup>Density of the coal assumed to be 1.5SG.

<sup>b</sup>Particle top size in feed.

<sup>c</sup>Median particle size in feed.

<sup>d</sup>Median particle size in the underflow.

The maximum value for %V<sub>MSU</sub> of 68% was obtained by Mular and Jull (1978), who treated ores with specific gravities ranging from 2.7 up to 4.2 and employed much larger hydrocyclones with spigot sizes ranging from about 50 up to 200mm. As mentioned previously, the high %V<sub>MSU</sub> is a consequence of increased fines in the underflow product due to increased short-circuiting of fines to the underflow. The same rationale could be used to explain the relatively high value of 62% reported by in Flintoff *et al.* (1987), shown in Fig. 2.10.

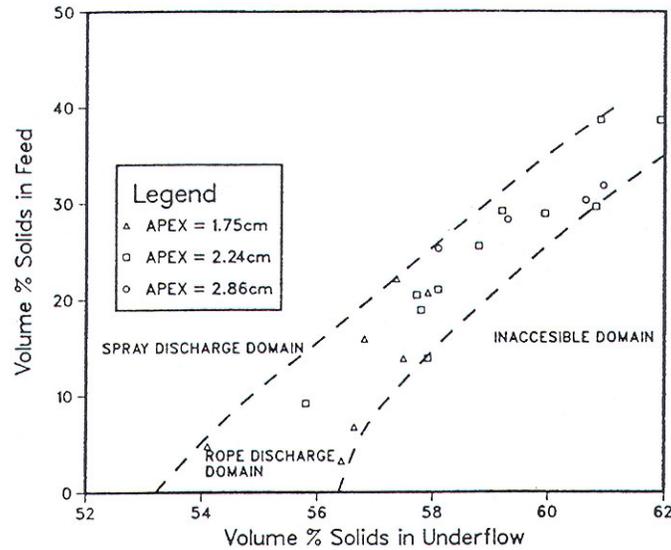


Figure 2.10. The influence of feed concentration on the critical underflow concentration at which roping commences. (Flintoff et al., 1987)

The lowest value for  $\%V_{MSU}$  obtained in Table 2.1 was 39% reported by Heiskanen (2000). This minimum value of 39% was obtained when the feed solids concentration was the lowest (6.6% solids by volume), and the highest  $\%V_{MSU}$  of 46% (obtained by Heiskanen) was observed at the highest feed concentration (Fig. 2.11). The effect of the feed concentration on  $\%V_{MSU}$ , as reported by Mular and Jull (1978) and Flintoff et al. 1987 (Fig. 2.6 and 2.10, respectively), is further confirmed by these observations.

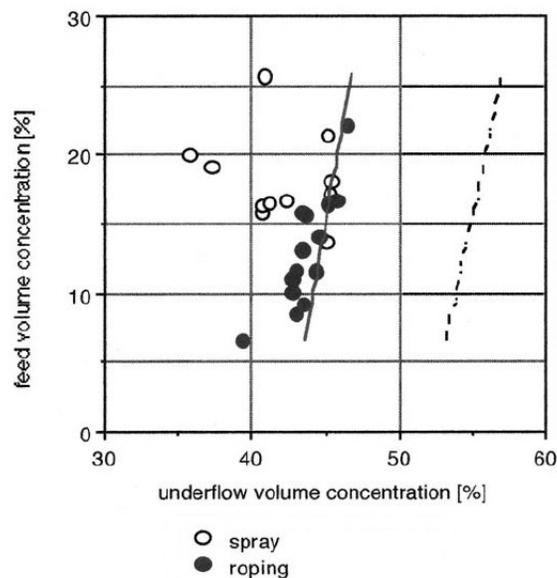


Figure 2.11. The influence of feed volume concentration on the underflow concentration during roping. The dotted line represents a plot of equation 2.1, and the solid line is equation 2.2. (Heiskanen, 2000)

**(c) Effect of Roping on Cyclone Operation**

Fahlstrom (1963) reported an abrupt increase in the overflow solids concentration at the onset of rope discharge (Fig. 2.12); this is due to misplacement of coarse particles to the overflow. Curve 1 in Fig. 2.12 was obtained with a 69mm test cyclone at various feed solids concentrations, while curves 2, 3, and 4 correspond to volumetric feed concentrations of 15.1, 21.7 and 37.4%, respectively, on the 300mm plant cyclone.

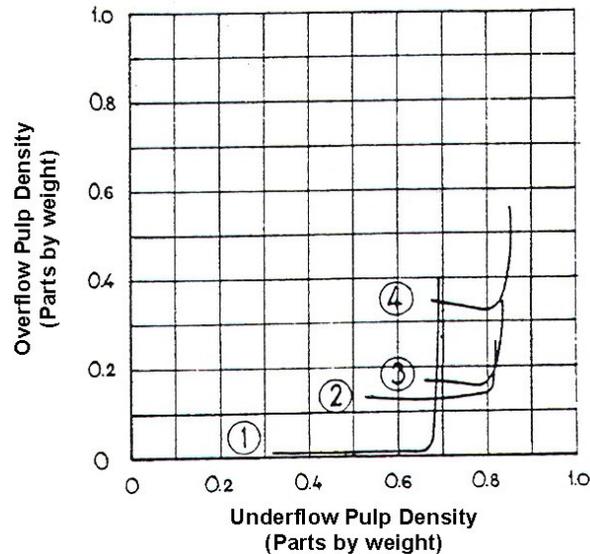


Figure 2.12. Overflow pulp density during the transition from spray to rope discharge. Curve 1: 69mm test cyclone at various %V<sub>SF</sub>. Curves 2, 3 and 4: %V<sub>SF</sub> = 15.1, 21.7 and 37.4%, respectively, with D<sub>c</sub> = 300mm. (Fahlstrom, 1963)

Roping or spigot overloading has widely been established to result in an increase in cut-size as a consequence of misplacement of coarse particles to the overflow (Dahlstrom, 1949; Abbot, 1967a; Trawinski, 1976; Mular and Jull, 1978; Plitt et al., 1987; Heiskanen, 2000; Neesse et al., 2004, etc.). This behaviour is illustrated in Fig. 2.13, 2.14 and 2.15.

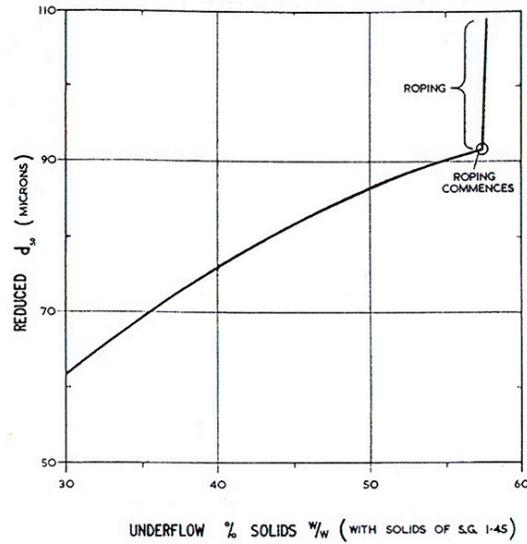


Figure 2.13. The influence of commencement of roping on the cut-size. (Abbot, 1967a)

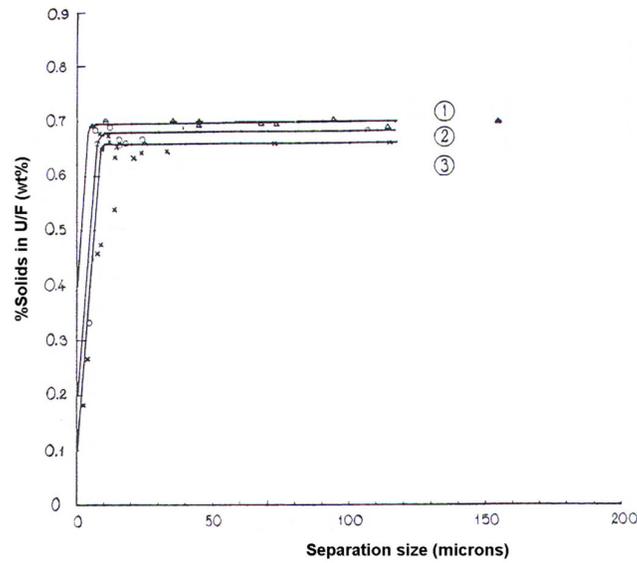


Figure 2.14. Change in the separation size during roping. Curve 1: %V<sub>SF</sub>= 3.9, 8.4 and 19.6%. (Fahlstrom, 1963)

Roping occurred at lower  $g_u$  values and spray discharge was encountered at higher  $g_u$  values. According to Fahlstrom (1963) the following relationship is valid (for a 69mm test cyclone), within the range  $0.4 < g_u < 1$ :

$$d_{50} = -196 \log(g_u) \quad (2.3)$$

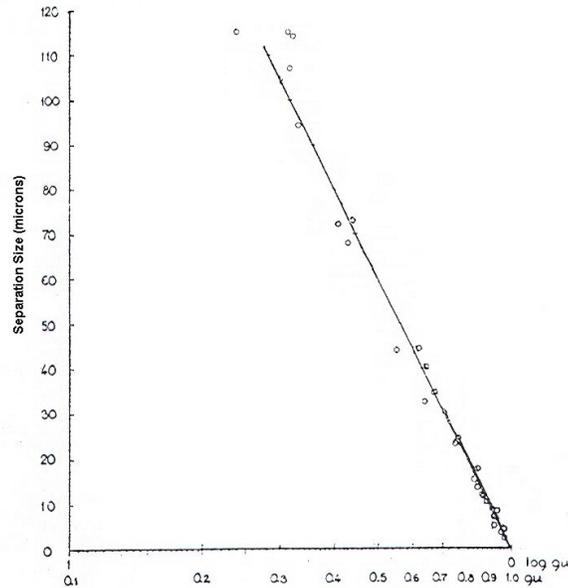
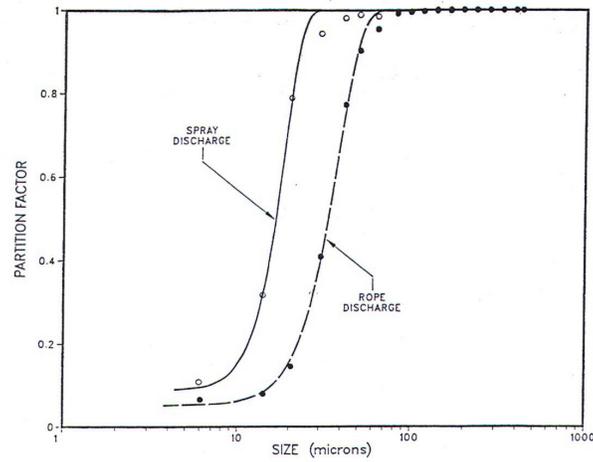
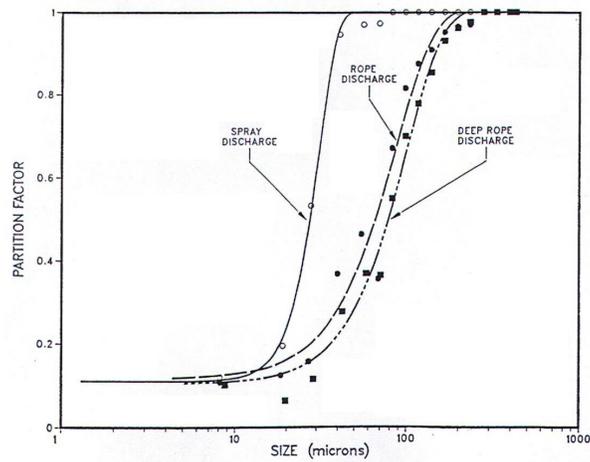


Figure 2.15. The relationship between separation size and solids recovery in U/F (mass fraction). (Fahlstrom, 1963).

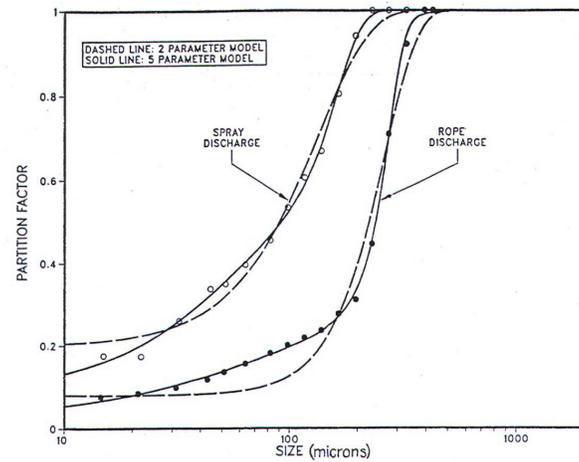
Plitt et al. (1987) reported that the impact of roping on the performance of a cyclone is dependent on the feed solids concentration. They distinguished between three categories of feed solids concentrations, namely: low, intermediate, and high; the partition curves obtained under these three solid concentrations are shown in Fig. 2.16. The feed concentrations were kept relatively constant for each set of the partition curves in Fig. 2.16; roping was induced by decreasing  $D_u$ . The increase in the cut-size in Fig. 2.16 is partly a consequence of the decrease in  $D_u$ , which was decreased from 25mm for both Fig. 2.16 (a) and (c) to 17 and 14mm, respectively. While  $D_u$  was decreased from 25mm to 20mm (roping) and then to 15mm (deep roping) in Fig. 2.16 (b). The effect of roping on the sharpness of separation was reported to be dependent on the feed solids concentration by Plitt et al. (1987). It is interesting to note that there wasn't much misplacement of coarse particles to the overflow in Fig. 2.16.



(a)



(b)



(c)

Figure 2.16. Influence of roping on cyclone performance at (a) low (~7% by volume) (b) intermediate (~18%) and (c) high (~34%) feed solids concentrations. (Plitt et al., 1987)

Fahlstrom (1963), on the other hand, reported the sharpness of separation to initially increase with decreasing  $g_u$  up to a maximum, and at low  $g_u$  values the sharpness of separation decreased with decreasing  $g_u$ . It is known that roping was prevalent at low  $g_u$  values, and it is thought that the decrease in the sharpness of separation with decreasing  $g_u$  is a consequence of roping.

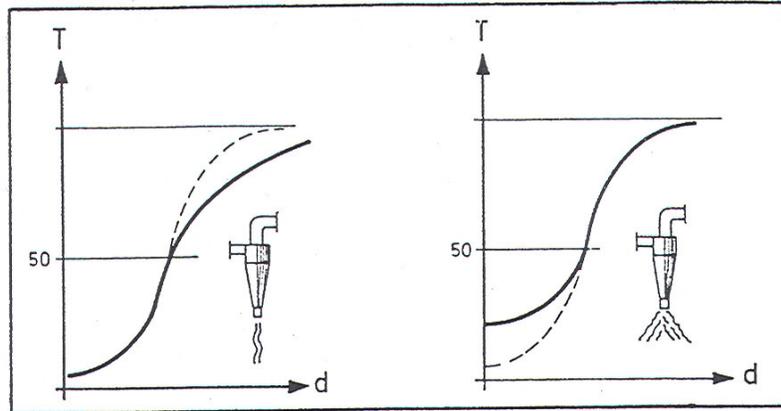


Figure 2.17. The influence of particle misplacement on the shape of the Tromp curve during rope and spray discharges. (Trawinski, 1976)

Trawinski (1976) illustrated the effect of particle misplacement to the overflow during roping as shown in Fig. 2.17, in the curve on the left; a disturbance on the upper part of the Tromp curve is observed during roping. A similar curve was presented by Kelly (1991) as shown in Fig. 2.18. According to Kelly (1991) there are two major causes of coarse particles misplacement to the overflow namely: roping and damaged vortex finder.

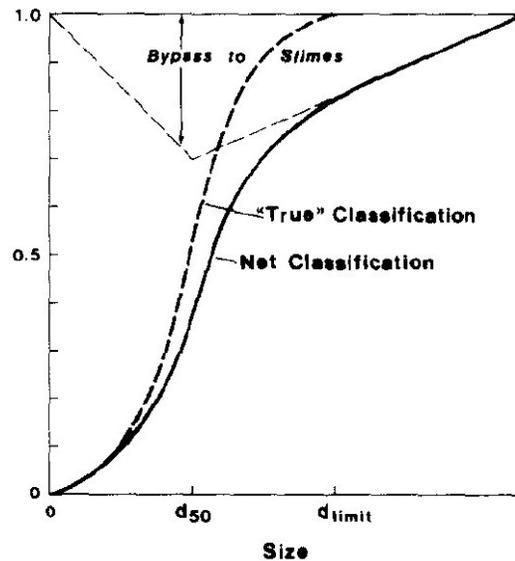


Figure 2.18. Effect of coarse particles misplacement to the overflow on the partition curve. (Kelly, 1991)

Fahlstrom (1963) encountered a similar type of disturbance on the upper part of the Tromp curve (as in Fig. 2.17); this is illustrated in Fig. 2.19. As the spigot diameter was decreased from 9mm down to 5mm (curves 4, 3 and 2) the cut-size increased consistently and the shape of the Tromp curve remained relatively unchanged; short-circuiting of fines to the underflow decreased steadily with decreasing spigot diameter. When the cyclone was operated with the smaller 3mm spigot, excessive short-circuiting of coarse particles to the overflow took place as illustrated by curve 1 (Fig. 2.19). It can be observed that close to 50% of the coarsest particles by-passed the separation process within the cyclone and went straight to the overflow stream.

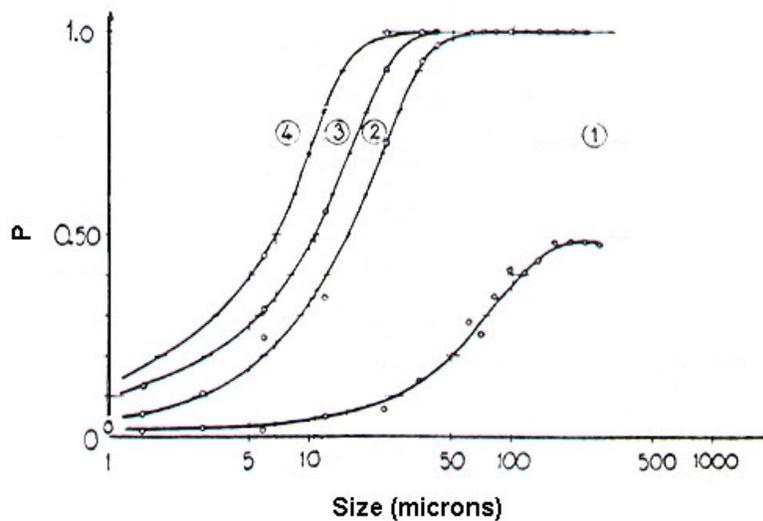


Figure 2.19. Influence of roping on cyclone performance.  $\%V_{SF} = 8.4\%$ ,  $D = 69\text{mm}$  and  $D_o = 16\text{mm}$ . Curves 1, 2, 3, 4 correspond to  $D_u = 3, 5, 7, 9\text{mm}$ . (Fahlstrom, 1963)

### 2.1.2. The Influence of Cyclone Geometry on the Spigot Capacity

Cyclone geometry includes inlet size, overflow diameter, underflow diameter, cone angle and barrel length (Fig. 1.1). Fig. 1.1 is repeated here for convenience. It is assumed that the influence of a particular variable on  $Q_U$  during spray discharge should give us an indication of that variables' effect on  $Q_{UM}$ .

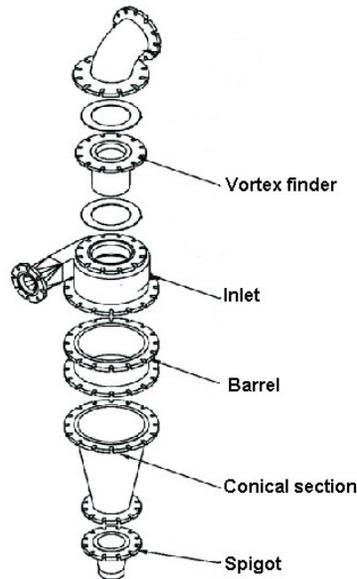


Figure 1.1. Cyclone geometry. (Adapted from Bosman 2003b)

#### (a) Inlet Size

At constant feed pressure, an increase in the inlet size is expected to increase the cyclone flow-rate. A number of correlations that relate the cyclone throughput to the inlet size have been proposed and they are of the following form:

$$Q_f (= Q_{OS} + Q_{US}) \propto D_i^n$$

The various quantities obtained for the exponent  $n$  above are shown in Table 2.2.  $D_i$  has a significant effect on  $Q$  as evident from the exponent  $n$  that ranged from 0.77 to 2.0 in the literature.

Table 2.2. The exponent  $n$  for the relationship between cyclone throughput and inlet diameter.

Source	exponent $n$
Bradley (1965)	0.9-2.0
Rao, Lynch and Nageswararao (1976)	0.85
Plitt (1976)	0.84
Svarovsky (1984)	0.85-0.94
Asomah and Napier-Munn (1997)	0.77

The inlet has previously been reported to have very little influence on the volume split ( $S$ ) within the cyclone (Svarovsky, 1984). Thus, increasing the inlet size should generally increase the flow-rates of slurry through both the spigot and the vortex finder, more or less equally. The inlet increases the flow-rate of slurry exiting through the outlets by increasing their exit velocities.

### (b) Spigot Diameter

A number of authors have proposed various relationships between the spigot diameter and spigot capacity for hydrocyclones. The relationship proposed by Tarr (1965) is shown in Fig. 2.20. The relevant data points used to plot the curves were unfortunately not given, and the spigot capacities were stated to be approximate. Tarr (1965) proposed a number of exponential curves, each at a specific underflow solids concentration, relating the spigot capacity to spigot diameter. The volumetric underflow solids concentrations ranged about 20% to 53% (by volume). It is not clear how these spigot capacities were defined or what the determining factor for these spigot capacities was. Volumetric underflow solids concentrations as low as 20% suggest that the hydrocyclone was not operating with a rope discharge at the spigot, and that spigot capacity was not defined according to the presence or absence of rope discharge at the underflow. It is interesting to note that the underflow concentrations were as high as 53% (by volume), whereby roping would be expected, yet the relationship between the spigot size and spigot capacity was similar to that of low underflow concentrations where roping should not have been taking place.

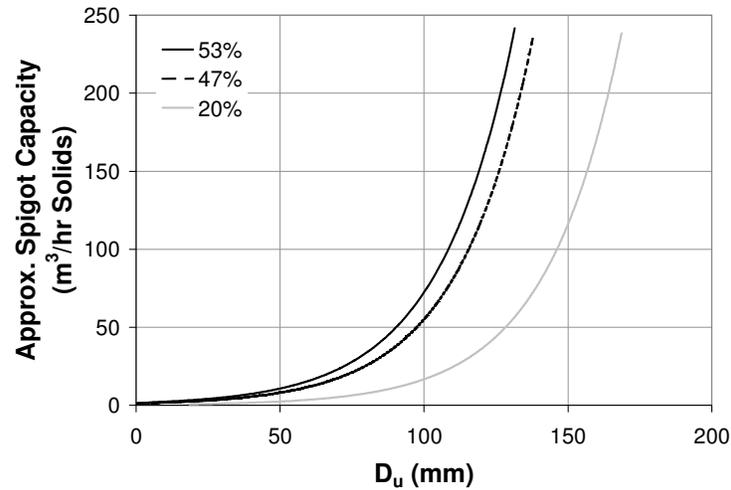


Figure 2.20. Effect of the spigot size on spigot capacity. (Tarr, 1985)

Mular and Jull (1978) also proposed a relationship between spigot capacity and spigot diameter; a similar relationship was reported in Jull (1972) as shown in Fig. 2.21. This curve was used to recommend an appropriate spigot size for a particular hydrocyclone with a specific spigot capacity. The spigot capacities were measured on cyclones operating just “short of roping”. Just as with Tarr (1965), the spigot capacities are said to be approximate and no data points were presented.

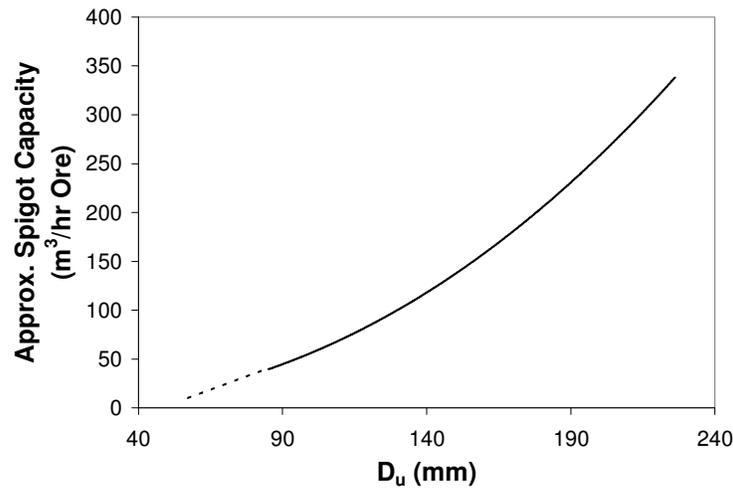


Figure 2.21. Effect of the spigot size on spigot capacity. (Jull, 1972)

The fact that these spigot capacities were obtained just “short of roping”, and not during roping is not expected to influence the reliability of these spigot capacities values considerably. This is because a semi-rope discharge precedes the onset of roping, and during

semi-ropeing the flow at the underflow switches continuously between spray and rope discharges. Closer to the onset of roping the flow at the underflow is predominantly in the form of a rope discharge, occasionally switching to spray discharge (Neesse, 2007). Thus, the slurry occupies the entire cross-section of the spigot for a significantly large proportion of the time just “short of roping”, such that the flow rates measured at this point should represent a reasonable approximation of the spigot capacity. The spigot ore loading during semi-ropeing, just ‘short of roping’, should therefore not differ too much from the actual spigot capacity.

A regression of the curve in Fig. 2.21 gives the following mathematical expression:

$$Q_{UM} = (2.3 \times 10^{-3}) D_u^{2.19} \quad (2.4)$$

with  $Q_{UM}$  the solids capacity of the underflow in  $m^3/hr$  and  $D_u$  the spigot diameter in mm. This relationship was observed to be variable at small spigot diameters; hence, the dotted line in Fig. 2.21 at small spigot sizes. This variability was not incorporated into equation 2.4.

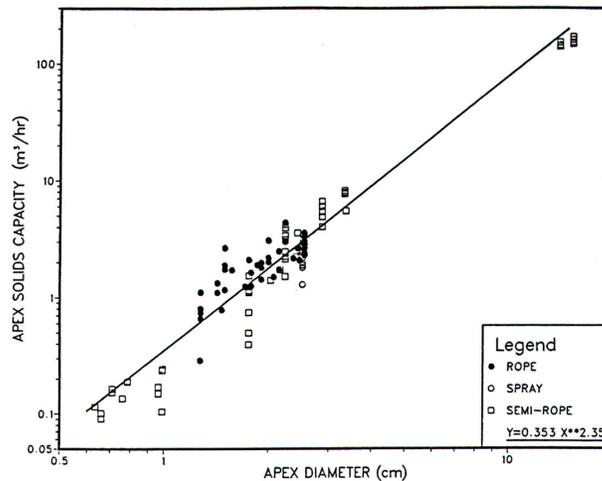


Figure 2.22. Spigot capacity under rope and near rope conditions. (Plitt et al., 1987)

A similar expression was obtained by Plitt et al. (1987):

$$Q_{UM} = 0.35 D_u^{2.35} \quad (2.5a)$$

with  $D_u$  in cm and  $Q_{UM}$  in  $m^3/hr$ . A plot of equation 2.5a is shown in Fig. 2.22. This expression can be rearranged so that the  $D_u$  is in mm not cm, which gives the following expression:

$$Q_{UM} = (1.563 \times 10^{-3}) D_u^{2.35} \quad (2.5b)$$

This relationship was based on a hydrocyclone operating in the semi-roping and roping regimes; data from spray discharge was not incorporated into equation 2.5. Equations 2.4 and 2.5 seem to suggest that, as expected, the spigot capacity is mainly a function of the cross-sectional area of the spigot. The dependence of the spigot capacity on the cross-sectional area of the spigot was also reported by Fahlstrom (1963); who quoted an expression for spigot capacity of  $2.5\text{ton/hr/cm}^2$ . The expression by Plitt et al. (1987) has been validated by Heiskanen (2000) as shown in Fig. 2.23. In validating Plitt et al.'s expression Heiskanen used data obtained during roping only.

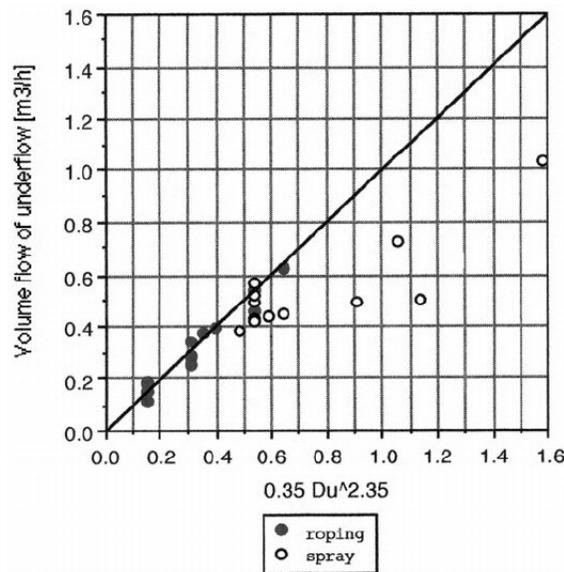
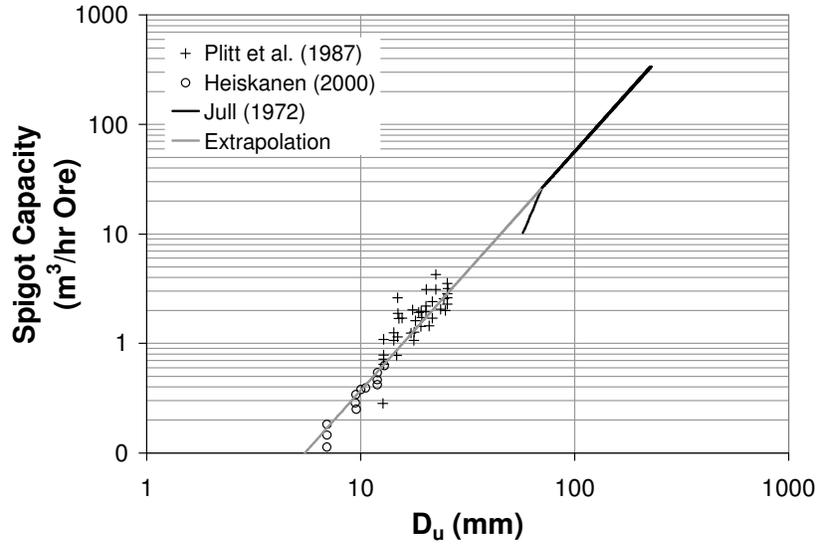
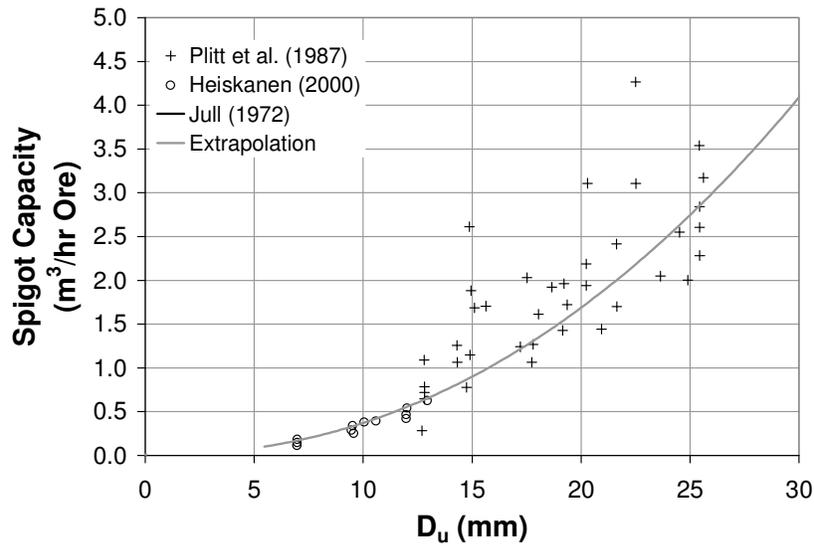


Figure 2.23. Relationship between spigot diameter and spigot ore capacity. (Heiskanen, 2000)

The level of agreement between the various relationships between spigot diameter and spigot capacity proposed by various authors is illustrated in Fig. 2.24. The curve obtained by Jull (1972) was extended down to much lower spigot diameters than those that he investigated. There is some agreement between this curve and the data points reported by Plitt et al. (1987) and Heiskanen (2000), although there is a considerable amount of scatter.



(a)



(b)

Figure 2.24. (a) Comparison of the spigot size-spigot capacity relationships proposed by various authors. (b) Curve in (a) at smaller spigot sizes on normal scale.

Fahlstrom (1963) reported  $\%V_{MSU}$  to change with  $D_o/D_u$  at constant  $\%V_{SF}$  as shown in Fig. 2.25; an increase in  $D_o/D_u$  appears to slightly decrease  $\%V_{MSU}$ . At low  $D_o/D_u$  values roping was not prevalent at the underflow. Heiskanen (2000) also reported a similar trend (Fig. 2.26).

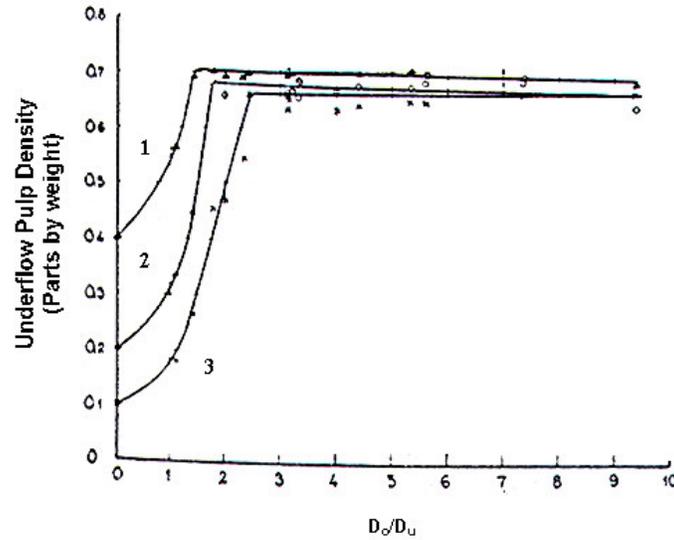


Figure 2.25. Underflow solids concentration during roping with changing  $D_o/D_u$ . Curves 1, 2 and 3 correspond to  $\%V_{SF} = 19.6, 8.4$  and  $3.9\%$ . (Fahlstrom, 1963)

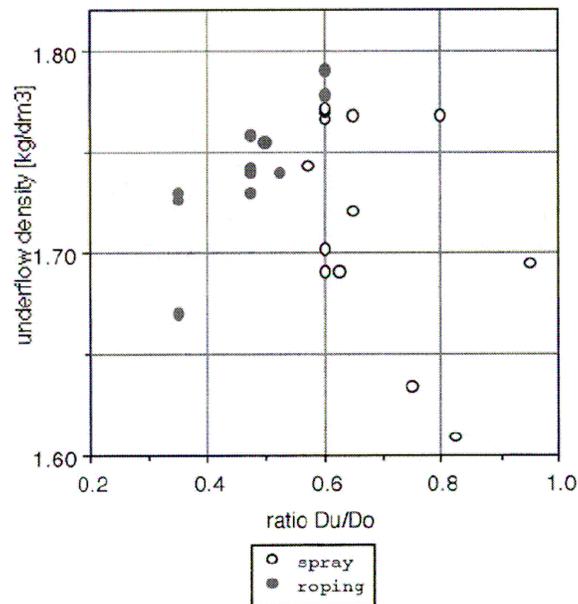


Figure 2.26. The influence of the spigot-to-vortex finder diameter ratios on the underflow density. (Heiskanen, 2000)

A clear distinction between  $\%V_{MSU}$  for the 1.75cm and 2.86cm spigots can be made in Fig. 2.27, and the trend is consistent with that reported by Fahlstrom (1963) and Heiskanen (2000). The data points for the 2.24cm spigot, however, do not seem to be following the same trend.

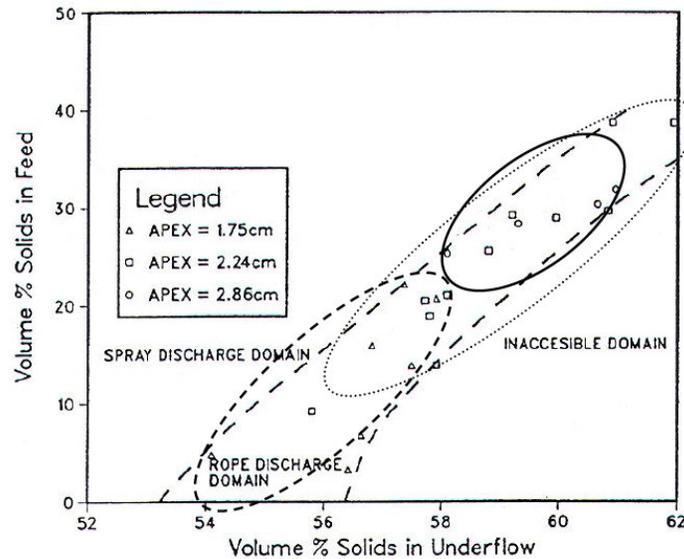


Figure 2.27. The influence of feed concentration on the critical underflow concentration at which roping commences. (Flintoff, 1987)

The above-mentioned observations that the onset of roping (expressed in terms of  $\%V_{MSU}$ ) is dependent on the  $D_u/D_o$  ratio, is in agreement with the findings of Concha et al. (1996). They proposed that the “...underflow concentrations alone (do) not determine the type of discharge in a hydrocyclone...” instead the “...ratio of apex to vortex diameters separates the regions of rope and spray discharge”. Furthermore, Concha et al. (1996) proposed that there is a specific range of underflow-to-overflow diameters ratios in which a rope discharge will be obtained at the underflow (Table 2.3 and Fig. 2.28).

Table 2.3.  $D_u/D_o$  ratios at which roping is likely to occur according to Concha et al. (1996).

$D_u/D_o$ ratio	Flow type at UF
More than 0.56	Spray discharge only
Between 0.45 and 0.56	Spray, semi-rope, rope
Less than 0.45	Roping only

It is the author’s opinion that although the  $D_u/D_o$  ratio influences the point at which roping commences; the onset of roping is determined mainly by the solids concentration within the cyclone. Therefore, it is expected that roping can occur at any  $D_u/D_o$  ratio provided the solids concentration within the cyclone is sufficiently high. At low  $D_u/D_o$  ratios roping takes place more readily (at lower feed solids concentrations) than at high  $D_u/D_o$  ratios.

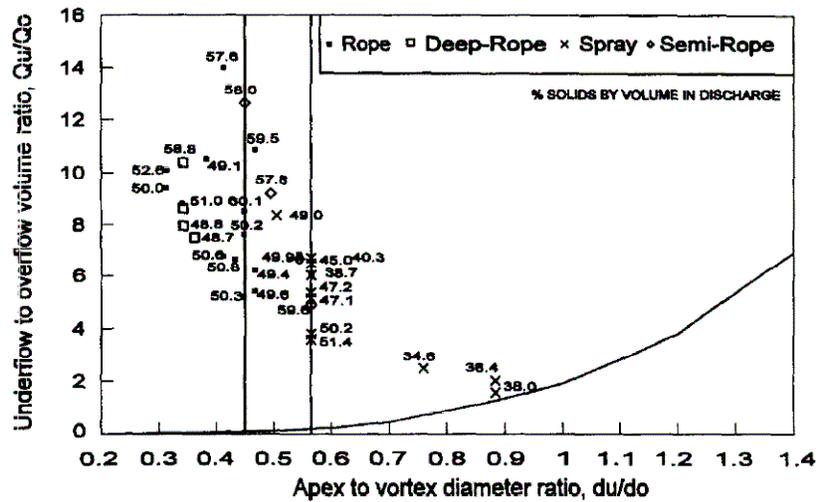


Figure 2.28.  $D_u/D_o$  ratios at which roping is likely to occur according to Concha et al. (1996).

### (c) Vortex Finder Diameter

According to Plitt (1976),  $D_o$  and  $D_u$  influence  $Q$  as follows:

$$Q \propto (D_u^2 + D_o^2)^{0.49}$$

While other authors proposed a relationship of the following form:

$$Q \propto D_o^n$$

Values obtained for the exponent  $n$  are given in Table 2.4;  $Q$  increases significantly with increasing  $D_o$ .

Table 2.4. The exponent  $n$  for the relationship between  $Q$  and  $D_o$  ratio.

Source	exponent $n$
Lynch and Rao (1975)	0.68-0.73
Lynch and Rao (1968)	1.0
Asomah and Napier-Munn (1997)	0.77

A decrease in  $D_o$ , with all other variables constant, increases the proportion of the feed slurry that exits at the underflow and decreases slurry flow at the overflow; this behaviour has been quantified by a number of authors as follows:

$$S = \frac{Q_{US}}{Q_{OS}} \propto \left( \frac{D_u}{D_o} \right)^n$$

Some of the values obtained for the exponent  $n$  are shown in Table 2.5. It can be inferred from the behaviour of  $S$  and  $Q$  with changing  $D_o$  that the spigot capacity should increase with decreasing vortex finder diameter.

Table 2.5. The exponent  $n$  for the relationship between  $S$  and  $D_u/D_o$  ratio.

Source	exponent $n$
Bradley (1965)	1.75-4.4
Plitt (1976)	3.31

Furthermore, Concha et al. (1996) reported that roping flow tends to occur more readily at larger vortex finder sizes (and smaller spigot sizes), as shown in Table 2.3.

#### (d) Cone Angle and Barrel Length

According to van Duijn and Rietema (1983), the residence times for hydrocyclones with smaller cone angles are smaller than those of large cone angle cyclones. Further, Bradley (1965) and Svarovsky (1984) reported that an increase in the overall length of the cyclone, either through a larger cylindrical section or a smaller cone angle, increases the capacity of the cyclone. In agreement with this view Plitt (1976) made use of the so-called free vortex height ( $h$ ), which is defined as the distance from the bottom of the vortex finder to the top of the spigot, to embody the effect of the barrel length and cone angle. The following relationship between the cyclone capacity and free vortex height was proposed by Plitt (1976):

$$Q(= Q_{OS} + Q_{US}) \propto h^{0.16}$$

with  $Q$  the volumetric flow-rate through the cyclone and  $h$  the free vortex height. This is in agreement with the behaviour reported by Asomah and Napier-Munn (1997).

Plitt (1976) further reported  $S$  to be related to the free vortex height as follows:

$$S = \frac{Q_{US}}{Q_{OS}} \propto h^{0.54}$$

Therefore, an increase in  $h$  should result in an increase in both  $Q$  and  $S$ , and accordingly, an increase in the spigot capacity.

Plitt (1976), however, proposed that there is a loss of rotational energy in the underflow region with increasing cone length (or decreasing cone angle), which implies a decrease in the

air core size. Further, Mular and Jull (1978) proposed, “The action of the cone is to squeeze coarse solids towards the centre to obtain a concentrated underflow product”. As a result roping would tend to occur at lower solids concentrations with smaller cone angles.

### 2.1.3. The Influence of Operational Variables on the Spigot Capacity

#### (a) Feed pressure

Feed pressure increases the cyclone capacity in accordance with the following relationship:

$$Q \propto P^n$$

Various values for the exponent  $n$  obtained by different authors are shown in Table 2.6.

Table 2.6. The exponent  $n$  for the relationship between cyclone capacity and feed pressure.

Source	exponent $n$
Bradley (1965)	0.38-0.5
Rao, Lynch and Nageswararao (1976)	0.49
Plitt (1976)	0.56
Svarovsky (1984)	0.42-0.56
Asomah and Napier-Munn (1997)	0.5

According to Svarovsky (1984) an increase in the feed pressure, with all other variables constant, is associated with a more concentrated underflow and a decrease in the proportion of feed material that exits at the underflow. Plitt (1976) also reported a decrease in  $S$  with increasing feed pressure:

$$S = \frac{Q_{US}}{Q_{OS}} \propto P^{-0.25}$$

The effect of feed pressure on  $S$  is not too strong. Accordingly the spigot capacity should increase with increasing feed pressure, although the effect should not be a major one due to the effect of pressure on  $S$ .

#### (b) Ore Size

Roping occurs at high solids concentrations within the cyclone, especially at the underflow, it follows then that slurry with finer particles in these conditions will tend to be more viscous than that with coarser particles. Hydrocyclones typically treat particles as large as about 1mm down to zero depending on the application in which they are employed. According to Plitt et al. (1987) higher slurry viscosities retard the rotational motion of the slurry. In agreement with this view, Concha et al. (1996), Davidson (1995), and Dyakowski and Williams (1995) reported increased slurry viscosity to bring about a decrease in the size of the air core. The influence of slurry viscosity on the maximum tangential velocity within a hydrocyclone

reported by Dyakowski and Williams (1995) is shown in Fig. 2.29. Further, Lynch and Rao (1975) reported the cyclone throughput to decrease with increasing fines content in the cyclone feed; they defined fines to be particles passing 53 $\mu\text{m}$ .

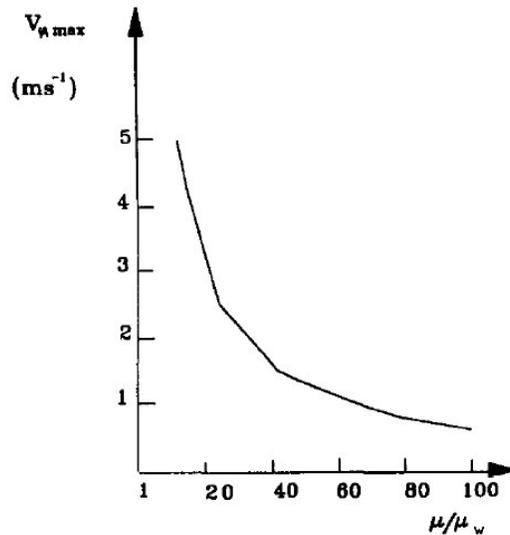


Figure 2.29. Effect of slurry viscosity on the maximum tangential velocity within a hydrocyclone. (Dyakowski and Williams, 1995)

It is therefore expected that the percent solids at which roping commences should be shifted to lower quantities at higher slurry viscosities (finer particle sizes). Plitt et al. (1987) illustrated this behaviour (Fig. 2.30), and proposed the following expressions to show the relationship between the size of the particles in the underflow and  $\%V_{MSU}$ :

$$\%V_{MSU} = 62.3 \left( 1 - \exp \left[ \frac{-d_u}{60} \right] \right) \quad (2.6)$$

where  $d_u$  is the mass median (50% passing) size of the underflow solids, and  $\%V_{MSU}$  is the “percent solids by volume at which the underflow begins to rope and remain during roping”. Equation 2.6 and Fig. 2.30 clearly show that at finer particle sizes roping is initiated at lower solids concentrations; hence, the increase in  $\%V_{MSU}$  with particle size.

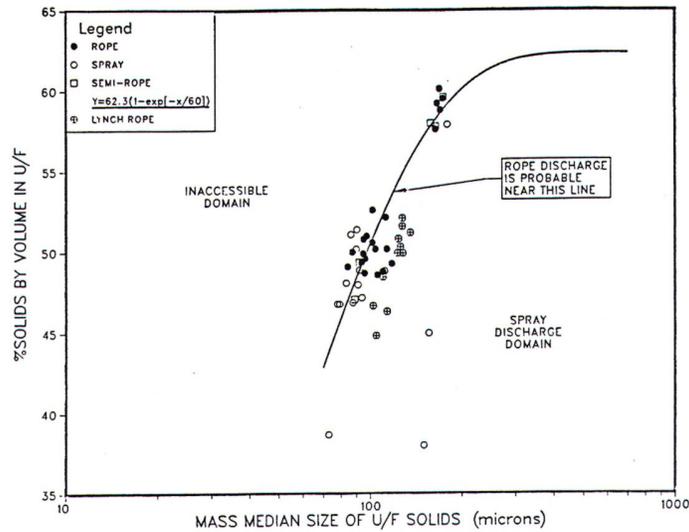


Figure 2.30. Effect of 50% passing particle size on underflow concentration during roping. (Plitt et al., 1987)

Heiskanen (2000), on the other hand, did not observe any relationship between  $%V_{MSU}$  and the 50% passing size (Fig. 2.31). It is expected that particle size influences  $%V_{MSU}$  by changing the packing characteristics of the particles, and the packing characteristics of the particles are more dependent on the size distribution rather than 50% passing size of the material. In agreement with this view Heiskanen (2000) observed, “there is a relationship between roping tendency and the width of particle size distribution” (Fig. 2.32).

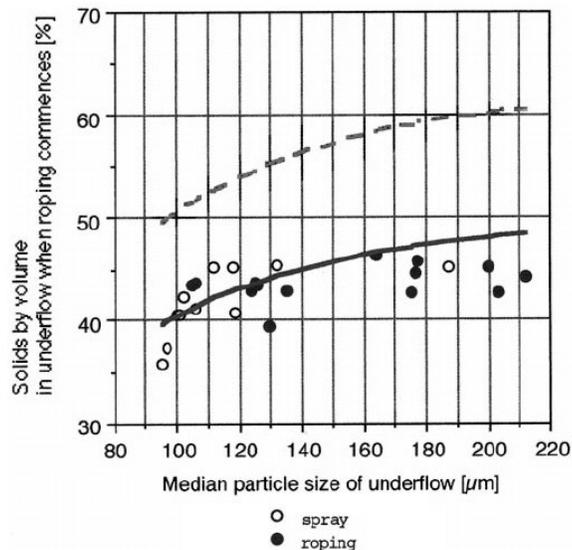


Figure 2.31. Effect of median particle size of underflow on  $%V_{MSU}$ . (Heiskanen, 2000)

It remains to be seen whether the behaviour of  $\%V_{MSU}$  with changing particle size described above has a significant influence on the spigot capacity.

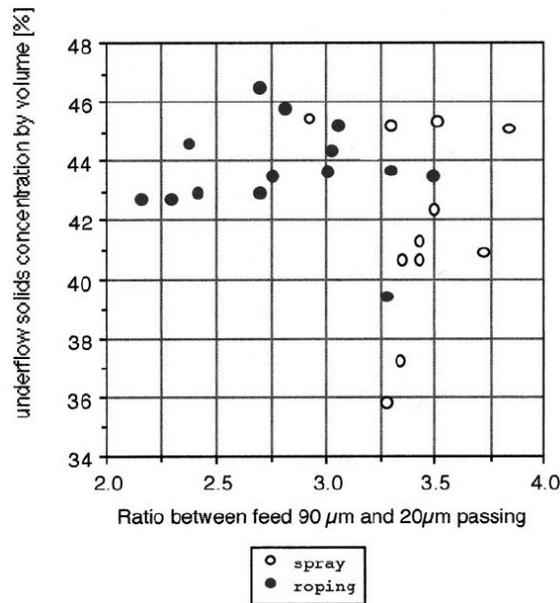


Figure 2.32. Effect of the size distribution of particles at the underflow on the underflow solids concentration at which roping commences. (Heiskanen, 2000)

**(c) Ore Density**

Particle density does not seem to have any significant influence on the spigot capacity; the effect of particle density on the spigot capacity is illustrated in Fig. 2.33.

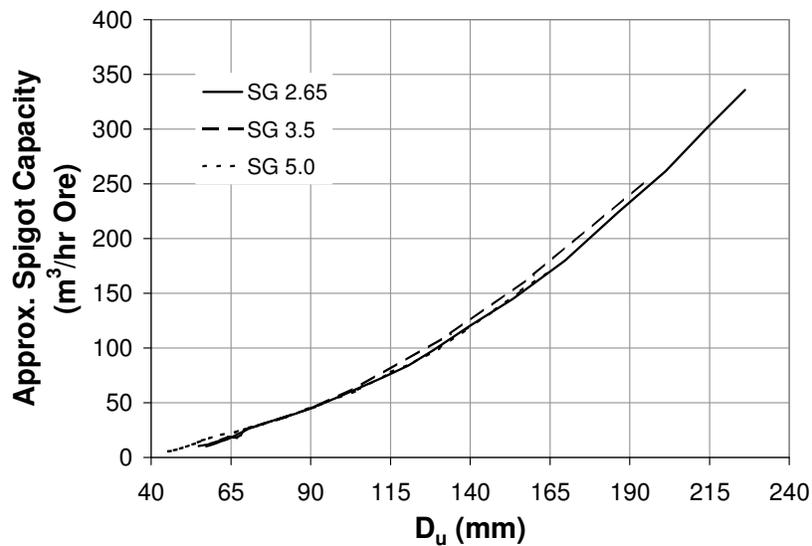


Figure 2.33. Effect of particle density on spigot capacity. (Jull, 1972)

Furthermore, Mular and Jull (1978) reported that particle density does not influence  $\%V_{MSU}$ ; this was illustrated previously in Fig. 2.6.

**(d) ‘Overflow Throttling’**

Neesse et al. (2004c) and Neesse et al. (2007) reported that the discharge capacity of the underflow can be increased by controlling the volume split of a battery of hydrocyclones. They proposed a volume split control method in which a control (or ‘throttle’) valve at the hydrocyclone overflow is used to regulate the split. By adjusting the ‘throttle’ valve and the feed pump speed simultaneously, the pressure within the cyclone is intensified resulting in increased underflow discharge capacity. This effect is due to a combination of increased feed pressure (due to feed pump speed) and increased counter-pressure in the overflow (due to ‘throttling’ valve). The effect of feed pressure on the spigot capacity has been described previously in this chapter, while the effect of the counter-pressure in the overflow on the spigot capacity is very similar to that of the vortex finder diameter. Throttling the overflow, through the control valve, influences the spigot capacity in a similar manner as reducing the overflow diameter.

## 2.2. DENSE MEDIUM CYCLONES

### 2.2.1. Characterisation of Overloading at the Sinks

Roping in dense medium cyclones has not been as widely researched as in classification cyclones. None of the literature (referenced in this report) intentionally investigated the overloading behaviour of the dense medium cyclone: roping and spigot overloading were stumbled upon while investigating other phenomena. Some of the interesting papers include those by van der Walt (1950), Stas (1957), Cohen and Isherwood (1960), and Upadrashta and Venkateswarlu (1982).

Both van der Walt (1950), and Cohen and Isherwood (1960) established that there was a maximum sinks ore carrying capacity. While Stas (1957) identified that the cyclone was operating in an “overloaded” condition when a rope discharge was prevalent at the sinks. Upadrashta and Venkateswarlu (1982) proposed that the sinks discharge capacity was exceeded when a rope discharge was encountered at the sinks, but without any evidence to support this notion. Further, Symonds and Malbon (2002) stated, “Apart from the feed capacity, the cyclone has a limit to how much reject material it can handle. This is due to the restriction caused by the apex”.

Stas (1957) observed that the “angle of dispersion” of the sinks slurry was reduced with increasing feed solids concentration. In addition he also reported an increase in the thickness (of the annulus) of sinks slurry with increasing feed solids concentration, and therefore a reduction in the air core size. The decrease in the air core size is a consequence of excessive solids concentration at the sinks. Additional increase in the feed concentration resulted in the collapse of the “conical jet” at the sinks (spray discharge) and, as a result, a collapse of the air core. Consequently, the sinks stream was straightened so that the slurry occupied the entire cross section of the spigot (rope discharge).

#### (a) Sinks Ore Concentration

According to van der Walt (1950), “the quantity of coal which can pass through the (spigot) in unit time, without overloading it, will determine the percentage of coal permissible in the pulp”. Peatfield (2003) recommended a medium-to-ore ratio of 3.5:1 (v/v), which is equivalent to 22% coal (v/v), in the feed for typical South African coals with high amounts of near gravity material. Further, Peatfield reported that the minimum recommended feed

medium-to-ore ratio could be as low as 2.5:1; this ratio is, however, applicable only for coal ores with low amounts of near-gravity material. DSM operated with medium-to-coal ratios ranging from 2.2:1 up to 2.7:1 in the feed for coal (Table 2.7). Peatfield proposed that the medium-to-ore ratio in the feed must be increased where the yields (to product of coal) are below 50% in order for the cyclone to be able to handle rejects. Thus, an increase in the proportion of ore in the feed that exits at the sinks necessitates a decrease in the recommended feed concentration to avoid spigot overloading. This implies that it is the sinks ore concentration rather than the feed concentration that is related to overloading at the sinks.

In support of this notion Stas (1957) proposed a mathematical expression that predicts the onset of spigot overloading by expressing it in terms of the sinks slurry density:

$$\rho_U = \rho_F + (\rho_F - \rho_o) \left( \frac{0.921D_o}{D_u} \right)^{3.5} \quad (2.7)$$

with  $\rho_U$  the relative slurry density in the sinks stream;  $\rho_F$  the relative slurry density in the feed and  $\rho_o$  the relative slurry density in the floats stream. Equation 2.7 makes use of the sinks slurry density as an indicator of when roping will occur; this expression is not expected to be of much value for two reasons:

- It is based on the expression

$$\frac{Q_{OS}}{Q_{US}} = \left( \frac{0.921D_o}{D_u} \right)^{3.5},$$

determined with a cyclone operating with clear water.

- The sinks slurry density at which roping occurred is specific to the conditions under which the tests were performed. Any variation in medium density or ore particle density cannot be taken account with this kind of expression.

What is interesting about equation 2.7, however, is that it is based on the premise that there is a critical sinks ore concentration beyond which roping takes place. Clarkson and Wood (1993) used a similar criterion, in which they propose that spigot overloading can be avoided by not exceeding the volumetric sinks ore concentration of 40% (medium to ore ratio of 1.5:1). Although Wood (1990) also recommended a minimum sinks medium-to-ore ratio of 1.5:1 to avoid spigot overloading, he reported a case in which the volumetric sinks medium-to-ore ratio was 0.9:1 (53% ore by volume) and no serious symptoms such as gross

misplacement of sinks particles to floats stream was observed. Further, he reported that only a ‘little disruption to efficient separation’ was encountered.

Table 2.7. Ore concentration at the feed and sinks for coal. Sinks concentrations based on assumption that 40% (v/v) of feed pulp was recovered in sinks. (DSM, 1985)

D (mm)	Feed		Sinks		R <sub>m</sub> (v/v)
	C <sub>vf</sub> (v/v%)	Med:ore Ratio (v/v)	C <sub>vu</sub> (v/v%)	Med:ore Ratio (v/v)	
200	31.3	2.2	39.1	1.6	0.35
250	30.0	2.3	35.0	1.9	0.37
350	26.8	2.7	31.3	2.2	0.38
400	29.9	2.3	29.2	2.4	0.40
500	29.6	2.4	28.0	2.6	0.41
550	29.0	2.4	27.4	2.6	0.41
600	28.9	2.5	26.3	2.8	0.41
650	28.9	2.5	26.7	2.8	0.41
700	29.1	2.4	25.5	2.9	0.42
750	29.0	2.4	25.8	2.9	0.42
800	28.8	2.5	24.0	3.2	0.43

The sinks ore concentrations and medium-to-ore ratios at which DSM possibly operated the cyclones when determining their capacities are shown in Table 2.7. These values are based on the assumption that 40% (v/v) of the feed pulp was recovered at the sinks for all the cyclones. This assumption seems reasonable because R<sub>m</sub> obtained with this assumption is in agreement with the maximum R<sub>m</sub> of 0.4 as specified by DSM. The maximum R<sub>m</sub> of 0.4 was actually specified for the high capacity spigot ( $D_u/D_o = 0.85$ ), at which the sinks ore concentration should be the highest. Further, the medium-to-ore ratios in the floats stream (Table 2.8), based on the above assumption, appear to suggest that the sinks ore concentrations in Table 2.7 are generally conservative. This is because the recommended minimum medium-to-ore ratio in the floats of 2.5:1 to avoid overloading the vortex finder (Clarkson and Wood, 1993) is exceeded for all the cyclones larger than 350mm in diameter. (The C<sub>vu</sub> values of 35 and 39% are probably an over-estimation of the values that DSM operated at, given the relatively low floats ore concentrations.) The medium-to-ore ratios given in Table 2.7 are in agreement with the minimum sinks medium-to-ore ratio of 1.5:1 to avoid spigot overloading recommended by Clarkson and Wood (1993). It is, therefore, expected that the spigot capacities specified by DSM were not obtained during roping conditions.

Table 2.8. Ore concentrations in the floats based on the assumption that 40% (v/v) of the feed pulp was recovered at the sinks.

<b>D</b> <b>mm</b>	<b>Floats</b>	
	<b>C<sub>vf</sub></b> <b>(v/v%)</b>	<b>Med:ore</b> <b>ratio</b>
200	26.0	2.8
250	26.7	2.8
350	23.8	3.2
400	30.3	2.3
500	30.7	2.3
550	30.1	2.3
600	30.7	2.3
650	30.4	2.3
700	31.4	2.2
750	31.1	2.2
800	32.0	2.1

As mentioned previously, DSM operated the cyclones at feed medium-to-ore ratios ranging from 2.2 to 2.7:1. England et al. (2002), on the other hand, quoted spigot capacities equivalent to those by DSM but the applicable feed medium-to-ore ratios ranged from 3.42-3.51:1 (Table 2.9). The data reported by England et al. (2002) was for ‘relatively difficult to treat South African coal’. This is in agreement Peatfield (2002) who recommended a feed medium-to-ore ratio of 3.5:1 for typical South African coals with high near-gravity material.

Table 2.9. Ore concentrations in the feed when the cyclones were operating at their spigot capacities.  
(England et al., 2002)

<b>D</b> <b>(mm)</b>	<b>Feed Med:Ore</b> <b>Ratio (v/v)</b>	<b>C<sub>vf</sub></b> <b>(v/v%)</b>
360	3.42	22.6
420	3.44	22.5
510	3.51	22.2
610	3.50	22.2
710	3.51	22.2
800	3.49	22.3
900	3.50	22.2
1000	3.49	22.2
1150	3.50	22.2
1300	3.50	22.2

Stas (1957) observed that once roping commenced the sinks slurry density remained constant with further increase in the feed solids concentrations. Cohen and Isherwood (1960) reported that the sinks slurry density obtained when the spigot was overloaded is dependent on the specific gravity and packing characteristics of the sinks solids. They further postulated that

the sinks slurry density should be relatively high when the spigot capacity has been reached or exceeded.

**(b) Effect of roping on cyclone performance**

Stas (1957) observed that the floats slurry density increased with increasing feed ore concentration when roping was prevalent at the spigot. The increase in the floats slurry density is due to misplacement of some of the sinks particles to the floats. According to Cohen and Isherwood (1960) this misplacement of sinks particles to the floats occurs because of “lack of accommodation” in the sinks. Upadrashta and Venkateswarlu (1982) proposed the following expressions:

$$S = \frac{Q_{US}}{Q_{OS}} = 1.44(1 - C_V)^{-0.18} Q^{-0.44} \left(\frac{D_u}{D_o}\right)^{2.32} \quad \text{(Spray discharge)} \quad (2.8)$$

$$S_R = \frac{Q_{USM}}{Q_o} = 1.91(1 - C_V)^{1.1} Q^{-0.44} \left(\frac{D_u}{D_o}\right)^{2.32} \quad \text{(Rope discharge)} \quad (2.9)$$

with  $C_V$  the volume fraction of the FeSi and ore in the feed. The increase in  $S$  with increasing  $C_V$  during spray discharge was explained to be a consequence of the reduction of the air core size at the sinks, which resulted in an increase in the proportion of material exiting through the spigot. The decrease in  $S_R$  with increasing  $C_V$  during rope discharge is a result of misplacement of the sinks particles to the floats stream due to the overloaded spigot.

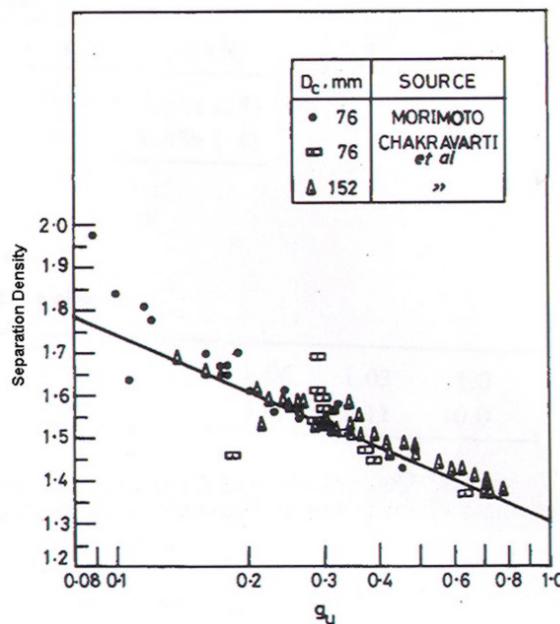


Figure 2.34. Separation density vs ore recovery in sinks (mass fraction) for coal. (Upadrashta and Venkateswarlu, 1982)

Upadrashta and Venkateswarlu (1982) reported the separation density to increase with a decrease in the ore recovery in the sinks for coal and other minerals (Fig. 2.34 and 2.35). Although Upadrashta and Venkateswarlu did not distinguish between separation densities obtained during roping and those obtained with a spray discharge (in Fig. 2.34 and 2.35), it is known that some of their results were obtained during roping. When roping is prevalent at the sinks stream the ore recovery in the sinks should generally be low due to misplacement of sinks particles to the floats. As illustrated in Fig. 2.34 and 2.35 the highest separation densities were obtained at the lowest ore recoveries in the sinks. It can therefore be deduced from this that the separation density should increase when the spigot is overloaded. In support of this view van der Walt (1950) and Cohen and Isherwood (1960) also reported the separation density to increase when the spigot was overloaded.

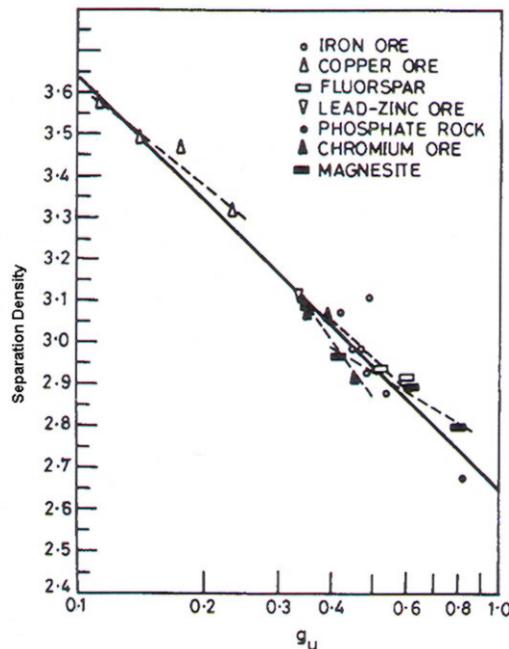


Figure 2.35. Separation density vs ore recovery in sinks (mass fraction). (Upadrashta and Venkateswarlu, 1982)

Upadrashta and Venkateswarlu (1982) proposed the following relationship between ore recovery in the sinks ( $g_u$ ) - mass fraction - and separation density ( $\rho_{50}$ ):

$$\rho_{50} = a_o \log(g_u) + a_1 \quad (2.10)$$

with  $a_o$  and  $a_1$  constants. The value of  $a_1$  is said to correspond to the relative density of the lightest constituent of the feed material. The values of constants  $a_o$  and  $a_1$  for coal and other ores (as listed in Fig. 2.35) are given in Table 2.10.

Table 2.10. Constants  $a_o$  and  $a_1$  for equation 2.10.

	Constant $a_o$	Constant $a_1$
<b>Coal</b>	-0.48	1.304
<b>Other ore</b>	-0.984	2.654

Stas (1957) also observed the separation density to increase when the spigot was overloaded, as illustrated in Fig. 2.36. Stas induced roping at the sinks by changing the spigot diameter from 19.5mm, at which a spray discharge was prevalent, to 12.5mm, at which a rope discharge was observed. The increase in the separation density observed in Fig. 2.36 when the spigot diameter was reduced from 19.5 to 12.5mm is partly due to the decrease in spigot diameter and partly due to spigot overloading. The most notable change on the partition curve obtained during roping is that on its shape (Fig. 2.36). During roping there is increased misplacement of sinks particles to the floats stream. The separation efficiency clearly suffers when the spigot is overloaded. This view has been expressed by a number of authors including: van der Walt (1950), King and Jukes (1984), Wood et al. (1989) and Sripriya et al. (2001).

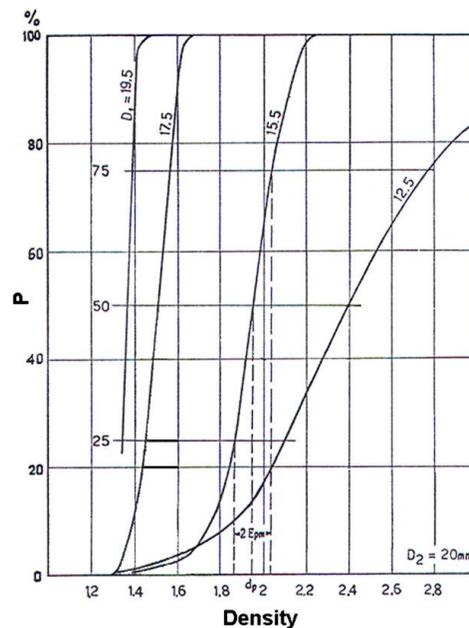


Figure 2.36. Influence of spigot overloading on the cyclone performance. Spigot overloaded at  $D_u = 12.5\text{mm}$  and normal operation at  $D_u = 19.5\text{mm}$ . (Stas, 1957)

Leonard and Leonard (1983) illustrated the effect of spigot overloading on the partition curve as shown in Fig. 2.37. Short-circuiting of sinks particles to the floats is illustrated to take place when the spigot is overloaded.

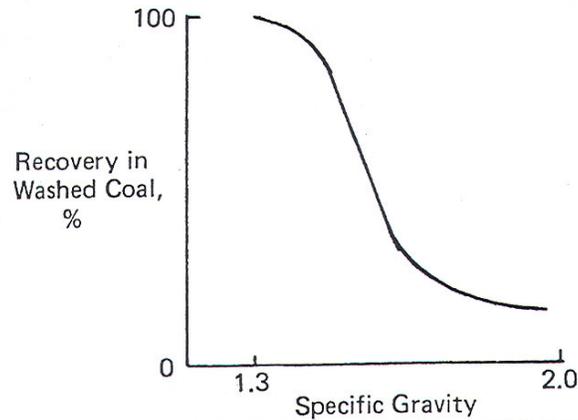


Figure 2.37. The spigot overloading on the shape of the partition curve. (Leonard and Leonard, 1983)

According to King and Jukes (1984) when the volumetric medium-to-coal ratio approaches 1:1 the coal particles interact with each other and this interaction changes the medium properties. As a result of this interaction the performance of the dense medium cyclone as a separating device is significantly affected. King and Jukes further reported that there is a lower limit for EPM of 0.01 when the volume proportion of coal in the slurry increased to values that are relevant to industrial practice, presumably at medium-to-ore ratios around 3:1.

## 2.2.2. Influence of Cyclone Geometry on Spigot Capacity

### (a) Inlet Size

Q is related to the inlet diameter in accordance with the following relationship:

$$Q \propto D_i^n$$

Various values for the exponent  $n$  obtained in the literature are given in Table 2.11. There is agreement in the literature that  $D_i$  has a strong influence on Q. Upadrashta and Venkateswarlu (1982) determined this relationship during spray and rope discharges, and Q was reported to be more sensitive to  $D_i$  during roping than when a spray discharge was prevalent.

Table 2.11. The exponent  $n$  for the relationship between inlet diameter and Q.

Source	Exponent $n$
DSM (1985)	1.0
Dunglison (1991)	1.0
Upadrashta and Venkateswarlu (1982)	1.0 <sup>*</sup>
Upadrashta and Venkateswarlu (1982)	1.8 <sup>#</sup>

<sup>\*</sup>Spray discharge.

<sup>#</sup>Rope discharge.

The inlet is not expected to have a significant influence on the volume split within the cyclone. Thus, increasing the inlet size should generally increase the flow-rates of slurry through both the spigot and the vortex finder, more or less equally. The inlet increases the flow-rate of material exiting through the outlets by increasing their exit velocities. Accordingly, the spigot capacity should increase with increasing inlet size.

### (b) Spigot Diameter

The spigot diameter influences Q in accordance with the following relationship:

$$Q \propto D_u^n$$

The values of the exponent  $n$  obtained by various sources in the literature are given in Table 2.12.  $D_u$  has a relatively small effect on Q.

Table 2.12. The exponent  $n$  for the relationship between  $Q$  and  $D_u$ .

Source	Exponent $n$
Clarkson and Wood (1993)	0.15
Dunglison (1991)	0.308
Vergheese and Rao (1994)	0.185
Wood et al. (1989)	0.15

Upadrashta and Venkateswarlu (1982), on the other hand, related  $Q$  with spigot diameter and vortex finder diameter as follows:

$$Q \propto (D_u^2 + D_o^2)^n$$

with  $n = 0.30$  during spray discharge and  $n = 0.26$  during rope discharge. According to Upadrashta and Venkateswarlu the nature of the influence of  $D_u$  and  $D_o$  on  $Q$  changes slightly with the change in flow type from spray to rope discharge.

Further, the volume split is related to the spigot and vortex finder diameters as follows:

$$\frac{Q_{US}}{Q_{OS}} \propto \left( \frac{D_u}{D_o} \right)^n$$

The values of the exponent  $n$  obtained by various sources in the literature are given in Table 2.13. Upadrashta and Venkateswarlu (1982) reported the effect of  $D_u$  on  $S$  to be the same during spray and rope discharges. This is surprising considering that there is an air core at the sinks during spray discharge and none during rope discharge.

 Table 2.13. The exponent  $n$  for the relationship between  $S$  and  $D_u$ .

Source	Exponent $n$
Stas (1957)	3.5 <sup>a</sup>
Upadrashta and Venkateswarlu (1982)	2.32 <sup>b</sup>

<sup>a</sup>Cyclone operated with water only.

<sup>b</sup>Valid for spraying and roping conditions.

Spigot diameter generally has a small but significant influence on  $Q$ . However,  $D_u$  does have a very strong influence on the slurry split to the sinks as shown in Table 2.13. In fact, it is expected that the spigot capacity should be determined mainly by the dimensions of the spigot diameter.

The relationship between spigot diameter and spigot ore capacity obtained by the original developers of the dense medium cyclone, Dutch State Mines (DSM), is illustrated in Fig. 2.38. This figure shows the spigot capacities for dense medium cyclones beneficiating coal whereby the medium was magnetite. The cyclone was operated at a head of 9D.

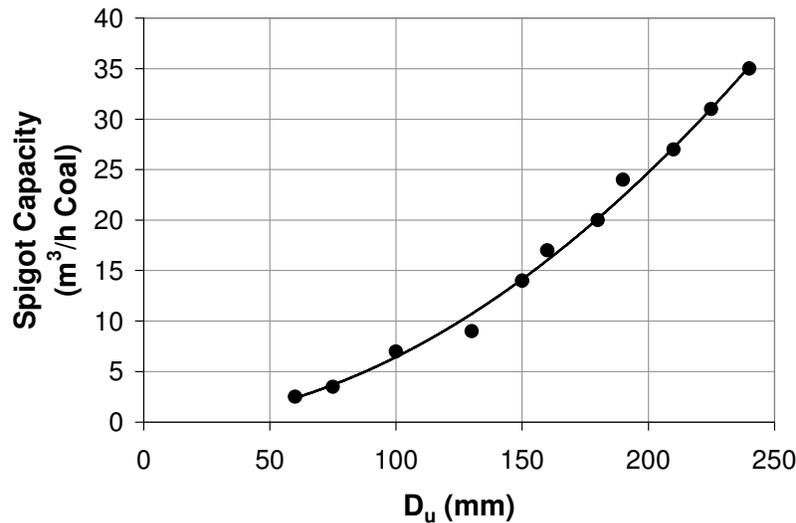


Figure. 2.38. The relationship between spigot diameter and spigot capacity for coal. (DSM, 1985)

A regression of the data in Fig. 2.38 gives the following relationship:

$$Q_{UM} = (0.9 \times 10^{-3}) D_u^{1.94} \quad (2.11)$$

with  $D_u$  in mm and  $Q_{UM}$  (ore only) in  $m^3/hr$  ( $R^2 = 0.9944$ ). The spigot capacity for dense medium cyclones appears to depend mainly on the cross-sectional area of the spigot. As previously illustrated, it is thought that these spigot capacities were determined under conditions in which roping was not prevalent at the sinks stream. England et al. (2002) reported spigot capacities that were equivalent to those specified by DSM; these are shown in Fig. 2.39. It appears that the spigot capacities specified by England et al. were actually based on DSM data.

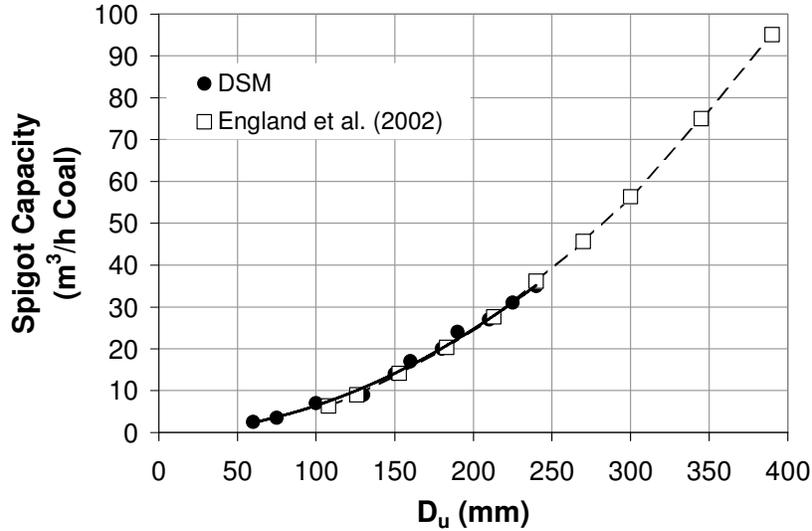


Figure 2.39. The relationship between spigot diameter and spigot capacity for coal.

The relationship between spigot diameter and spigot capacity for industrial minerals and ores at various feed pressures are shown in Fig. 2.40. Regression analysis of the data in Fig. 2.40 yielded the following expression:

$$Q_{UM} = (0.17 \times 10^{-3}) D_u^{2.05} H^{0.19} \quad (2.12)$$

with H the feed head in D (cyclone diameter) and  $R^2 = 0.9911$ . This expression is consistent with equation 2.11 above.

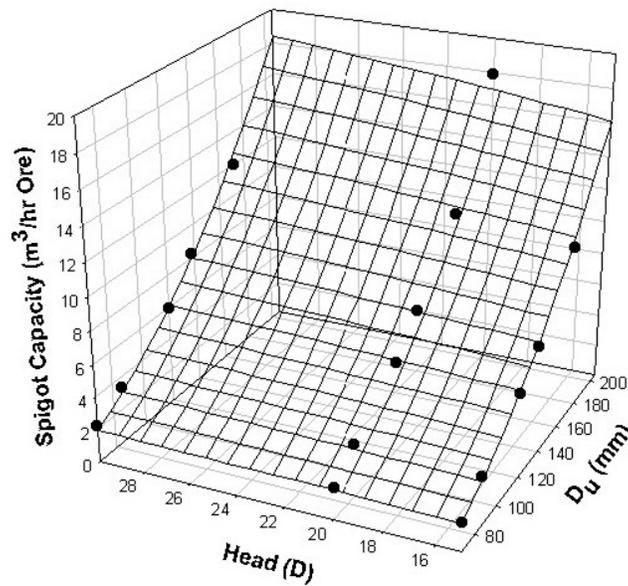


Figure. 2.40. The relationship between spigot diameter and spigot capacity for industrial minerals and ores with increasing feed pressure. (DSM, 1985)

Equation 2.11 was obtained from geometrically similar dense medium cyclones ranging from 200 to 800mm in diameter. The same can be said of equation 2.12, although the cyclone diameters ranged from 200 to 600mm. Each of the cyclones employed had a standard DSM configuration as shown in Table 2.14. The standard  $D_u$  size for other minerals (not being coal), which are separated at higher feed pressures, is  $0.8D_o$  and not  $0.7D_o$  as is the case for coal. The actual dimensions (in mm) are given in Table A.1 in the Appendix. According to DSM (1985), the maximum allowable spigot diameter on a dense medium cyclone is 85% of the vortex finder diameter; beyond this separation efficiency suffers.

Table 2.14. Dimensions of the cyclones employed by DSM, as a fraction of the cyclone diameter.

$D_i/D$	0.20
$D_o/D$	0.43
$D_u/D$	0.3
$\alpha$ (deg.)	20
$B_l/D$	0.6-0.7

Furthermore, Stas (1957) illustrated that larger spigot-to-vortex finder diameters ratios tend to shift the onset of roping to commence at much higher flow-rates (of slurry and ore) at the sinks. Although Stas (1957) did not measure the spigot capacity, his observations support the notion that spigot capacity increases with increasing spigot size.

### (c) Vortex Finder Diameter

The vortex finder diameter has been reported to influence  $Q$  in accordance with the following relationship:

$$Q(= Q_{os} + Q_{us}) \propto D_o^n$$

The values of the exponent  $n$  obtained by various sources in the literature are given in Table 2.15. The decrease in  $Q$  with increasing vortex finder diameter, reported by Clarkson and Wood (1993), and Wood et al. (1989), is counter-intuitive. Like Verghese and Rao (1994), Restarick and Krnic (1991) also observed  $Q$  to increase with the vortex finder diameter, although they did not quantify the effect.

Table 2.15. The exponent  $n$  for the relationship between  $Q$  and  $D_o$ .

Source	Exponent $n$
Clarkson and Wood (1993)	-0.15
DSM (1985)	1.0
Vergheese and Rao (1994)	0.414
Wood et al. (1989)	-0.15

As shown previously, Upadrashta and Venkateswarlu (1982) related  $Q$  with spigot diameter and vortex finder diameter as follows:

$$Q \propto (D_u^2 + D_o^2)^n$$

with  $n = 0.30$  during spray discharge and  $n = 0.26$  during rope discharge.

It is, therefore, expected that  $Q$  should increase with increasing  $D_o$ . With all other conditions being the same,  $D_o$  strongly increases the slurry flow through the vortex finder at the expense of slurry flow at the sinks. The effect of the vortex finder diameter on  $S$  was illustrated previously in Table 2.13. According to Cohen and Isherwood (1960) overcrowding at the floats forces some of the floats material to exit at the sinks. Further, Stas (1957) reported larger spigot-to-vortex finder diameters ratios to shift the onset of roping to commence at much higher flow-rates (of slurry and ore) at the sinks. Therefore, the spigot capacity should increase with decreasing vortex finder diameter. However, it is not clear to what extent the vortex finder will have an effect on the spigot capacity ( $Q_{USM}$  and  $Q_{UM}$ ).

#### (d) Cone Angle

Van der Walt (1950) observed that the rate of flow through the cyclone increases as the cone angle decreases. This trend was generally true when operating the cyclone with water only and with pulp. Further, van der Walt determined that the actual volume of the cyclone increases with decreasing cone angle. The proportion of feed water exiting at the sinks was observed to increase with decreasing cone angle when operating the cyclone with water only. Thus, according to van der Walt (1950) a decrease in the cone angle should increase the slurry flow through the spigot and therefore the spigot capacity as well.

Cohen and Isherwood (1960), on the other hand, observed that at a given feed solids density, “a 15° cone would be completely choked, a 30° cone would give a ‘ropey discharge’ and a

60° cone would spray freely, all other conditions being equal”. Thus, an increase in the cone angle shifted the onset of roping to commence at higher feed solids contents.

**(e) Barrel Length**

The effect of the length of the cylindrical section on the spigot capacity is illustrated in Fig. 2.41; an increase in the barrel length did not influence spigot capacity in anyway. The standard/normal cylindrical section had a length of about 0.6D, and the extra long cylindrical section was 2.5D long.

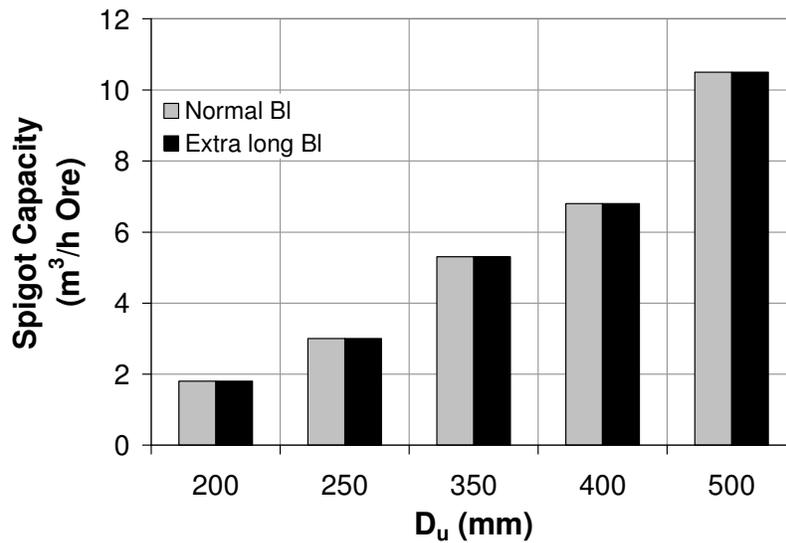


Figure 2.41. The influence of the barrel length on the spigot capacity. (DSM, 1985)

An increase in the cyclone capacity, however, accompanied the increase in the length of the cylindrical section (Fig. 2.42).

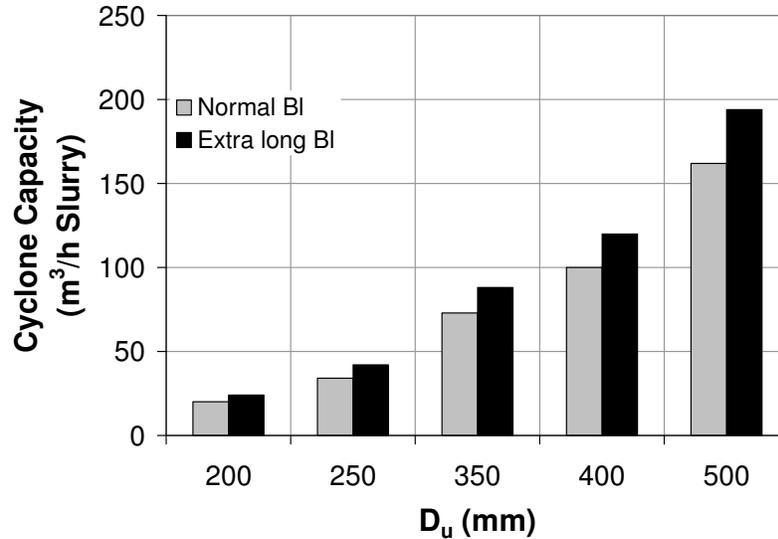


Figure 2.42. The influence of the barrel length on the cyclone capacity. (DSM, 1985)

The solids concentrations for the data presented in Fig. 2.41 and 2.42 are given in Table 2.16. The cyclones with the normal barrel length were operated with lower medium-to-ore ratios ranging from 3.49 to 4.27:1 (18.98 – 22.27% vol. feed concentrations), while those with the extra long barrel were operated at higher medium-to-ore ratios ranging from 4.33 to 5.16:1 (16.24 – 18.75% vol. feed concentrations). These differences in the feed medium-to-ore ratios are possibly due to the fact that the extra long cylindrical sections are used mainly for difficult-to-separate ores. Cyclones generally separate more efficiently at higher feed medium-to-ore ratios. Assuming that *S* is not influence by BI, it would be expected that a cyclone with a longer barrel length should have a higher spigot capacity for constant medium-to-ore ratios in the feed when treating the same ore.

Table 2.16. Feed concentrations for the curves in Fig. 2.41 and 2.42. (DSM, 1985)

D <sub>c</sub> (mm)	H (D)	Normal barrel		Extra long barrel	
		Feed Med:Ore ratio (v/v)	C <sub>vf</sub> (v/v%)	Feed Med:Ore ratio (v/v)	C <sub>vf</sub> (v/v%)
200	15	3.49	22.27	4.33	18.75
250	15	3.82	20.75	4.60	17.86
350	15	4.09	19.64	4.87	17.05
400	15	3.84	20.67	4.71	17.50
500	15	4.27	18.98	5.16	16.24

### 2.2.3. Influence of Operational Variables on Spigot Capacity

#### (a) Feed pressure

Feed pressure /head has been reported to influence Q as follows:

$$Q \propto H^n$$

Various values of the exponent  $n$  in the literature are given in Table 2.17. As expected, an increase in the feed pressure results in an increase in Q. Upadrashta and Venkateswarlu (1982) reported Q to be slightly more sensitive to changes in pressure during roping than when a spray discharge was prevalent at the sinks.

Table 2.17. The exponent  $n$  for the relationship between Q and feed pressure.

Source	Exponent $n$
Clarkson and Wood (1993)	0.15
DSM (1985)	0.5
Upadrashta and Venkateswarlu (1982)	0.41 <sup>*</sup>
Upadrashta and Venkateswarlu (1982)	0.58 <sup>#</sup>
Wood et al. (1989)	0.45
Wood (1990)	0.46

<sup>\*</sup>Spray discharge.

<sup>#</sup>Rope discharge.

S is influenced by the feed pressure in accordance with the following relationship:

$$\frac{Q_{US}}{Q_{OS}} \propto H^n$$

Various values of the exponent  $n$  in the literature are given in Table 2.18. An increase in head appears to bring about a decrease in the proportion of the feed slurry that exits at the sinks.

Table 2.18. The exponent  $n$  for the relationship between S and head.

Source	Exponent $n$
Clarkson and Wood (1993)	-0.37 <sup>*</sup>
Wood et al. (1989)	-0.5 <sup>*</sup>
Wood (1990)	-0.46

<sup>\*</sup>Determined with zero ore loading.

Van der Walt (1950) reported that the ‘maximum permissible spigot loading’, that is the spigot capacity, increased with increasing feed pressure. The effect of feed pressure (expressed as head) on the spigot capacity, as reported in the DSM handbook for cyclones beneficiating industrial minerals with ferrosilicon as medium, is shown in Fig. 2.43. Spigot capacity increases with increasing feed pressure. Note Fig. 2.43 is the same as Fig. 2.40 above. The effect of feed pressure on the spigot capacity was illustrated previously in equation 2.12, which is repeated here for convenience:

$$Q_{UM} = (0.17 \times 10^{-3}) D_u^{2.05} H^{0.19} \quad (2.12)$$

Wood (1990) reported head to have a small influence on the sinks flow-rate.

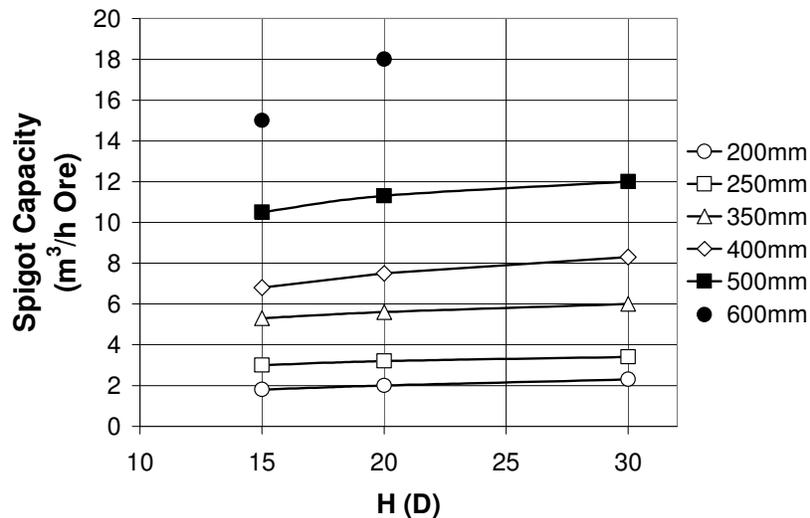


Figure. 2.43. The effect of feed pressure on spigot capacity. (DSM, 1985)

According to Cohen and Isherwood (1960), the effect of pressure on the rate of flow through the spigot is restricted by the high viscosity of the sinks pulp. Napier-Munn (1986) reported that the pressure drop across a dense medium cyclone appears to be a function of the total medium rheology. He proposed that the relationship between flow through cyclone and pressure at low Reynolds numbers is as follows:

$$Q \propto H^{0.59},$$

and medium viscosity plays little or no part in determining the pressure drop. At high Reynolds numbers the relationship between flow through cyclone and pressure can be represented as follows:

$$Q \propto H^n,$$

with  $n < 0.5$ . The actual value of the exponent  $n$  is related to the prevailing medium viscosity.

### (b) Medium Density

Medium density has been reported to influence  $Q$  as follows:

$$Q \propto \rho_{med}^n$$

The values of the exponent  $n$  obtained by various sources in the literature are given in Table 2.19;  $Q$  decreases with increasing  $\rho_{med}$ .

Table 2.19. The exponent  $n$  for the relationship between  $Q$  and medium density.

Source	Exponent $n$
Napier-Munn (1986)	-0.59 <sup>a</sup>
Napier-Munn (1986)	-0.79 to -0.99 <sup>b</sup>
Vergheese and Rao (1994)	-2.17

<sup>a</sup>Low Reynolds number.

<sup>b</sup>High Reynolds number.

Upadrashta and Venkateswarlu (1982), on the other hand, reported medium density to influence  $Q$  in accordance with the following relationship:

$$Q \propto (1 - C_v)^m \rho_{med}^n$$

with  $C_v$  the volume fraction of FeSi and ore in the feed, and  $\rho_{med}$  the relative medium density. The values for the exponents  $m$  and  $n$  are given in Table 2.20.

Table 2.20. The exponent  $n$  for the relationship between  $Q$  and medium density according to Upadrashta and Venkateswarlu (1982).

Source	Exponent $n$	Exponent $m$
Upadrashta and Venkateswarlu (1982)	-0.41 <sup>*</sup>	0.12 <sup>*</sup>
Upadrashta and Venkateswarlu (1982)	-0.58 <sup>#</sup>	0.56 <sup>#</sup>

<sup>\*</sup>Spray discharge.

<sup>#</sup>Rope discharge.

$\rho_{med}$  is not expected to influence  $S$  and  $S_R$  significantly, thus, the spigot capacity should decrease with increasing medium density.

It is interesting to note that DSM does not specify medium densities for the spigot capacities given in the DSM handbook. This omission implies that medium density has no influence on the spigot capacity. Cohen and Isherwood (1960), on the other hand, postulated, "A rise in

flow-rate and a rise in the proportion of ferrosilicon both increase the feed rate of (sink) material and hence both lead to overloading of the apex orifice”.

**(c) Medium Grade**

The medium grade refers to the particle size distribution of the medium particles; finer medium grades tend to be more viscous than coarser grades. He and Laskowski (1995b) reported the cyclone flow-rate, when operated with medium only, to be the highest when operating with the coarsest medium. The medium split was unaffected by changes in the medium grade. Assuming that these trends would still hold at low medium-to-ore ratios, then the spigot capacity should increase when the medium particles are relatively coarse.

Medium segregation within dense medium cyclone is dependent on medium grade, and coarser grades tend to segregate more (He and Laskowski, 1995b).

**(d) Ore Size**

Of all the literature that has been considered none has proposed or implied any correlation between cyclone flow-rate and particle size. The same can be said of the relationship between S and particle size.

Cohen and Isherwood (1960), on the other hand, reported that the sinks slurry density obtained when the spigot was overloaded is dependent on the specific gravity and packing characteristics of the sinks solids. And the packing characteristics of solids are dependent on the particle size and size distribution.

The effect, if any, of particle size on the spigot capacity is unclear.

**(e) Ore Density**

The effect of ore density on the spigot capacity is illustrated in Fig. 2.44. Assuming that the use of ferrosilicon as medium does not influence the spigot capacity significantly, then it can be deduced from Fig. 2.44 that ore density significantly decreases the spigot capacity.

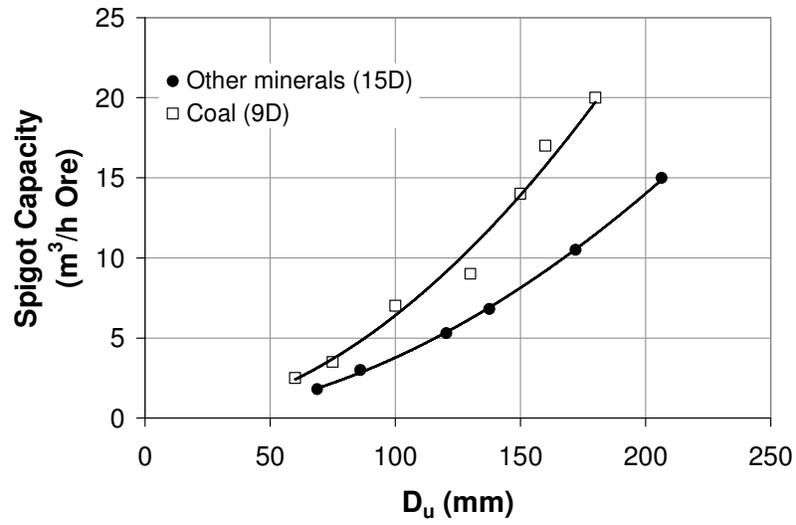


Figure 2.44. The effect of ore density on spigot capacity. (DSM, 1985)

## 2.3. Summary of Literature Review

### (a) Characterisation of Overloading at the Spigot

- There is consensus in the literature that the maximum spigot capacity is reached at the onset of roping, although no clear evidence has thus far been presented to support this notion; this applies to both classification and dense medium cyclones.
- There is a critical underflow/sinks solids concentration beyond which roping commences. The air core at the underflow/sinks has been reported to collapse during the commencement of roping for both cyclonic devices. It has been proposed that excessive solids concentrations at the underflow/sinks are responsible for the collapse of the air core during the onset of roping (Plitt et al., 1987 and Stas, 1957). Before roping commences, an increase in solids content within the cyclone has been reported to steadily reduce the air core size until sufficient solids accumulate at the underflow/sinks to bring about the collapse of the air core (Gutiérrez et al., 2000 and Stas, 1957). The effect of the solids concentration can be explained by considering the effect of the solids concentration on the slurry viscosity. Slurry viscosity increases slightly with increasing solids concentration at relatively low solids loadings; however, once a certain critical solids concentration is reached further increases in the solids concentration result in very sharp increases in the slurry viscosity. Plitt et al. (1987) proposed that once the critical underflow solids concentration is reached the slurry viscosity becomes so high that the rotational motion at the underflow can no longer be sustained, as a result the air core collapses and roping commences. This notion was also proposed by Dyakowski and Williams (1995).
- A number of authors have developed mathematical expressions that attempted to predict the onset of roping. All these expressions make use the underflow/sinks solids concentration as an indicator of the onset of roping; this applies to both dense medium and classification cyclones.
- A number of authors have reported the underflow solids concentration during roping for classification cyclones ( $\%V_{MSU}$ ) to remain constant once roping has been initiated, even with further increase in the feed solids concentration. While, on the other hand, some have reported  $\%V_{MSU}$  to increase with further increases in the feed solids concentration. It is

thought that the increase in  $\%V_{MSU}$  with increasing feed solids concentration is a consequence of increased short-circuiting of fines to the underflow; water split to the underflow has previously been shown to increase with increasing feed solids concentration (Lynch and Rao, 1975, and Asomah and Napier-Munn, 1997). The volumetric sinks ore concentrations during roping for dense medium cyclones have also been reported to be constant (Stas, 1957).

- Various authors operating classification cyclones of different sizes and configurations under a variety of conditions have reported  $\%V_{MSU}$  ranging between 39 and 68% (by volume). Clarkson and Wood (1993) proposed that spigot overloading in dense medium cyclones could be avoided by not exceeding the volumetric sinks ore concentration of 40%. The volumetric sinks ore concentrations inferred from the DSM data are in agreement with this value.
- Once roping commences, misplacement of particles that normally exit at the underflow/sinks to the overflow/floats has been widely reported. In the case of classification cyclones coarse particles are misplaced to the overflow, while with the dense medium cyclones sinks particles are misplaced to the floats stream.

### (b) Influence of Roping on Cyclone Performance

- Roping has widely been established to result in an increase in the cut-size of classification cyclones due to of misplacement of coarse particles to the overflow. The separation density has also reported to increase once roping commenced within a dense medium cyclone. The following expressions, in which roping was prevalent at low  $g_u$  values, were proposed:

$$d_{50} = -196 \log(g_u) \quad (2.3)$$

$$\rho_{50} = a_o \log(g_u) + a_1 \quad (2.10)$$

with  $a_o$  and  $a_1$  constants; their values are given in Table 2.10. Equation 2.3 is applicable to classification cyclones, while equation 2.10 applies to dense medium cyclones.

- Fahlstrom (1963) reported the sharpness of separation to decrease once roping commenced. Plitt et al. (1987) also reported the same trend, although they reported that the effect of roping on the sharpness of separation was dependent on the feed solids

concentration. There is consensus in the literature that the separation efficiency of a dense medium cyclone suffers when roping is prevalent at the sinks stream.

### (c) Effect of Cyclone Geometry on Spigot Capacity

- The nature of the relationship between spigot ore capacity and spigot diameter obtained by Jull (1972), Plitt et al. (1987) and DSM was generally of the following form:

$$Q_{UM} = k_o D_u^n \quad (2.13)$$

with  $D_u$  the spigot diameter in mm;  $Q_{UM}$  in  $m^3/hr$  of ore. The values for the constant  $k_o$  and the exponent  $n$  are shown in Table 2.21. Heiskanen (2000) validated the expression developed by Plitt et al. (1987). Plitt et al. (1987) operated their cyclone with a rope discharge at the underflow, while Jull (1972) operated theirs “just short of roping”. It is thought that DSM did not operate their cyclone under roping conditions. Thus, the ‘spigot capacities’ specified by DSM do not represent the maximum spigot capacity.

Table 2.21. Comparison of spigot diameter-spigot capacity relationships in the literature.

Source	Cyclone Type	$k_o \times 10^3$	Exponent $n$
Jull (1972)	Classification	2.3	2.19
Plitt et al. (1987)	Classification	1.563	2.35
DSM	Dense medium	0.654	1.99
DSM	Dense medium	-*	2.05

\* Dependent on head.

- $\%V_{MSU}$  has been reported to increase with increasing  $D_u/D_o$  ratio by Fahlstrom (1963) and Heiskanen (2000). Concha et al. (1996) proposed that there is a specific range of underflow-to-overflow diameters ratios in which a rope discharge will be obtained at the underflow. It is, however, the author’s opinion that the onset of roping is determined mainly by the solids concentration, and roping can occur at any  $D_u/D_o$  ratio provided the solids concentration within the cyclone is sufficiently high.
- Increasing  $D_i$  generally increases the flow-rates of slurry through both the spigot and the vortex finder, more or less equally since  $S$  is unaffected by changes in  $D_i$ . Thus, the spigot capacity should increase with increasing  $D_i$ . This applies to both classification and dense medium cyclones.

- A larger  $D_o$  tends to increase  $Q$ , and strongly increase the proportion of feed slurry exiting at the overflow/floats at the expense of the underflow/sinks. The spigot capacities of both classification and dense medium cyclones should, therefore, decrease with increasing  $D_o$ .
- According to Bradley (1965) and Svarovsky (1984) an increase in the overall length of a classification cyclone, either through a larger cylindrical section or a smaller cone angle, increases the capacity of the cyclone. Further, Plitt (1976) reported  $S$  to increase with increasing free vortex height, which is defined as the distance from the bottom of the vortex finder to the top of the spigot. Accordingly, spigot capacity is expected to increase with decreasing cone angle and increasing barrel length.
- Van der Walt (1950) reported the cone angle to have the same effect on a dense medium cyclone as that reported by Bradley (1965), Svarovsky (1984), and Plitt (1976) for the classification cyclone. It can be inferred from the data reported by DSM that the spigot capacity should possibly increase with increasing barrel length. Further, Cohen and Isherwood (1960) reported that at a given feed solids density, “a  $15^\circ$  cone would be completely choked, a  $30^\circ$  cone would give a ‘ropey discharge’ and a  $60^\circ$  cone would spray freely, all other conditions being equal”. Thus, an increase in the cone angle shifted the onset of roping to commence at higher feed solids contents.

#### **(d) Effect of Operational Variables on Spigot Capacity**

- An increase in feed pressure is associated with an increase in  $Q$  and a relatively small decrease in  $S$ . Accordingly, the spigot capacity should increase with increasing feed pressure for both classification and dense medium cyclones. However, the effect of feed pressure on the spigot capacity is expected to be relatively small due to its effect on  $S$ . Further, DSM reported spigot ore capacity to increase slightly with increasing feed pressure.
- Plitt et al. (1987) reported  $\%V_{MSU}$  to increase with increasing  $d_u$ , which is the mass median (50% passing) size of the underflow solids. Heiskanen (2000), on the other hand, observed, “there is a relationship between roping tendency and the width of particle size distribution”. Further, Cohen and Isherwood (1960) implied that the sinks ore

concentration during roping is dependent on particle size and size distribution. The effect of particle size on the spigot capacity is, however, unclear from the literature; this applies to both classification and dense medium cyclones.

- Jull (1972), and Mular and Jull (1978) reported particle density to have no influence on the spigot capacity. Further, Jull (1972) reported  $\%V_{MSU}$  to be unaffected by changes in particle density. There are indications that the heavier ore particles tend to reduce the spigot capacity.
- Neesse et al. (2004c) and Neesse et al. (2007) reported that the discharge capacity of the underflow can be increased by controlling the volume split of a hydrocyclone through 'overflow throttling'. Throttling the overflow, through the control valve, influences the spigot capacity in a similar manner as reducing the overflow diameter.
- An increase in medium density has been reported to decrease both  $Q$ , and  $S$  is not expected to be dependent on medium density. The spigot capacity is, therefore, expected to decrease with increasing medium density.
- He and Laskowski (1995b) reported the cyclone flow-rate, when operated with medium only, to be the highest when operating with the coarsest medium. The medium split was unaffected by changes in the medium grade. Assuming that these trends would still hold at low medium-to-ore ratios, then the spigot capacity should increase when the medium particles are relatively coarse.

#### (e) Classification vs Dense Medium Cyclones

- There are strong indications that the underflow/sinks overloading behaviour of both cyclonic devices are similar:
  - Roping is characterized by excessive solids concentration at the underflow/sinks stream. The value of this solids concentration is around 40% (v/v) and higher, for both devices.
  - The underflow/sinks solids concentration during roping has been reported to be constant for both devices. However, some authors have reported this solids concentration to increase with feed concentration in classification cyclones.

- Misplacement of particles to the overflow/floats stream occurs at the onset of roping.
- Spigot capacity is reported to be associated with roping flow. The exceptions in this regard being Tarr (1965) and DSM (1985).
- The impact of roping on the performance of the two cyclonic devices is also reported to be similar:
  - The onset of roping is reported to be associated with an increase in the separation size and separation density.
  - The separation efficiency of both devices is reported to suffer during roping.
- There are indications that changes in cyclone geometry influences the spigot capacities of classification and dense medium cyclones in a similar manner:
  - Spigot diameter is reported to influence the spigot capacity the most, and the sensitivity of  $Q_{UM}$  to  $D_u$  is similar for both devices (Table 2.21).
  - $D_i$ ,  $D_o$ , cone angle and barrel length are expected to influence the spigot capacity in a similar manner for both devices.
- It is anticipated that feed pressure should influence spigot capacity of a classification cyclone in a similar manner to that of a dense medium cyclone.
- There is no reason to expect ore size to influence the spigot capacities of the two devices in a similar manner, given the difference in particle sizes of the solids being beneficiated by classification and dense medium cyclones. However, medium particles have previously been reported to classify in a similar manner to particles being separated in classification cyclones (Verghese and Rao, 1994). Therefore, it is not unexpected that medium grade might influence the spigot overloading behaviour of a dense medium cyclone in a manner that is related/similar to the effect of ore size on the spigot overloading behaviour of a classification cyclone.