AN INVESTIGATION OF THE EFFECT OF OPERATING VARIABLES ON SEPARATION PERFORMANCE OF TEETERED BED SEPARATOR

KABARAN YATAKLI AYIRICIDA İŞLEM DEĞİŞKENLERİNİN AYIRIM PERFORMANSINA ETKİSİNİN İNCELENMESİ

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This worked named “**An Investigate of The Effect of Operating Variables on Separation Performance of Teetered Bed Separator”** by **ATAALLAH BAHRAMI** has been approved as a thesis for the Degree of **DOCTOR OF PHILOSOPHY IN MINING ENGINEERING** by the below mentioned Examining Committee Members.

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ETHICS

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- I did not do any distortion in the data set
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ATAALLAH BAHRAMI

ABSTRACT

AN INVESTIGATION OF THE EFFECT OF OPERATING VARIABLES ON SEPARATION PERFORMANCE OF TEETERED BED SEPARATOR

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The aim of this study is to investigate the effect of operating variables on separation performance of Teetered Bed Separator TBS used in fine coal beneficiation.

For this purpose, experimental studies were performed by using laboratory and pilot scale teetered bed separator (Crossflow® separator, Eriez).

Tests with calcite were performed using laboratory scale TBS to evaluate size separation performance without interfering density effects. Then, using a pilot scale TBS unit, tests were performed in both Dereköy Washing Plant and Ömerler Washing Plant. A leak from a spiral concentrator feed was used in both plants. Effects of pressure set point and teetered water flowrate were studied in size by size basis.

Tests with single density material, showed that the teetered water has the larger effect on separation size. Increasing teetered water, increases superficial velocity at the separation zone, hence the coarser particles to report to overflow. From the ANOVA results it is observed that the set point has the maximum effect on EP.

The results show that good separations were possible for fine lignite coal with teetered bed separators. Especially the coarser particles have lower probable errors (0.08-0.10) and lower separation densities. It was found that the separation was greatly affected by the teeter water flowrate (TW) and the set point (SP). Although both variables induce similar effects, the changes in set point generate much greater magnitudes of the effects. The fractional recoveries of fine particles were more sensitive to the changes in operating variables. The separation for narrow size fraction is better, and this can be explained by the equal settling ratio. Therefore, the feed of TBS should have a narrow size range for an efficient separation in single stage.

This study showed that the different sized particles will have different cut density. The separation densities for +2 mm, -0.5+0.2 mm particles were 1.4 g/cm^3 and 1.8 g/cm^3, respectively. Therefore, for a given SP and TW only some of the particles will be separated at the desired density and provide the desired quality product. It is not possible to make sharp separations as in dense medium processes. A second stage separation will improve the performance significantly.

Teetered bed separator produced much higher reject ash content (75-85% Ash) than spiral concentrator reject ash content (50-70% Ash).

Keywords: Teetered bed separator, fine coal cleaning, coal washing plant, cut density, Ep

ÖZET

KABARAN YATAKLI AYIRICIDA İŞLEM DEĞİŞKENLERİNİN AYIRIM PERFORMANSINA ETKİSİNİN İNCELENMESİ

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Bu çalışmanın amacı, ince kömür zenginleştirmede kullanılan kabaran yataklı ayırıcılarda işlem değişkenlerinin ayırma etkisinin incelenmesidir.

Bu amaçla, laboratuvar ve pilot ölçekli kabaran yataklı ayırıcılarla (Crossflow® separator, Eriez) zenginleştirme deneyleri yapılmıştır.

Ayırıcının yoğunluk etkileri olmadan sınıflandırma performansını belirlemek üzere, laboratuvar ölçekli ayırıcıyla kalsit kullanılarak deneyler yapılmıştır. Daha sonra, pilot ölçekli ekipmanla Dereköy ve Ömerler kömür yıkama tesislerinde testler yapılmıştır. Her iki tesiste de bir spiral zenginleştiriciye gelen besleme kullanılmıştır. Basınç ayar değeri ve yukarı yönde yıkama suyu miktarının etkisi tane boyuna bağlı olarak incelenmiştir.

Sonuçlar ince kömür zenginleştirmede kabaran yataklı ayırıcıyla iyi ayırımlar elde edilebildiğini göstermiştir. Özellikle iri boylarda daha düşük ayırım yoğunluğu ve olası hata elde edilmiştir. Sonuçlar ayırımın, basınç ayar değeri ve yıkama suyu miktarından büyük ölçüde etkilendiğini göstermektedir. Her iki değişkende benzer etkiye sahip olmasına karşın basınç ayar değerinin ayırım üzerinde mutlak değer olarak daha büyük etkiye sahip olduğu belirlenmiştir. İnce tanelerin oransal verimi, işlem değişkenlerine daha fazla duyarlı olmaktadır. Dar boyut fraksiyonlarının ayrımı daha iyi olmakta ve bu çökelme oranınıyla açıklanabilmektedir. Bu yüzden tek aşamada başarılı bir ayırım için beslemenin dar boyut aralığında olması gerekmektedir.

Bu çalışma, farklı boyda tanelerin farklı ayırım yoğunluğuna sahip olduğunu göstermiştir. +2mm ve -0.5+0.2 mm taneler için ayırma yoğunluğu sırasıyla 1.45 g/cm^3 ve 1.8 g/cm^3 olmuştur. Bu yüzden sabit bir basınç ayar değeri ve yukarı yönde yıkama suyu için, sadece bazı taneler istenen yoğunlukta ayrılacak kalitede istenen ürün verecektir. Ağır ortam süreçlerinde olduğu kadar keskin bir ayırım yapmak mümkün değildir. İkinci aşama ayırım performansı önemli ölçüde iyileştirecektir.

Kabaran yataklı ayırıcıyla(%75-85 kül), spiral zenginleştiriciye oranla (%50-70)çok daha yüksek atık kül değeri elde edilmiştir.

Anahtar Kelimeler: Kabaran yataklı ayırıcı, ince kömür zenginleştirme, Basınç ayar değeri, ayırma yoğunluğu, kömür yıkama tesisi, Ep.

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1 INTRODUCTION

The Teetered Bed Separator (TBS) has been developed from hydraulic classifier concept which had been used separating mono density particles into size fractions for the first time in 1934. TBSs have been used for coal recovery from waste piles and tailings lagoons since the 1960s and used to treat run of mine coal in the UK, US and Europe since the 1980s. There are over 400 units installed worldwide and applications include coal, iron, sand, foundry sand sizing, glass sand, mineral sands and hematite.

The treatment of coal fines is one of the important environmental and economic issues for most of the coal washeries. Small improvements in efficiency result in significant increase in profitability. As a result, the large number of studies are available in the literature on fine coal processing[1].

The industrial application of fine coal cleaning has been dominated by spiral concentrators, although their lower efficiency is known. Main drawbacks of the spirals are:

* Higher Ep value, ie, lower separation efficiency which results in coal loss to the tailings.
* High cut density which produces middling rather than a clean coal product
* Sensitive to the variations in feed solid content and flowrate
* Low capacity of individual equipment
* Requires an elaborate pulp distribution system
* Requires frequent manual adjustment of product splitters.
* Requires regular washing and cleaning due to the sticking of mud on the surface of spirals and around splitters.

The developments in application and design of TBS enable the use of them as a replacement to the spiral concentrators. There are considerable number of studies in the literature describing the performance of various designs available in the market [1-4].

TBS usually process hydrocyclone underflow. A rising stream of water, across the whole bed meets the settling particles. The particles are subjected to hindered settling in the teeter zone, its density is controlled by the use of a pressure probe linked to the discharge valve. The TBS is controlled by a combination of the velocity of the rising water (Teetered Water "TW") and the apparent density in the teeter zone (Set Point "SP"). A particle will sink or float against a column of water at a particular teeter density depending on its size and density.

The smallest particle that could be processed by heavy medium process is limited to 0.5mm. However, this limit is increased to 2-3mm in almost all of the coal washing in plants in Turkey to decrease magnetite of losses in the process. This increases the amount material processes by low efficiency spiral separators. Considering that the amount of -2mm material in the feed is 20-25%, it is very important to process fine coal efficiently.

In this study, the aim is to investigate the performance of TBS on lignite coals and also evaluate the effects of operating parameters on separation.
Tests with single density material were performed using laboratory scale TBS (CrossFlow separator-Eriez) to evaluate size separation performance without interfering density effects. Then, using a pilot scale TBS unit, tests were performed in both Dereköy Washing Plant and Ömerler Washing Plant. A leak from a spiral concentrator feed was processed in both plants. Effects of pressure set point and teetered water flowrate were studied on size by size basis.

2 PARTICLES SEPARATION USING TEETERED BED TECHNIQUES

2.1 Mathematical formulation

2.1.1 Description of particle movement

Separation process in the TBS depends essentially on the particle dynamics. Particles move through the teeter bed where both the apparent density of the bed and rising teeter water try to oppose the downward movement of particles. Particles having sufficient mass overcome the resistance and report to the underflow. Otherwise, they are carried away by the teeter water into the overflow stream. Hindered settling introduces additional resistance to the falling particles. The flow resistance, other than the viscous and the buoyant resistance, may be expressed in terms of the inter particle distance and the total resistive force on a particle may be expressed by the following functional relationship [4]:

$$R=f(\mu, \rho_f, d, V, \varepsilon) \tag{2.1}$$

where, R is total resistive force, μ is dynamic viscosity of fluid, ρ_f is density of the fluid, d is particle diameter, V is particle velocity and ε is bed voidage. Considering the total resistive force, it may be shown that the particle velocity relative to the fluid, the slip velocity, is a function of the volume fraction of solids and the terminal settling velocity of the particle (Richardson and Zaki, 1954):

$$V_{ij} = U_{tij}(1-\phi ij)^{n_{ij}-1} \tag{2.2}$$

Where, n_{ij} is Richardson–Zaki index which is a function of Reynolds number, V_{ij} is particle slip velocity, U_{tij} is particle terminal settling velocity, ϕij is particle volume fraction, i and j denote the size and density fractions, respectively.

For a fluidized suspension, particles volume fraction is expressed as a function of dissipative pressure gradient, and the slip velocity of a particle can be described as a function of this gradient as follows[2]:

$$V_{ij} = U_{tij}(1-(dp/dh)/((p_{ij}-p_f)g))^{nij-1} \tag{2.3}$$

Where, dp/dh is the dissipative pressure gradient and is expressed as:

$$dp/dh = \phi ij\ (p_{ij} - p_f)\ \mathrm{g} \tag{2.4}$$

A more convenient form of Eq. (2.3) is proposed by Galvin et al. (1999a) considering the composition of the suspension:

$$V_{ij} = U_{tij}(1 - (p_{ij} - p_{sus})/((p_{ij} - p_f)g))^{nij-1} \tag{2.5}$$

Where, p_{sus} is the suspension density.

2.1.2 Averaging of parameters specific to the TBS

Material deposition in the form of a bed and formation of a dense suspension inside the unit is a special feature of the TBS. A distributed voidage gives rise to the interstitial teeter water velocity that is different from the superficial teeter water velocity. Suspension density inside the bed is controlled by the bed pressure setting. Of course, the interstitial teeter water velocity is dependent on the superficial teeter water velocity. Therefore, before proceeding to compute the performance of the TBS using the above model, the suspension density and interstitial water velocity must be estimated. It is observed that both the suspension density and the bed voidage change along the axis of the TBS. Suspension density is highest at the bottom and it decreases with increasing distance from the bottom in the axial direction. Consequently, the voidage is lowest at the bottom and increases with axial distance. While the consideration of suspension density and voidage distribution enhances the accuracy of the predictions, it increases the computational complexity manifold. On the other hand, working with the average values of these two properties greatly simplifies the computations without losing much accuracy.

2.1.3 Mass balance

If the tracking of particles is combined with the component-wise and overall mass balances over the unit, it gives a complete description of the separation process. Component-wise mass balance and the overall mass balance over the unit are expressed by the following two relationships:

$$Ff_{ij} = Uu_{ij} + Oo_{ij} \tag{2.6}$$

$$F = U + O \tag{2.7}$$

where, F is feed mass flow rate, U is underflow mass flow rate, O is overflow mass flow rate, f_{ij}, u_{ij} and o_{ij} are mass compositions of the feed, underflow and overflow, respectively.

Simultaneous solution of Eqs. (2.5)– (2.7) gives composition and hence, the size and density distributions of the overflow and underflow products. Thus, a complete description of the overall performance can be obtained.

2.1.4 Suspension density

Suspension density inside the TBS is controlled by adjusting the bed pressure which may be expressed in terms of composition of the suspension as:

$$P/H= \{\Sigma \phi_{ij}.\rho_{ij} + (1- \Sigma \phi ij)\, p_{f\}}\, g. \qquad (2.8)$$

Concentration of solid particles and hence, the suspension density, decreases with height from bottom to top. It is assumed that the effective suspension density is the average suspension density inside the separator, and it is expressed as:

$$p_{sus} =\Sigma \phi_{ij}\rho_{ij} + (1- \Sigma \phi_{ij})\, p_f. \qquad (2.9)$$

Therefore, from Eqs. (2.8) and (2.9), the average suspension density and the bed pressure are correlated as:

$$\rho_{sus} = \frac{p/h}{g}\, g \qquad (2.10)$$

Average suspension density can also be computed as follows

$$p_{sus}=\frac{p}{p_{waterbed}}\rho_{water} \qquad (2.11)$$

Where $P_{waterbed}$ is bed pressure when the separator is filled only with water, and ρ_{water} is density of water.

2.1.5 Voidage

The interstitial water velocity is calculated by estimating the bed voidage, which is averaged over some property of particles. The volume average density of the particles is used for voidage determination in this investigation.

$$\varepsilon_{avg} = \frac{\rho_{avg.partcle}-\rho_{sus}}{\rho_{avg.partcle}-\rho_{water}} \qquad (2.12)$$

Where $\rho_{avg,\ particle}$ is particle average density and ε_{avg} is average bed voidage. The interstitial teeter water velocity is then computed by dividing the superficial teeter water velocity by the voidage.

2.1.6 Other constitutive correlations

The physical process inside the TBS has been described in the previous section using a simple mathematical correlation. However, before using the above model one must compute n_{ij}, Richardson and Zaki index, and the terminal settling velocity of the particle.

a. Estimation of Richardson and Zaki index

The Richardson and Zaki index has been correlated with Reynolds number by several investigators (Richardson and Zaki, 1954; Graside and Al-Dibouni, 1979; Rowe, 1987). Dependence of the Richardson and Zaki index, n_{ij}, on Reynolds number is given in explicit form by Graside and Al-Dibouni (1979). However, a more accurate correlation for determination of n_{ij} is proposed by Rowe (1987):

$$n_{ij} = \frac{2(2.35+0.175Re_2^{0.75})}{(1+0.175re_t^{0.75})}. \qquad (2.13)$$

b. Terminal settling velocity

The terminal settling velocity is computed by considering a simple force balance under gravitation or centrifugal field. However, accurate prediction of the drag coefficient, which is strongly dependent on the settling regime, is a key issue. Reynolds number (Ret) of a particle at its terminal settling velocity (Ut_{ij}) is given by

$$Re_t = \rho U_{t,ij} d/\mu \qquad (2.14)$$

Galvin et al. (1999b) computed Reynolds number of the particle at its terminal settling velocity using an explicit correlation proposed by Zigrang and Sylvester (1981). Although this correlation is supposed to be independent of settling regime, Hartman et al. (1989) have shown that the terminal settling velocity calculated using the above correlation has substantial error. They proposed a more accurate correlation for the determination of the Reynolds number as a function of Archimedes number that predicts terminal settling velocity within an estimated error of ±1%. The correlation proposed by them is as follows:

$$log_{10}Re_t = [(c_1A - c_2)A + c_3]A - c_4 + log_{10}(c_5 + c_6\sin(c_7A - c_8) \qquad (2.15)$$

Where, $A = \log_{10}$ Ar and $Ar = \frac{d^3 g\rho_f(\rho_{ij}-\rho_f)}{\mu^2}$ the latter is the dimensionless Archimedes number. Since this correlation is also claimed to be independent of settling regime and gives more accurate estimation of the terminal settling velocity, it has been used throughout the present work.

2.2 Principles of Operation

Slurry feed enters the unit by means of a tangential feedwell and a fluidized, or a teetered, bed is built up against a Teetered Bed Separator fluidizing water (UCW) supply. Appropriate valving regulates the TBS fluidizing water flowrate such that the water flows up through the tank at an average upward interstitial velocity (V_{ucw}). In simplistic terms, when steady state is reached, particles of feed, which are less dense than the average density of the teetered bed will have a hindered settling velocity (V_{hs}) less than the average TBS fluidizing water velocity $V_{hs} < V_{ucw}$). These particles will tend to float on top of the teetered bed and are ultimately displaced to the overflow stream. Conversely, feed particles of higher density than the teetered bed will have a hindered settling velocity greater than the average TBS fluidizing water velocity ($Vhs > V_{ucw}$). These particles will percolate through the bed and report to the sinks stream via the spigot.

In order for the unit to operate effectively, the average relative density of the teetered suspension within the tank is to be kept constant. To achieve this, a simple feedback control loop is incorporated in the commercial unit design. A capacitance type differential pressure cell measures the effective density of the teetered suspension. A single loop PID controller receives a 4-20 mA signal from the probe, proportional to the effective density of the teetering suspension above the probe. The effective density is compared to the operating set point and the spigot valve is actuated to discharge excessive bed solids if the effective density is too high. Conversely, the control system acts to restrict the discharge of the bed solids if the effective density is too low.

2.3 The Teetered Bed Separator Components and Their Operation

A sectional view of a standard TBS machine is provided below. Each of the major components of the TBS are listed and described below in figures 1, 2.

2.3.1 Main Tank

The main tank consists of four main sections. Pressure or plenum chamber, sorting column, TBS fluidizing water manifold and overflow launder. The Pressure chamber is located at the base of the tank and is isolated from the main vessel or sorting column by the teeter plate(s). Water enters the pressure chamber via the TBS fluidizing water manifold and passes up into the main vessel or sorting column through the teeter plate(s). The sorting column as the name suggests is where the beneficiation of the coal feed takes place (see section 2.1 above). The sorting column has to be sized correctly for the feed size distribution and feed tonnage to ensure sufficient settling area is available for the process. The TBS fluidizing water manifold consists of a channel welded around the circumference of the tank. The channel's function is twofold; it provides structural stiffness to the tank and a ring-main to supply the water to the pressure box via 3 manifold pipes. The overflow launder is a tiled launder to collect the TBS product and divert it away for subsequent processing. The tank internal surface is subject to very low particle velocities and hence is not susceptible to any major abrasive wear. A paint specification similar to that used in tailings thickeners or un-lined process sumps is adequate for the TBS internal surfaces. Peripheral items located on the tanks are as follows:

Washout doors: Washout doors are hinged doors that allow inspection access to the pressure chamber.

Inspection windows: Optional windows can be supplied so that operators can observe the mobility and consistency of the material in the sorting column.

Drain valve: A drain valve is located centrally underneath the pressure box. The drain valve allows the water in the pressure box to be drained prior to opening the washout doors for inspection of the pressure box.

Tank Footings: The tank footings are usually located on the TBS fluidizing water manifold channel, however the footings can be located at almost any elevation on the tank wall so as to suit site conditions, providing sufficient bracing is incorporating in the tank design.

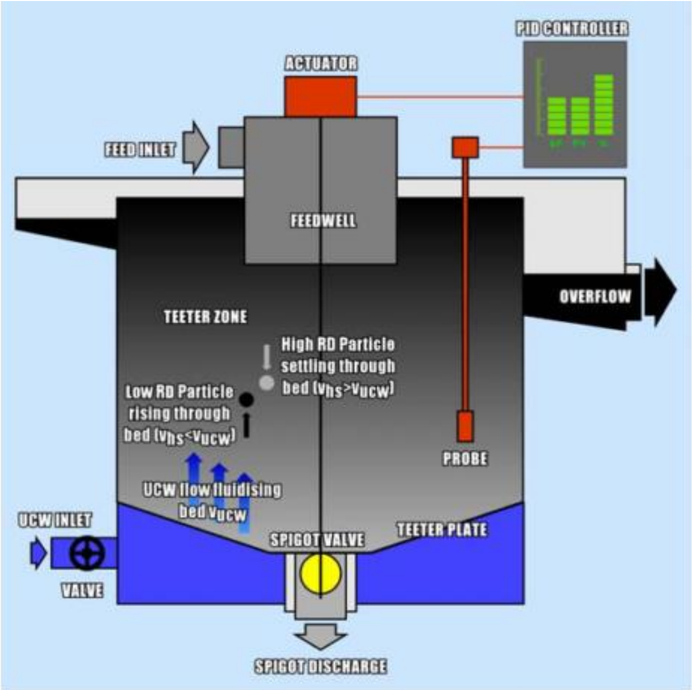

Figure 1. The Teetered Bed Separator Operation [5].

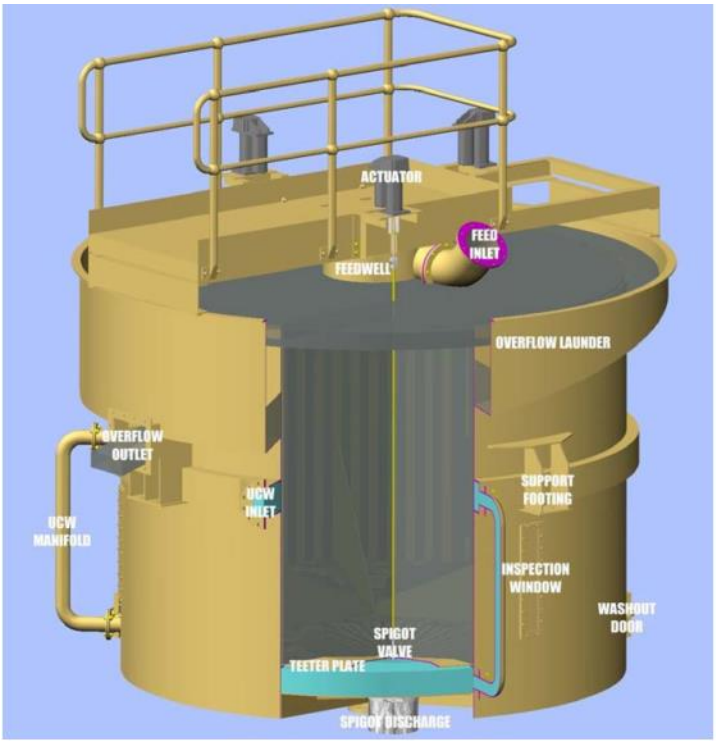

Figure 2. Sectional View of the TBS[5]..

2.3.2 Access Platform

The access platform complete with handrails, kick plate and flooring is designed so that the operator can gain safe access to the top of the TBS to monitor the TBS operation and to inspect and calibrate the density probe(s), control panel (if supplied) and pneumatic actuators. The access platform also provides the mounting point for the feedwell.

2.3.3 Feedwell

The function of the standard tangential entry feedwell is to present the solids into the center of the TBS. All feedwells are lined with 90% Alumina tiles to provide abrasion resistance.

2.3.4 Actuator(s)

The actuator assembly comprises a pneumatic type thruster valve, mechanical linkages and a positioner, configured to accept a 4-20 mA signal direct from the local controller or plant PLC. Each actuator assembly is connected to a spigot rod and a ceramic dart valve. A downward movement of the actuator thruster displaces the dart from the ceramic seat, thus opening the valve. The actuator has a linear stroke length of 60 mm. Each actuator assembly comes complete with a manual override facility so that the thruster valve can be manually positioned in the event of a positioner failure.

2.3.5 Probe(s)

The density probe is mounted on the access platform and consists of a sensing element which is immersed in the sorting chamber of the tank, the stem approximately 1800 mm in length and the electronic insert with electrical terminations located on the top of the probe stem. The sensing element converts the hydrostatic pressure within the teeter bed into an electronic 4-20 mA signal. Any change in the bed density will produce a variation in the 4-20 mA input signal that is sent to the PID controller. The probe is calibrated to indicate the average specific gravity of the pulp above the sensing element. Spigot Assembly - Dart Valve(s) and Seat(s)

The dart valve(s) sit under the valve seat(s). When conditions in the tank call for the valve(s) to be opened, the actuator(s) push the spigot rod(s) down, thus moving the dart valve(s) away from the seat(s), allowing discharge of coarse or heavy solids. Both the darts and seats are made from 90% Alumina ceramic so as to ensure that abrasive wear of these components is minimized.

2.3.6 Teeter Plate

The teeter plate usually consists of three separate dished sectors which are fixed onto mounting gussets around the internal circumference of the tank. The teeter plate assembly divides the tank into the sorting column and pressure chamber. For TBS configurations of 2.1 m in diameter (or less) the teeter plate comprises one only dished circular plate, which is flange mounted between the separate pressure box and main vessel or sorting column assemblies.

The purpose of the teeter plate is to evenly distribute the upward current water throughout the whole tank area. Each teeter plate has a specific number of holes (depending on the diameter of the TBS machine). Actual teeter plate inserts with an internal diameter of 5.0mm are interference mounted into each teeter plate hole. An optional insert is also available which contains a high strength silicone duckbill valve. The duckbill valve allows TBS fluidizing water through the valve, however if the TBS fluidizing water supply pressure is lost the duckbill valve closes reducing the likelihood of solids pegging the insert assembly.

2.3.7 Control System

The bed density required to accurately beneficiate the feed material is continuously maintained and controlled by the control system. The TBS control system comprises one centrally located density probe, a loop (PID) controller and pneumatic actuator(s). The measured specific gravity of the pulp in the sorting column is compared to the set point specific gravity and an output signal is sent to the actuator loop proportional to the error in the density signal.

Note that some installations utilize 3 density probes spaced equidistantly around the vessel. The 3 probe signals are averaged to indicate an “average” specific gravity of the pulp in the sorting column and control is achieved as described above.

The loop controller can be carried out using a local control panel which is supplied by the vendor or constructed according to the vendor’s specifications. Alternatively the TBS density loop control can be undertaken by the plant PLC controller if available. Regardless of the control hardware used, the controller must be configured to provide stable operating conditions subject to process disturbances and step density changes.

3 INDUSTRIAL DEVLOPMMENT IN TEETERED BED SEPARATORS TECHNOLOGY

3.1 Historical

Hydraulic classifiers have been in use since 1934, typically employed to sort out and group particles of different specific gravities and different size distributions. Historically the hydraulic classifiers have been differentiated in two distinct types based on the degree of crowding of particles in the separation zone. When the concentration of solids in the separation zone is small, the particle-particle collisions are infrequent and the particles settle under free settling conditions. This type of hydraulic classifier is called a free settling type or an “elutriator”. When the sorting column is designed such that particle-particle collisions are common by virtue of a much higher suspension specific gravity compared to the free settling type, the hydraulic classifier is called a hindered settling type. It is this type of classifier that will be discussed in detail.

The design of the hindered settling classifier can further be divided in two types. The launder-type and tank-type designs. The launder type design consists essentially of a launder with sorting columns attached to the bottom of the launder at convenient intervals. Conversely the tank-type consists of a relatively deep trough or tank with the sorting column attached to the bottom of the tank or integral to the tank. Over the years, there have been numerous pieces of equipment developed which fall into the category of hindered settling classifiers, namely:

•The Richards-Janney Separator

•The Fahrenwald Sizer

•The Bunker Hill Classifier

•The Pellett Classifier

Schematics of some of the early type classifiers (Taggart 1945) are given below in Figures 3 and 4.

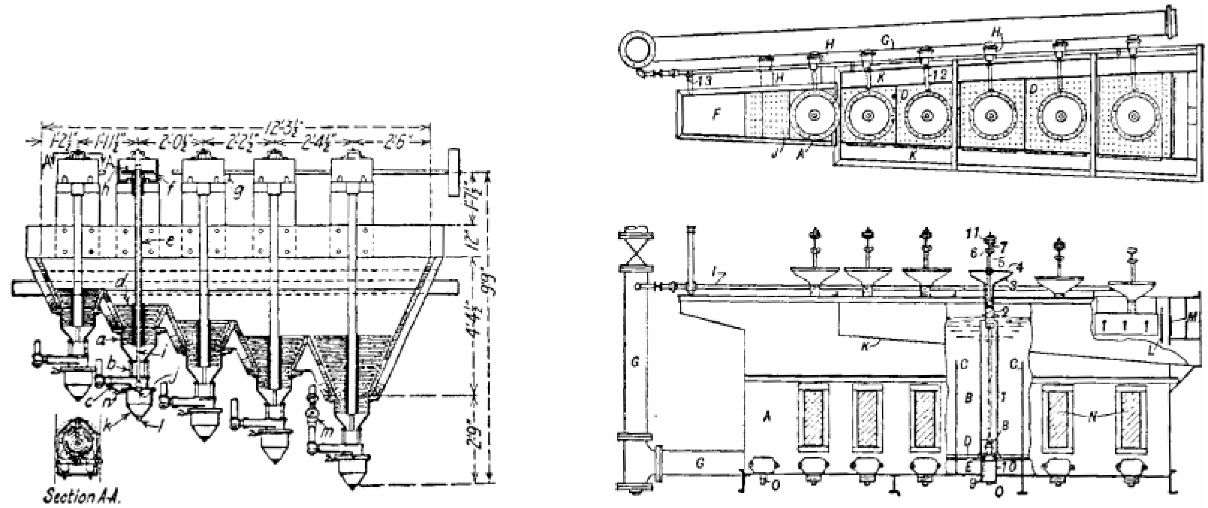

Figure 3. Richards Janney Classifier and Fahrenwald Sizer

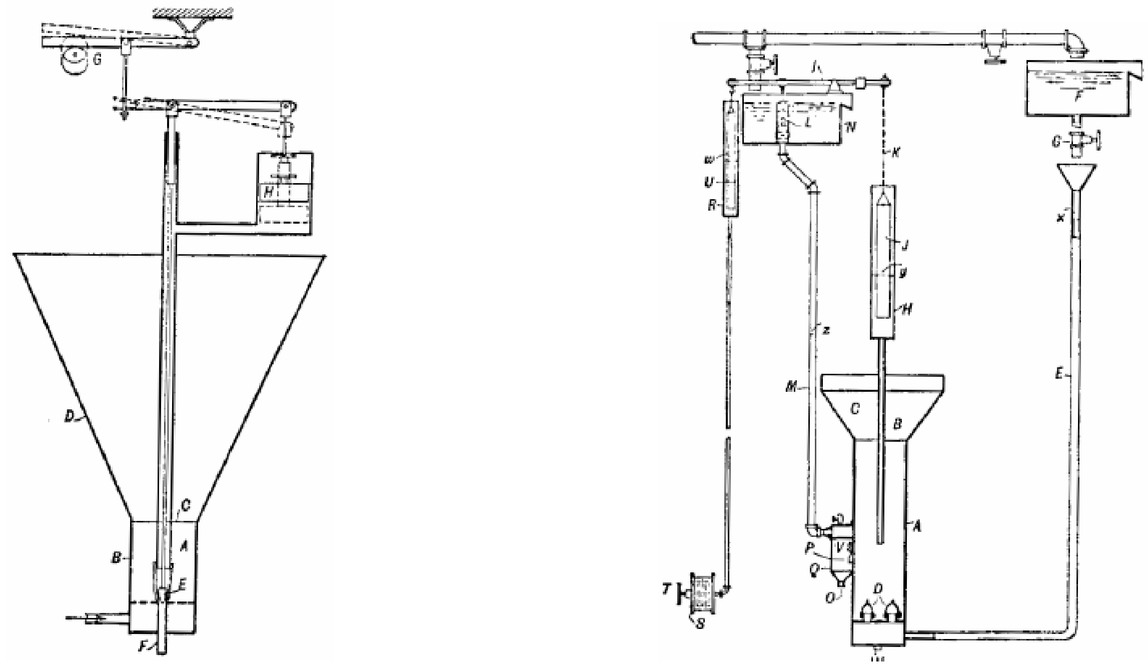

Figure 4. Bunker Hill Classifier and Compartment of the Pellett Classifier

Each type featured alternate means of controlling and metering the reject material rate from the discharge spigots and introducing the hydraulic water into the sorting columns. In the Richards-Janney Separator the reject material was discharged in a batch wise operation depending on the weight of material contained in the sorting column. In the Fahrenweld,

Bunker Hill and Pellet type classifiers mechanical means were used to determine the suspension density (via hydrostatic pressure) and mechanical linkages were deployed to evacuate material from the sorting column to maintain a uniform suspension density.
Advances is electronic sensing instrumentation and pneumatic and electrical process actuation have seen the development of the modern tank-type hindered settling classifiers employing sophisticated closed loop sorting chamber density control. The most common types of hindered settling classifiers in commercial use today are:

- Stokes (MEP) Hydrosizer: coal beneficiation, iron ore, silica sands, mineral sands, acid washing
- Linatex "T" Type Hydrosizer: silica sands, mineral sands
- Floatex Separator: coal beneficiation, iron ore, silica sands, mineral sands, acid washing
- Allflux: iron ore
- Reflux Classifier (RC): coal beneficiation

The modern type hindered settling classifiers can be categorized according to the table1.

Table 1. Modern type hindered settling classifiers

	Sorting Chamber Geometry	Water Distribution	Density Measurement	Reject Valve Configuration
TBS	Circular	Perforated Plate	DP Probe	Dart Valve/Seat
Linatex "T"	Square	Pipe	DP Cell	Pinch Valve
Allflux	Circular	Perforated Plate	DP Cell	Pinch Valve
Floatex	Square	Pipe	DP Cell	Pinch Valve
Reflux Classifier	Square	Pipe	DP Cell	Pinch Valve

The first hindered settling classifier was installed in an Australian washery in 1997. This machine was a Stokes (MEP) type Hydrosizer. To differentiate the coal beneficiation duty of the classifier from the particle sizing duty used in silica sands grading, the Hydrosizer was thereafter called and marketed as the Teetered Bed Separator (TBS) by the Australian agents for the Stokes (MEP) type Hydrosizer - Advanced Separation Engineering Australia Pty Limited (ASE).
The TBS has gained gradual industry acceptance in the Australian coal industry since 1997, such that by the end of 2005 there will be approx. 20 TBS machines installed in Australian coal washeries deployed in duties such as, raw coal beneficiation, flotation tailings scavenging and spiral product reprocessing[5].

The Teetered Bed Separator (TBS) has been developed from the classical ‘Hydrosizer’ concept, and the initial designs have been manufactured since 1934. Originally coal was separated on the basis of particle size, but the present day systems have been developed and optimized to separate primarily on the basis of density. This development has enabled cut points as low as 1.35 to be achieved, while maintaining good separation efficiency. The units have been employed for coal recovery from waste piles and tailings lagoons since the 1960s and have been used to treat run of mine coal in the UK since the 1980s. Today over 200 such units have been installed worldwide, in applications including, run of mine (ROM) coal processing, tailings coal recovery, construction grade sand decontamination, foundry sand sizing, glass sand production, mineral sands processing and hematite processing. The first TBS in Australia was installed in the Stratford Coal preparation plant in 1997[5]. An eighty ton per hour unit was designed to re-treat spiral product to produce an enhanced yield of low ash coking coal. The unit treated coal between 1.2mm and 0.35mm fines and had a payback period of two months. A second unit was installed in Bayswater Colliery in Australia. The plant yield increased by 2% and the throughput rate increased by 100 tph. This resulted in a reduction in normal and overtime operating hours. There was also an increase in the washed product tonnage and export quality of the coal[3].

Nicol (1998) found that the TBS had many operational advantages over other units. These include controllable density cut points as low as 1.38, a good separation efficiency (Ep) of approximately 0.06 compared to spirals which ranged between 0.07-0.12, and a high solids handling capacity in a single unit. The unit also covered a small footprint area with minimal feed slurry distribution. Due to these findings, it was proposed to use the TBS instead of spirals in industry as it yielded a higher recovery of coarse particles and could be easily upgraded[6].

Hyde (1998) investigated hindered settling classifiers in fine coal washing. He conducted experiments comparing the Stokes Hydrosizer to a spiral on a pilot scale. Water was added at a rate to ensure that the coarsest coal was held in suspension and reported to the overflow. He used a water box at the bottom of the cell to ensure an even water distribution. The test work was conducted at different teeter water and feed flows. He found that the hydrosizer had a higher mass yield, ash rejection and recovery to the overflow compared to the spiral. Spirals were found to be sensitive to feed variations. When the volumetric feed rate is lower than normal, material was lost to the tailings. The separation efficiency of the spiral was greater however a significant loss of coarse low density material was noted.

Galvin et al (1999), have conducted most of the work in TBS technology in recent years. The research was conducted at the University of Newcastle, Australia. They related the suspension density to the settling velocities. This explained how the slip velocity was dependent on the hydrodynamic resistance. It was noted that as the volume fraction of the species was increased, the slip velocity decreased. This was used to develop an equation for slip velocity by modifying the Richardson and Zaki equation (1954). The equation relating the pressure drop to the hindered settling velocity was as follows[2]:

$$U_i = U_{ti}(1-(dp/dh)/((pi-p)g))^{ni-1} \qquad (3.1)$$

Where, ${dp}/{dh}$ is the pressure gradient term.

They stated that only data required for the model was the mono-component fluidisation data for each species. The pressure gradient is common to all particle species and is a consequence of the drag forces produced by the liquid to support the weight of all the particle species.

The authors also presented a more generalized form of the Richardson and Zaki equation that is useful for all suspensions whether it be a single species, different size or density. This equation describes a dimensionless density parameter used to describe hindered settling.

$$U_i = U_{ti}((p_i - p_m)/((p_i - p))^{ni-1} \qquad (3.2)$$

Where, p_m is the density of the suspension medium (kg/m^3).

If $p_m > p_i$ the suspension will be unstable and generate streaming or lateral effects (Galvin et al. 2000). Galvin used a fluidised bed to conduct experiments. From the analysis of the solids volume fraction, he proposed that the slip velocity of a multi species suspension, involving particles of different size and density could be used.

Galvin et al. (Sept, 1999) investigated the effect of dense medium separation using a TBS by varying the suspension density. They used three different types of media, namely clean coal, clean coal with mineral matter and clean coal, mineral matter and magnetite. They used a low fluidisation rate with the heavy media having a settling velocity similar to the particle settling velocity.

A lab scale TBS was used with an internal diameter of 0.173m, 1.36m high. The coal feed was obtained from the hydrocyclone underflow. Galvin stated that according to theory, high suspension densities as close as possible to low ash coal particles yield the best separation and these are achieved by operating at low fluidisation velocities.

From their investigations, they concluded that at a low suspension density, separation is governed by particle size, however at a high suspension density, it is dependent on particle density. When the system is fluidised, the underflow discharge rate governs the separation. They concluded that the selected particles for the dense medium should be of a density higher than the coal feed, with a narrower size range, and with the settling velocity of the dense particles in the bed being as close as possible to the desired cut point velocity. This would make it possible to generate a higher suspension density resulting in an improved separation efficiency. The error of separation (Ecart Probable, Ep) and Imperfection (I), of a feed with a continuous distribution of sizes and densities is usually defined as:

$$E_p = \frac{D_{25} - D_{75}}{2} \qquad (3.3)$$

$$I = \frac{E_p}{D_{50} - 1} \qquad (3.4)$$

Where, D_{25} and D_{75} are the densities at which particles have a 25% and 75% probability respectively of reporting to the overflow and effective density of separation (D_{50}), is the cut point density at which 50% of the feed reports to the overflow. It can be reported on the overall feed or on specific size fractions. It is therefore the error or deviation from ideal separation [7].

Pilot studies using the TBS, questioned industries use of the E_p, since the efficiency of hydrocyclones were found to be similar to a TBS, however the hydrocyclones had a higher amount of fine low-density coal rejection. The only problem experienced by the Australians, were process disturbances due to the feed. This affected the closed loop density control. It caused a cyclical density response due to oversize material causing fines to be lost in the tailings during feedback control. Screening the feed, before running the process, solved the problem[8].

Richardson and Zaki (1954) proposed an empirical slip velocity model to describe the particle movement in sedimentation and liquid fluidization processes where slip velocity is defined as a function of void fraction and particle terminal settling velocity.

Van Der Wielen et al. (1996) proposed a steady state force balance model to estimate classification velocity of fluidizing particles. They also proposed that the effective Archimedes buoyancy should be calculated considering the bulk density of the suspension rather than the density of the liquid alone. They concluded that the overall friction can be decomposed into solid–liquid and solid–solid components. In the upper transition (laminar to turbulent) and turbulent regime, particle–particle friction is shown to be proportional to the product of hold up of the fluidized particles and slip velocity of the dense fluidized particles. In case of the stationary fluidized bed, the slip velocity is equal to the classification velocity.

Galvin et al. (1999a) proposed an empirical slip velocity equation considering the terminal settling velocity and the density difference. As per their claim the model is applicable to particles of varying densities in homogeneous suspensions. Substantial work has been done to describe the particles separation in a liquid fluidized bed [9],[10].

However, most of these studies are restricted to binary or ternary mixtures varying either in size or density. It is well established that in a teeter bed separator both the density and size play significant roles ([2],[11],[12]). Although it is possible to predict separation using a mass transfer approach with the Fickian diffusivity model, its application is severely restricted because of unavailability of reliable diffusivity values [9]. Binary particle separation mechanism using the density separation driving force and the size separation driving force has been discussed in this work. The potential for alumina removal from iron ore fines using the TBS has been established by Sarkar et al. (2006). It is proposed that the misplacement of less than 45 μm particle fractions in the underflow increases linearly with the underflow moisture content[12].

Description of separation performance of the TBS for a multi-solid feed with changing teeter water flow rate and bed pressure has not yet been attempted. The formation of a dense suspension has a significant influence on the separation performance. The coupling effect of the bed pressure and the teeter water flow rate makes the problem more complex and challenging. The objective of the present study is to provide a simplistic and yet realistic mathematical description of the process to predict the effect of particle size and density distribution (multi-solid) of the feed, bed pressure and teeter water flow rate which affect the performance of the TBS. Better classification efficiency (EP value) is obtained by maintaining lower teeter water, lower set point, lower feed rate and high pulp density. At higher level of both feed rate and teeter water flow rate misplacement of particles increases, thereby decreasing the efficiency[13].

Laboratory-scale hindered-settling column equipment was tested to evaluate the separation efficiency for cleaning Korean anthracite under various operating conditions. Results indicated that the yields of products increased as the set point and teeter water flow rate increased, but ash contents remained about the same due to the pre- dominance of the fine coals[14].

This chapter was beneficial in providing a detailed summary of recent research conducted industrially to improve the density separation process of the TBS. Various modified separators were developed to improve the separation efficiency, cut point densities and size range that the unit can separate. The information gathered from this Chapter was significant in respect to the design criteria considered.

3.2 Cross flow

Kohmuench (2000) developed a modified separator, called the CrossFlow separator. It utilizes a tangential low velocity feed entry system that introduces slurry at the top of separator using a feed well. It has parallel-perforated pipe spargers rather than a distributor plate for the teeter water supply. It has an innovative feed presentation system. The velocity of the feed flow is reduced, by allowing the feed to enter a side well before entering the chamber. This approach allows the water to travel across the top of the unit and report to the overflow launder with minimal disturbance of the fluidsation water within the separation chamber[15]. Peng et al.[16],found that this eliminates the excess feed water rapidly, thus a higher handling capacity and separation efficiency is achieved[17].

Most Hindered-bed separators utilize a down counter to introduce feed material to the system. This material enters the feed zone and may encounter either free or hindered settling conditions, depending on the concentration of particles in the separator. The settling particles form a fluidized bed (teeter-bed) above the fluidization water injection point. A simplified schematic of a typical hindered-bed separator is shown in Figure 5.

More recently, a new hindered-bed classifier separator has been developed that utilizes an innovative feed presentation system. This device, which is known as the CrossFlow separator, is shown in Figure 6. The CrossFlow utilizes a tangential, low-velocity feed entry system that introduces slurry at the top of the classifier. This approach allows feed water to travel across the top of the unit and report to the overflow launder with minimal disturbance of the fluidization water within the separation chamber. To reduce the velocity of the feed flow, the feed stream enters a side well before flowing into the separation chamber. The feed then overflows into the top of the device. Solids settle into the separation chamber as they travel between the feed entry point and overflow launder. The result of this feed presentation system is the elimination of excess feed water in the separation chamber, which can adversely affect separation efficiency[15].

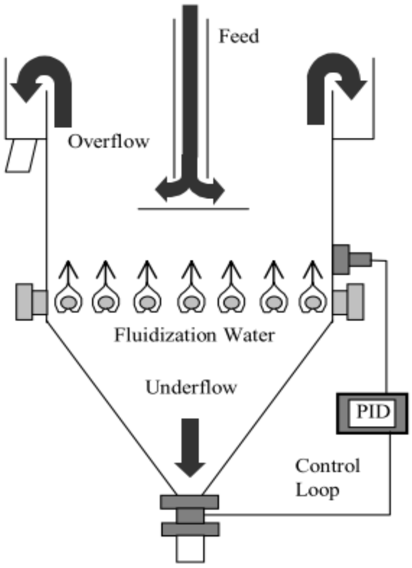

Figure 5. Schematic diagram of a conventional hindered-bed separator.

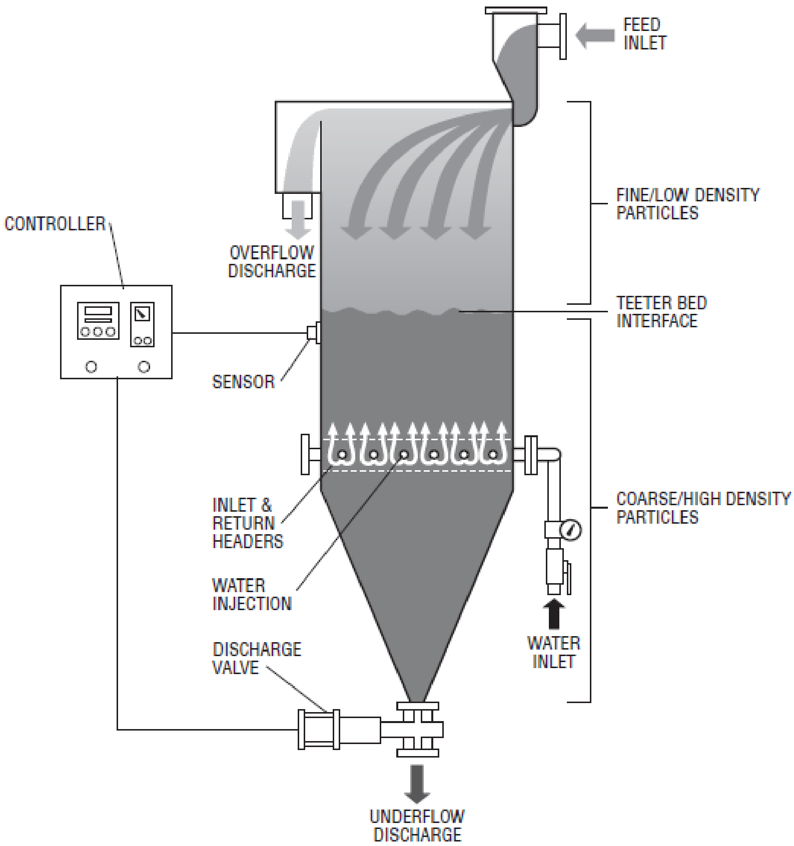

Figure 6. Schematic of CrossFlow hindered-bed separator.

The Eriez CrossFlow is a hydraulic teeter-bed separator used to upgrade minerals/coal based on size and SG (particles ranging from 0.2-4 mm). The device operates based on the principle of hindered settling of solids against a rising water flow. Figure 7 shows Comparison of teetered bed separator to Spiral concentrator for upgrading 2.0*0.15 mm coal and in figure 8 typical size distributions generated during normal operation using two CrossFlow separators in series to produce 3 tightly – sized product stream for sand application

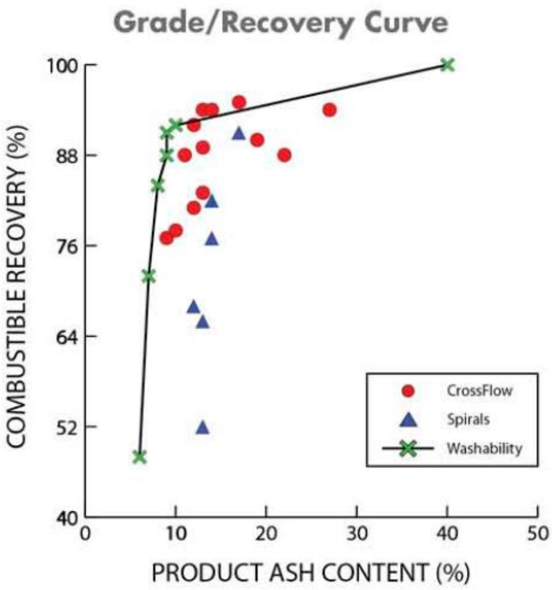

Figure 7. Comparison of teetered bed separator to Spiral concentrator for upgrading 2.0*0.15 mm coal[18].

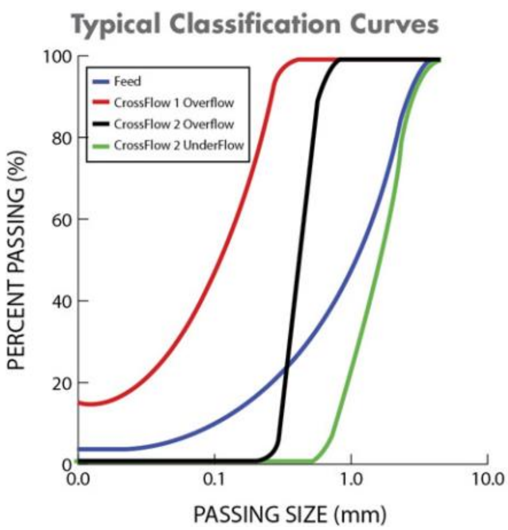

Figure 8. Typical size distributions generated during normal operation

Figure 9. CrossFlow separator for Potash, Tungsten and heavy minerals recovery

3.3 Hydrofloat

To overcome the shortcomings of traditional hindered-bed separators, a novel device known as the Eriez HydroFloat Separator was developed. As shown in Figure 10, the HydroFloat unit consists of a rectangular tank subdivided into an upper separation chamber and a lower dewatering cone. The device operates much like a traditional hindered-bed separator with the feed settling against an upward current of fluidization water. The fluidization (teeter) water is supplied through a network of pipes that extend across the bottom of the entire cross- sectional area of the separation chamber. However, in the case of the HydroFloat separator, the teeter bed is continuously aerated by injecting compressed air and a small amount of frothing agent into the fluidization water. The air is dispersed into small bubbles by circulating the water through a closed-loop configuration with a centrifugal pump. The air bubbles become attached to the hydrophobic particles within the teeter bed, thereby reducing their effective density[19].

HydroFloat Separators Improve Coarse Particle Recovery through:

- Increased bubble/particle collision rates
- Increased bubble/particle sliding time
- Increased residence time
- Decreased mixing
- Decreased turbulence and detachment
- Decreased buoyancy restrictions

The particles may be naturally hydrophobic (e.g. coal) or made hydrophobic through the addition of flotation collectors. The lighter bubble-particle aggregates rise to the top of the denser teeter bed and overflow the top of the separation chamber. Unlike flotation, the bubble-particle agglomerates do not need to have sufficient buoyancy to rise to the top of the cell. Instead, the teetering effect of the hindered bed forces the low-density agglomerates to overflow into the product launder. Hydrophilic particles that do not attach to the air bubbles continue to move down through the teeter bed and eventually settle into the dewatering cone. These particles are discharged as a high solids stream (e.g., 75% solids) through a control valve at the bottom of the separator. The valve is actuated in response to a control signal provided by a pressure transducer mounted to the side of the separation chamber. This configuration allows a constant effective density to be maintained within the teeter bed. In coal applications, the selective attachment of air bubbles makes it possible to recover very coarse, low- ash particles that would otherwise report to the reject stream of traditional hindered-bed separators.

The first in fluidized-bed flotation with more than 50 units installed worldwide. Eriez, a world leader in separation technology, has designed the new HydroFloat Separator for coarse particle mineral concentration delivering the capacity of a density separator while maintaining the selectivity of a flotation device. Using a novel aeration system to disperse fine bubbles into a fluidized-bed environment, the HydroFloat Separator significantly increases the selective recovery of coarse particles by applying flotation fundamentals to gravity separation. Can be applied to Coal, Iron Ore, Industrial Minerals, Base Metals and Sulfides. Applications include:

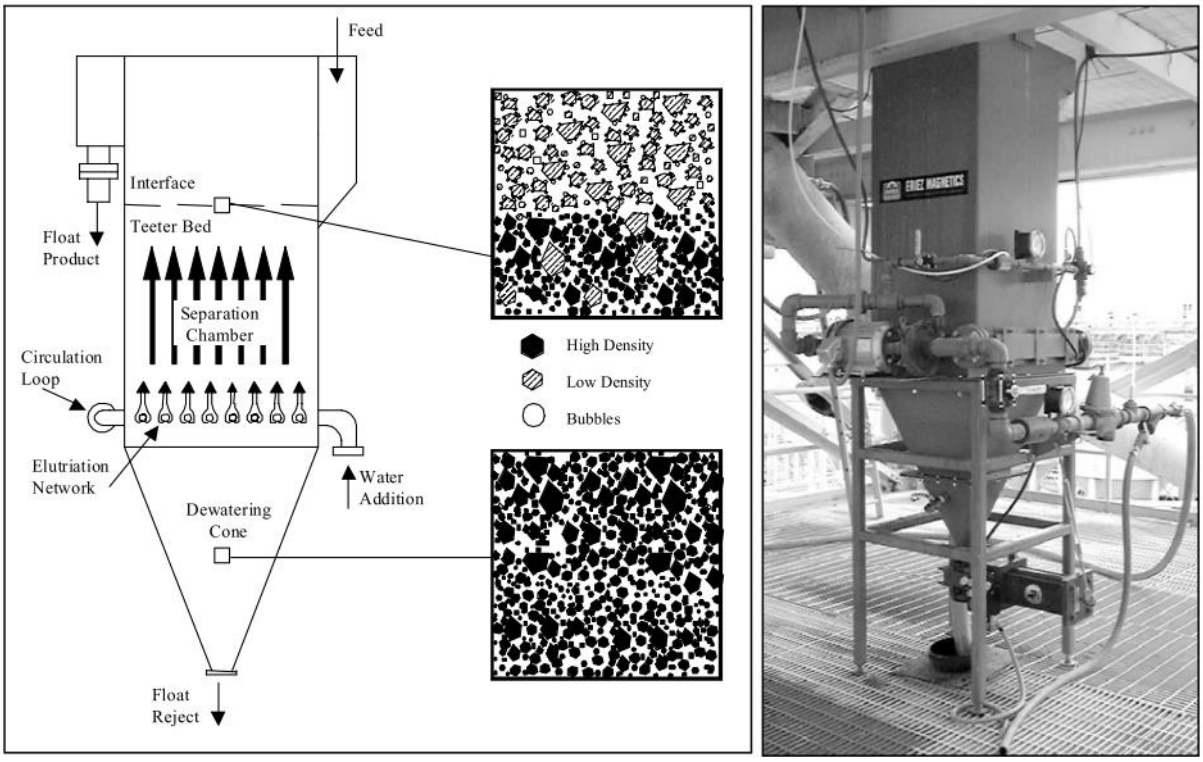

Figure 10. Schematic of the Eriez HydroFloat separator.

a. ***• Coarse Recovery in Split-Feed Flotation Circuits***

Eriez developed the HydroFloat Separator specifically to treat coarse material. With this new separator, process engineers can now maximize efficiency by designing split-feed flotation circuits where coarse material is treated separately from the fines.

The HydroFloat Separator was invented to provide a solution for industry to overcome a long-standing challenge - the efficient recovery of particles coarser than 150-200 micron. Conventional and column flotation cells are well suited for concentrating ores ranging from 50-150 micron. However, their effectiveness when treating particles coarser than this threshold is suspect due to turbulence and buoyancy issues.

Process engineers no longer have to try to achieve optimum performance in a single unit operation. Coarse material can now be isolated and treated in a separator specifically designed for and ideally suited to selectively recover coarse particles that are otherwise lost using conventional methods.

b. ***• Tailings Scavenging***

The development of the HydroFloat was based on applying flotation fundamentals to teeter-bed separation. The presence of the fluidized bed increases collision rates beyond that which can be obtained in open flotation cells. As a result, the HydroFloat excels as a scavenging device. It can be installed on the tail end of processing circuits to capture the “hard-to-recover” coarse and middling particles. These particles are typically lost when using conventional technology. Both test work and industrial data show that the HydroFloat is able to recover particles up to and exceeding -3mm in potash and up to -2mm in sulphides.

Most importantly, the HydroFloat is able to recover particles with minimal exposed hydrophobic surface area. Mineral liberation analysis has verified the high flotation rate offered by this device, as SEM back scatter images showed no valuable species present on the mineral surface after treatment in the HydroFloat.

c. • Flash Flotation in Grinding Circuits

The ability of the HydroFloat Separator to recover both coarse and middling material combined with its high flotation rate lends itself well to flash flotation applications. In fact, data show that for some applications, the HydroFloat can produce a throw-away tail which can dramatically reduce grinding costs.

No longer is it required to grind the entire flotation feed stream to a size suitable for traditional flotation technology. With fluidized-bed flotation, it is only necessary to grind the feed to a size sufficient for bubble attachment. This greatly reduces the tonnage that must be ground to achieve liberation for the sake of attaining grade. The savings in grinding may exceed an order of magnitude based on a simple Bond Work Index calculation. While the HydroFloat has been proven to work with particles exceeding 1-mm, it is important to realize even small changes in grind size will yield significant cost savings.

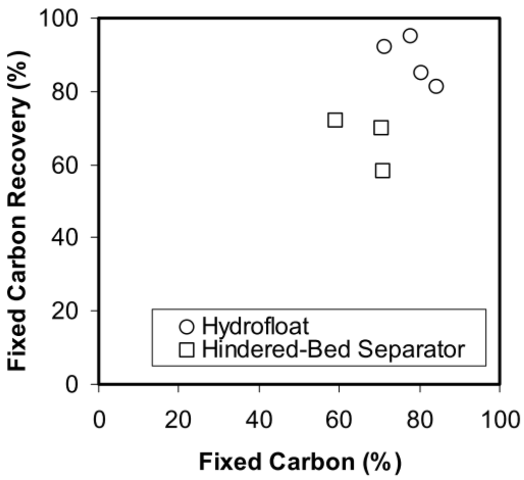

Figure 11. Performance of the Hydrofloat separator for the upgrading of anthracite

3.4 Reflux

Nuyentranlam and Galvin, (2001) found the Reflux classifier to be an innovative device for both particle classification and density separation. Their research provided key findings on the operational advantages of the reflux classifiers over conventional gravity separation devices. They stated that within the inclined channels between the plates, particles of coarser size or higher density, having a higher settling velocity, settle short distances within the channels and onto the upward-facing plates, form sediment layers and rapidly slide down below. Finer or less dense particles are carried through the channels by the fluidisation liquid into the overflow zone.

They explained that the reflux action develops as a result of the fluidised particles segregating onto the inclined plates, and returning to the fluidised zone below. This self-recycling effect should eliminate misplaced materials, thus enhancing the separation quality. Fine high-density material fails to pass through the upper inclined plates and accumulates in the system. This creates the high suspension density without an excessively high volume fraction of solids. The authors stated that since conventional liquid fluidised beds such as the TBS have a one to one correspondence between the suspension concentration and the fluidisation rate, they are forced to operate at the lowest possible fluidisation rate in order to effect satisfactory gravity separation.

Galvin et al. (2002) did a pilot trial on a reflux classifier. The Ludowici LMPE reflux classifier was designed for classifying and separating particles on a size and density basis. The unit had 3 sets of plates inclined at 60 0. The reject plates were 0.6m long and 100mm apart. The middling plates were 0.6m long and 50mm apart. The overflow plates were I.2m long and 30mm apart. The authors investigated the gravity separation and throughput performance using coal mineral matter less than 2mm in size. The plates significantly increased the throughput of the device compared to conventional systems.

Water flows up through the distributor plate at the base of the vessel. This suspends particles within the vessel. The feed slurry was delivered through the side of the vessel. Fluidised mixing zones are created between each set of plates. This permitted the option of withdrawing a stream from each zone above and below each set of plates if multiple sets of inclined sections were used. The particle trajectory within the inclined channel is parallel and normal to the plate. The parallel plates act as classification zones as described by Nguyentranlam and Galvin (2001).

Figure 12. Diagram representing a Reflux Classifier.

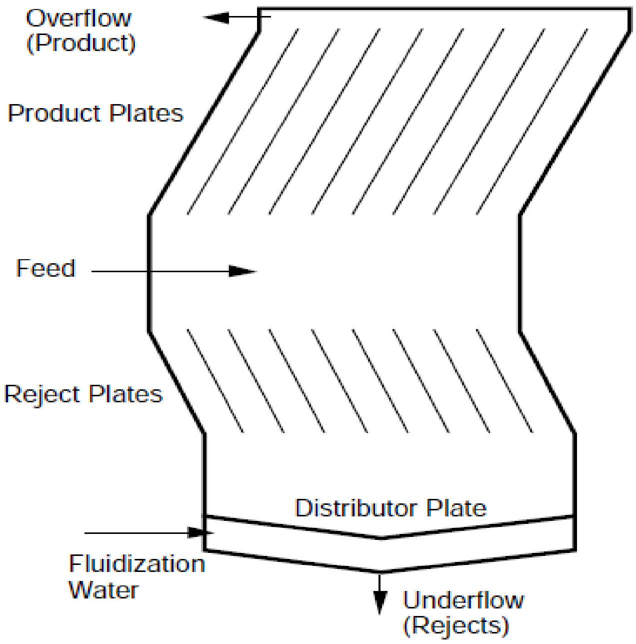

Figure 13. Schematic of Reflux separation operations

The results showed that the reflux classifier had a higher solids loading (33-47 t/m2h) than the TBS. Honaker and Mondal (2000) found the nominal solids throughput of the TBS to be 14 t/m2h. This was three times lower than the reflux classifier (RC). The TBS had a higher pulp density in the overflow (35 - 41%). The RC could be run with a lower feed pulp density and hence overcame the need to install cyclones as a pre-concentration step. A feed washability curve was plotted for the RC. This indicates the maximum possible yield for a given ash product. In this case it indicated a high combustible yield. Partition curves were also plotted for the RC. This curve indicates the probability of a particle of a given density reporting to the product stream. The authors found a shift towards higher densities as particle size decreased. A comparison was also made between the TBS and RC on the effect of increasing the fluidisation

Galvin and Nguyentranlam (2002) found that parallel inclined plates within a liquid fluidised bed permit a broad range of suspension concentrations at the one-fluidisation rate. This allows suspensions to form at fluidisation rates higher than the particle terminal velocities, which would benefit a broad range of systems.

Galvin et al. (2002) also investigated the influence of a jigging action on the gravity separation achieved in a TBS in order to extend the operating size range. The authors conducted this study in order to determine an operating size range of a TBS by cyclic variations in fluidisation water supply. They used a 0.174 internal diameter, 1.36 m high TBS. The vessel was designed for a steady state or pulsed flow. The particles were of varying size range determined by the authors. Coal and other minerals were used as feed material. Despite several tests, only a subtle change in separation was noted [20]. No changes were noted by the jigging action. If the jigging improved the separation, the rate of change of the Dso versus Particle Size would have been less and the Bp would be lower. The effective density of separation (Dso) is a function of particle size, and since the Dso increased as the size range increased, it showed that jigging was insignificant in improving the separation performance over a broad size range. The authors noted that the jigging action did improve the separation efficiency of fine particles from rejects, however it resulted in a loss of large low ash coal to the rejects.

3.5 Floatex

Floatex separations LTD design and manufacture sand classification equipment and process plant to meet the majority of requirement of Glass foundry and construction sand producer, together with certain machines for incorporation in heavy mineral gravity separations plant. Floatex have served the mineral process industry since 1946. Floatex Density Separator is a high capacity hindered settling classifier for separating particles based on size and/or density. Versatile in operation, the units can be sized to treat from 1 tph to 600 tph. Performance of a traditional wet-gravity separation circuit is greatly improved with the introduction of a Floatex unit and at less cost. The combined effect of teetering bed and simplified rising water current distribution system of the Floatex, makes it possible, to increase the separation efficiency while minimizing the possible misplacement of heavier minerals in the overflow stream[21].

The Floatex Density Separator has been continuously developed and perfected for more than 40 years. Today, in addition to industrial minerals, Floatex separators are routinely used in iron, chromite, and titanium ore operations where the more immediate and higher recovery of quality products allows for simpler and less costly operations. In glass sand operations, Floatex units are routinely used to answer the challenges of increasing size and quality specifications. Separators range from laboratory to industrial scale, and the applications from simple to complex. Incorporating Floatex technology. Applications are:

- Production of consistently graded sand products
- Removal of light contaminant material such as Coal, Lignite, Peat etc., from sands
- Concentration of heavy minerals
- Separation of minerals of sufficiently different specific gravities
- Preparation of sands for direct stockpiling
- Removal of silts
- Coal/Shale separation
- Preparation of sands for attrition scrubbing, acid treatment or froth flotation and for the rinsing of the sands following these processes[22].

An integral part of a Floatex Multi-Blend Plant

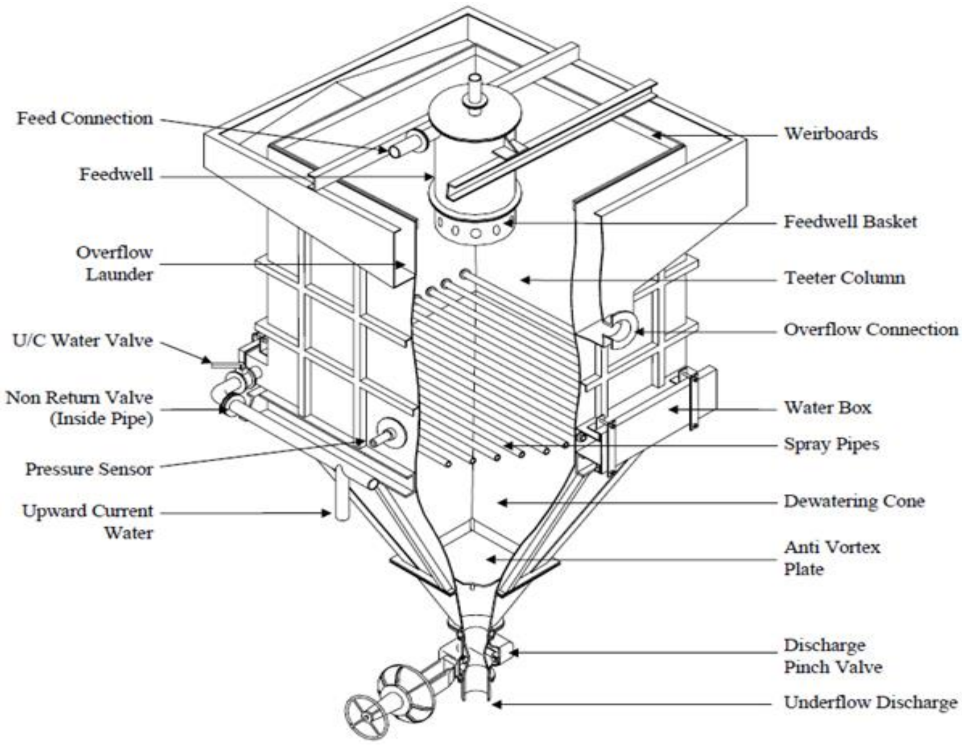

Figure 14. Floatex density separator schematic

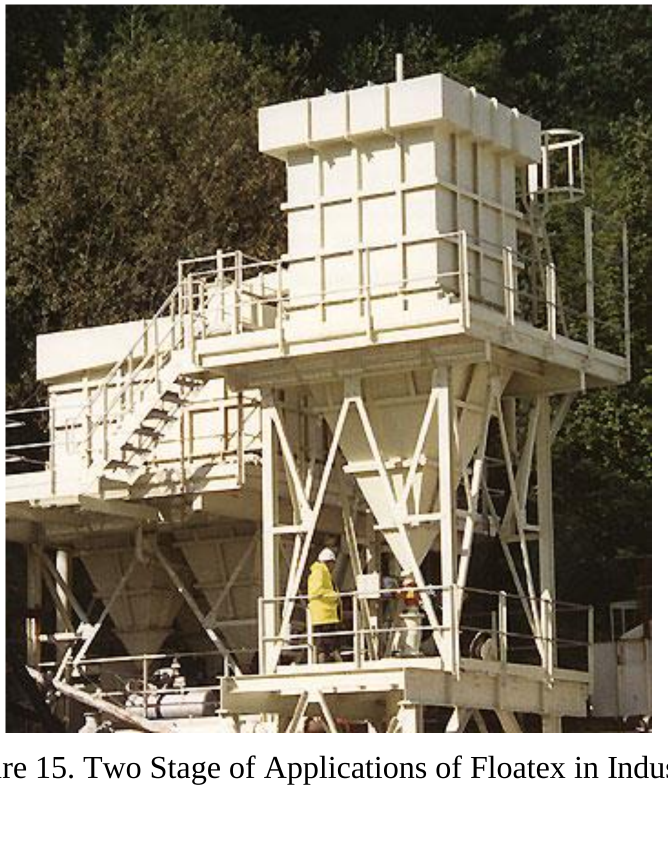

Figure 15. Two Stage of Applications of Floatex in Industry

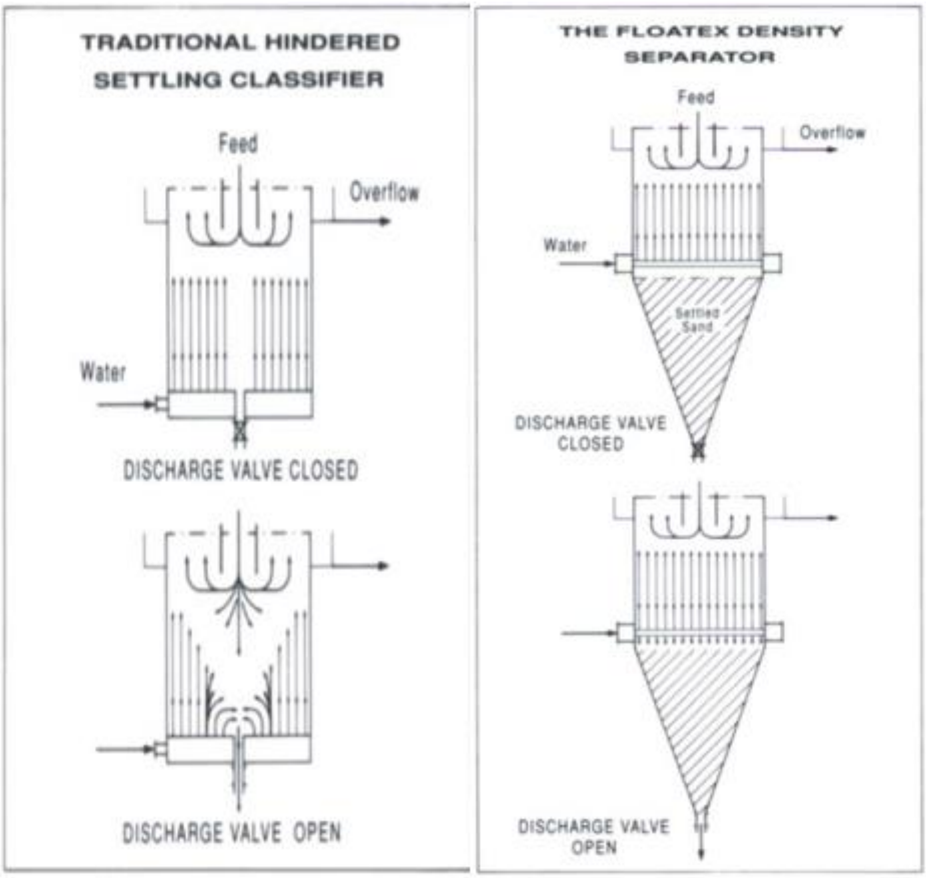

Figure 16. Discharge Valve System in Traditional Hindered Settling Classifiers and in the Floatex Density Separators

3.6 Allflux

Allmineral Aufbereitungstechnik GmbH & Co. KG was founded in Duisburg in March 1988. In the early nineties the company introduced its all-new **allflux**® fluidized bed separator. This machine made it possible for the first time to classify large volumes of sand/water slurries and concurrently remove organic impurities in a single pass. The high technical functionality and distinct economic benefits of these machines resulted in a quick market breakthrough for the Duisburg Company (The full scale upflow separator is known as the 'Allflux', whilst the smaller test model is the 'Miniflux').

The Allflux is a double stage teetered bed separator utilizing an up flowing current water and an autogenously teetered bed of fine coal and impurities to separate the feed material. The up flow currents and the bed level can be adjusted independently and are the main control variables[23].

Figure 17. Shows a diagram of an Allflux. The system has two separation stages. The inner section separates the heavy material from the middle/light material, whilst the outer section

separates the middle and light materials from each other[24]. The device produces three product fractions; heavy, middle and light. Feed material is suspended in water in a separate vessel. It flows into the top of the machine and down the central core. At the bottom the material encounters an upflow of water. The velocity of the up flowing water is set so that the lighter particles fluidise and are carried upwards whilst the heavy particles are able to settle downwards. During operation the water flow rate is adjusted in order to find the optimal setting for the separation. The heavy particles exit at the bottom of the machine.

The lighter material flows up and over into the outer section of the machine where it encounters another upflow of water. The water velocity in the outer separation section is less than in the inner separation section. The lightest material is fluidized but the middle fraction sinks, as its settling velocity is greater than the water velocity. The light material is carried over the weir and is collected. The middle fraction meanwhile collects in the bottom of the outer section and a valve periodically opens to allow the material to flow out of the bottom of the machine. The upward water flow rate in the outer separation chamber depends on the size and density of the particles to be separated. The machine can be supplied without the outer separation section if it is only required to separate two products (heavy and light).

An Allflux separator can be used to recover copper from copper-plastic mixtures produced during WEEE recycling, if the particle size of the material is below 3mm. The copper products from the trial on the hammer milled material met the specification required by metal processors. The separator itself is a high throughput low operating cost device. However the feed material must be size reduced in a hammer mill, with high power and wear costs, in order to make it suitable for processing[25].

Overall the economics of the separation look good, even when the capital and operating costs of the feed preparation process are taken into account.

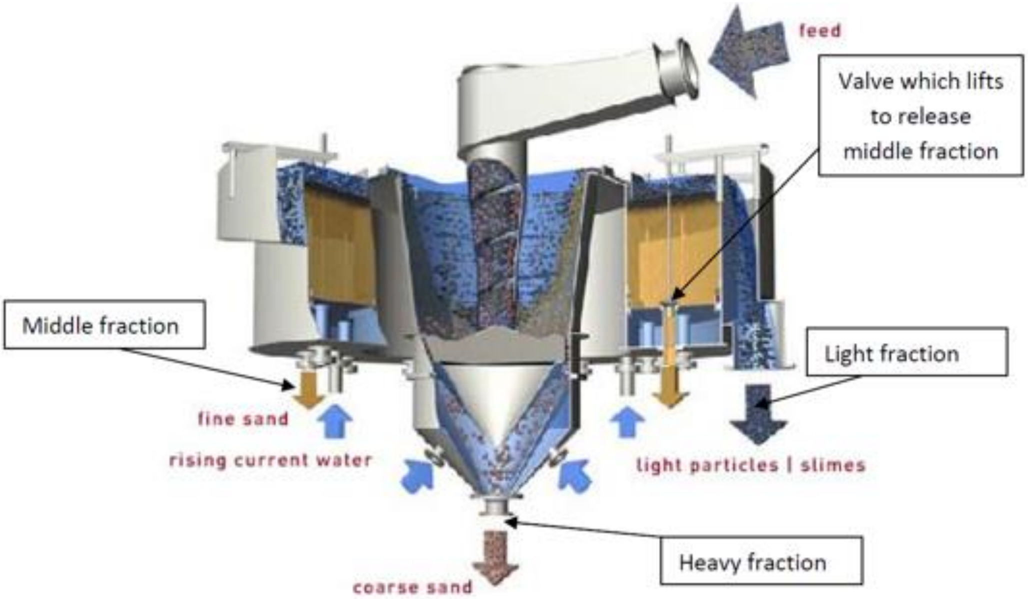

Figure 17. Diagram of an Allflux[24].

Figure 18. Application of Allfux in Industry

3.7 Teetered Bed Separators (TBS)

QVA Process Technology (Pty) Ltd was established in 2002 by Mark Craddock and Peter Hand. .It was formed to market and manufacture the MEP range of Teetered Bed Separators in Africa. It has the exclusive rights to the MEP/STOKES Teetered Bed Separator. At QVA it is our goal is to perfect process technology for beneficiation of fine coal, diamonds, mineral sands, aggregates and chrome fines.

The TBS Hydrosizer is a hindered settling Classifier, which is used to separate mineral particles into two groups either by size or where there is a mixture of relative densities, by specific gravity. It uses an upward current of water to create a 'column of teeter' within the vessel.

The condition of 'teeter' is created when particles fall through a current of water passing upwards through a vessel, those particles with a free settling rate equal to the velocity of the upward current water are arrested and held in a state of 'teeter'. This in turn creates the condition of 'hindered settling' because a bed or layer of similar-sized particles is held in suspension within the vessel. This bed or layer becomes in effect a dense-medium using the natural material within the Hydrosizer. We refer to this bed of material as the teeter column. Therefore, where the feed material consists of two or more specific gravities (e.g. a mixture of coal/shale), the particles with the greater mass will create the teeter column. The coarser, heavier material will penetrate the zone of teeter and report to the discharge spigot. The lighter material (including the fine heavier material) will be buoyed to the overflow. The upward current water is introduced into the pressure box from where it is evenly distributed into the settling chamber through the teeter plate. During the process of separation, the controls sense the condition of the teeter column within the vessel and as the quantity of similar sized particles builds up the density of the pulp within the vessel increases. The variation in density is measured using a hydro-static density probe which is immersed into the teeter column and sends a signal to the electronic controller. Any increase/decrease of the hydrostatic head is converted into a signal to the discharge valve to open/close proportionately. This automatic electronic control system is able to accurately maintain a preset condition regardless of the variation in the feed rate and provide a very accurate and consistent separation. A further Screening/Dewatering function maybe required to remove the fine heavy particles that report to the overflow of the Hydrosizer [18].

a. Upward Current water

The upward current water supply must be from a dedicated source and at a constant pressure (75-100 KPa). It is essential that this water be from a pipe large enough to prevent a significant loss of flow by friction. The design of a pumped feed pipe system should include a non-return device such as a "Swan neck" with an air relief valve to prevent syphoning of the water and solids back through the teeter plate causing unnecessary wear to the Hydrosizer, flow meter and pump. The volume of water required by a machine in continuous production can only be determined after a close study of the duty required. This will depend on various factors and is quoted for each application. A flow meter and valve should be installed to indicate and adjust the flow rate of upward current water, this can be adjusted manually or using a PID function in conjunction with an electrically controlled valve.

b. Feed

The slurry feed should ideally be 50% solids by weight.

c. Control Function

The Hydro-static level sensor is positioned at a fixed height within the Hydrosizer vessel, the sensor in the probe requires a two wire 24 V dc power supply which is calibrated during commissioning. The probe provides a 4-20ma input into a PID loop (PV) which in turn provides a 4-20MA output to the three Electro Hydraulic Actuators in order to maintain the desired set point. The actuators modulate and adjust the rate of refuse discharge to maintain the process variable at the set point.

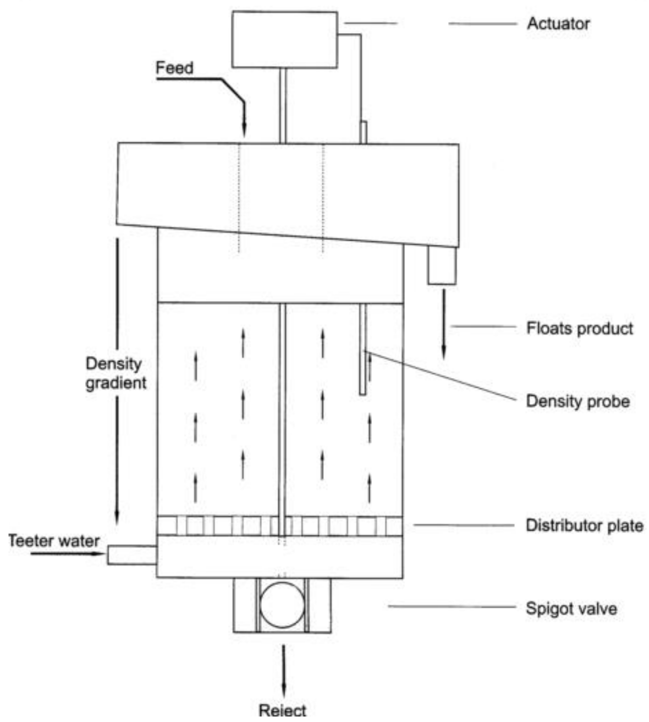

Figure 19 schematic of the Stokes/ASE teetered bed separators.


Figure 20 Application of Teetered Bed Separators (QVA) in industry

4 TEETERED BED SEPARATORS COAL WASHING APPLICATION

4.1 Raw Coal processing – Single Stage

The TBS presents a simple and low capital cost option to increase plant throughput capacity. If an existing circuit utilizes DMC processing down to 1.0 w/w mm, with spirals or flotation processing of the -1.0 w/w +0.125 mm fraction, then a parallel processing TBS circuit can be slotted in between these two circuits to optimally treat a nominal -1.4w/w+0.25 mm (or similar) size fraction. Further, by cutting out the inefficiently processed fines from the DMC circuit, and the poorer yielding coarse material from the spiral or flotation circuits, the overall plant yield may be increased, in addition to the plant capacity increase. The suggested flowsheet for an interposing TBS circuit is outlined below. Treatment of raw coal in this type of interposing TBS circuit can provide the following benefits:

•Increased throughput capacity in both the coarse and fine coal circuits.

•Reduced magnetite consumption due to the removal of the fine material from the DMC circuit.

•Increased desliming screen capacity and efficiency, as the screen aperture size is increased.

• Additional plant cut-point flexibility and control.

4.2 Raw Coal processing – Two Stage

The size range to the interposing TBS circuit can be increased further by utilizing a two stage TBS processing circuit. This type of flow sheet is commonly implemented in the UK to treat waste tip coal.

In this washing scenario small coal up to approximately 5.0 mm (and deslimed at 0.125 mm) can be washed in a primary TBS circuit. The primary TBS product can be sized using a sieve bend or low head screen at around 1.0w/w mm and the fines passing the primary product screening can be thickened in a cyclone and rewashed in a secondary TBS circuit treating the -1.0w/w+0.125 mm size fraction. Similar to the single stage wash scenario the secondary TBS product can be sized and the -0.25 mm fines diverted to the flotation circuit. The benefits of this type of processing scenario are similar to the single stage washing scenario.

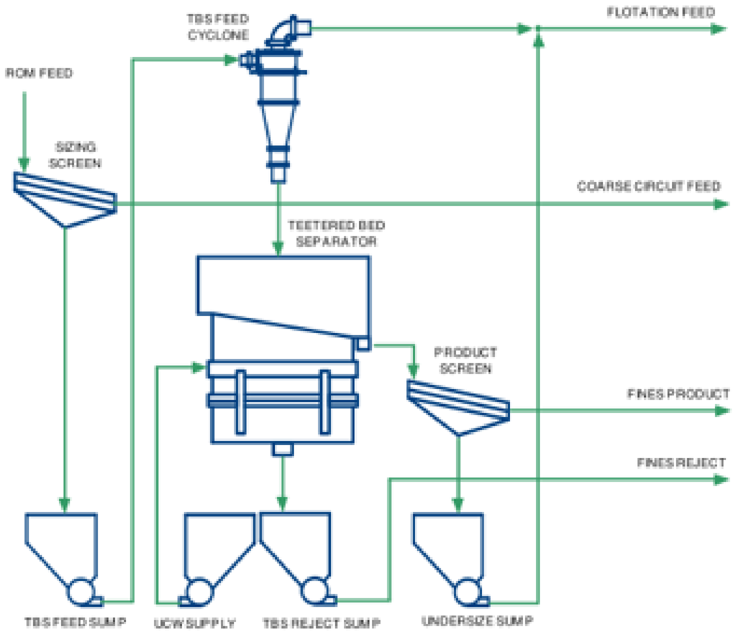

Figure 21. Suggested Raw Coal processing – Single Stage Flowsheet

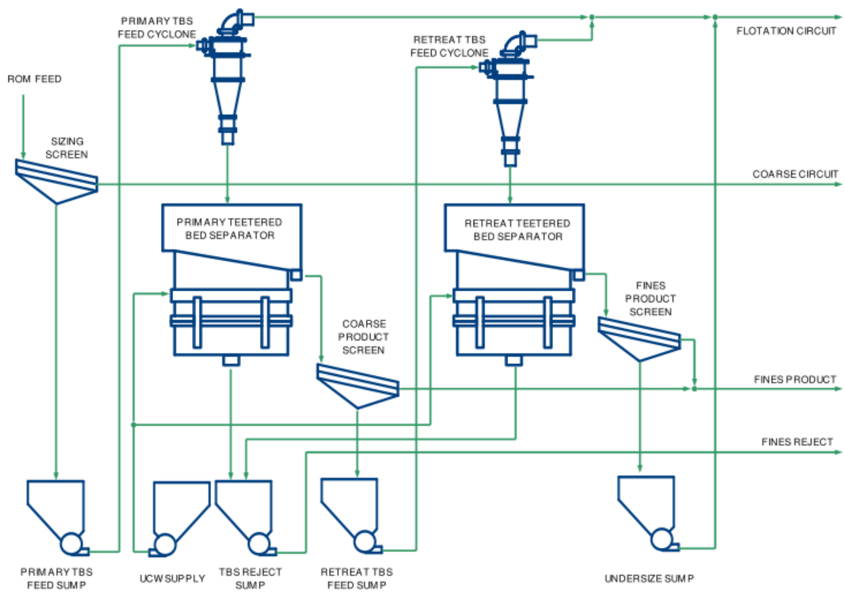

Figure 22 . Suggested Two Stage Raw Coal Processing Flowsheet[5]

4.3 Spiral Product Upgrading

In some spiral plants, inefficient and high cut-point operation of the existing spiral circuit can preclude the optimum processing conditions of the coarse coal circuit from being achieved. Under these circumstances the TBS presents a simple option to reduce the fines product ash and, as a result, allow the coarse circuit to be operated at an increased cut-point. This will result in optimized total plant operation whilst still maintaining overall product specification. Spiral product can be thickened and diverted to a retreat TBS, operating in the low cut-point regime. The resultant TBS product can be deslimed to yield a fine coal product at lower ash levels than those achieved by the existing spiral circuit.

4.4 Flotation Tailings Re-Processing

Advances in froth flotation technology have seen the introduction of high rate column cells to treat fine coal in the –0.5w/w mm size range. Whilst the column cells achieve high levels of combustibles recovery and maintain very low concentrate ash levels, some coarse coal will always be lost to tailings. This is especially critical if the desliming screen, screen decks are allowed to wear and a significant amount of +1.0 mm fines are misplaced to froth flotation. It has been demonstrated that implementation of the TBS technology, on the classified froth flotation tailings stream, can recover an economically viable quantity of good quality fine coal. As the flotation tailings stream is generally a wasted resource, the payback period in this application is likely to be less than a year (depending on the quantity of recoverable fine coal present in the flotation tailings stream).

It is essential that very efficient TBS product desliming is implemented as the clean coal TBS product will be associated with a large proportion of very high ash slimes material. Use of spray water on the TBS desliming screen will assist in the removal of the high ash slimes material.

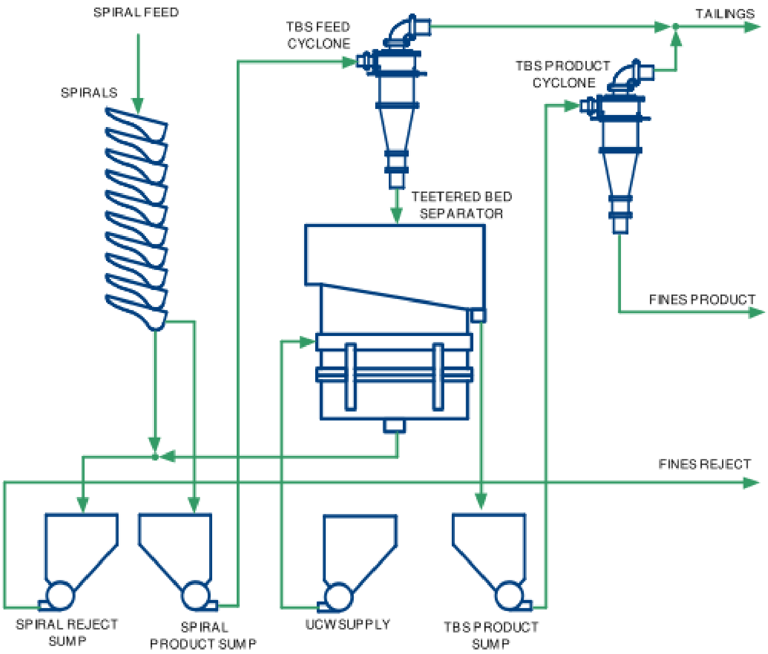

Figure 23. Suggested Spiral Product Reprocessing Flowsheet[5]

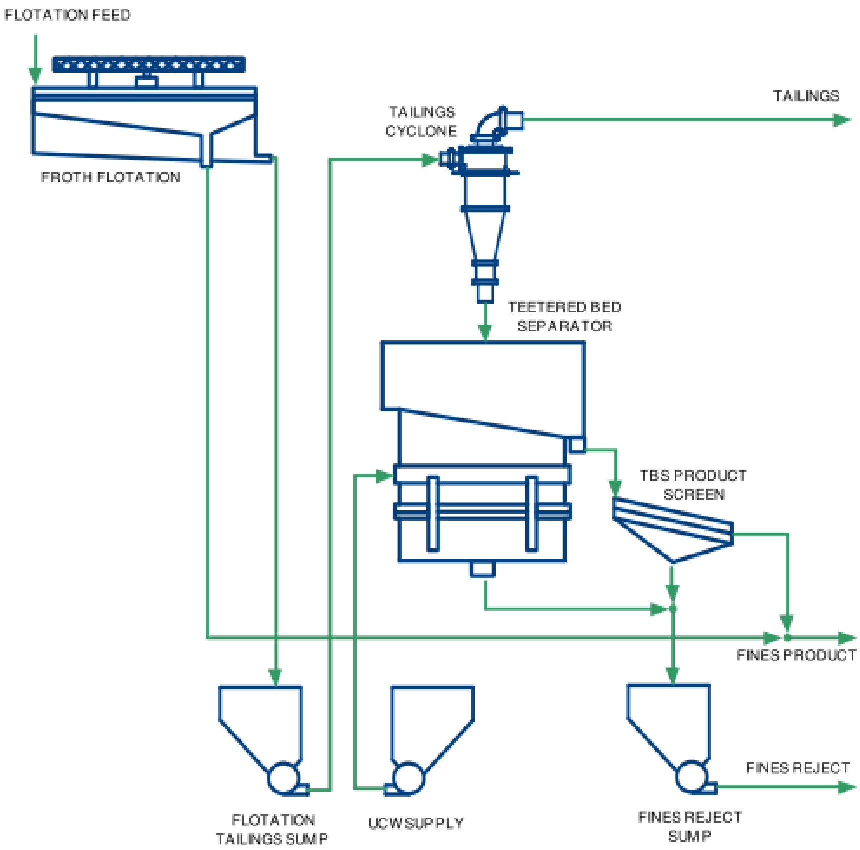

Figure 24. Suggested Flotation Tailings Re-Processing Flowsheet[5]

5 EXPERIMENTAL STUDIES AND RESULTS

5.1 Single density material

Experiments were carried out using a CrossFlow Density Separator of 2×8''Lab model. The setup consists of slurry tank with stirrer and sample container for collecting the products (underflow and overflow). Samples from overflow and underflow streams were collected at steady state. In order to analyze the dependence of process variables on classification performance, feed particles of a single density (pure calcite) were used to ensure the separation would be based on the particle size only. The feed size distribution is given in Figure 26. 80% of the material is coarser than 150 microns.

The experimental range studied is given in Table 2. For each experiment after attaining steady conditions, both products were collected, dried, weighed and their size distribution were determined. The size distribution of the samples are given in Appendix. Then, the results were used to determine cut size (D_{50}) and Efficiency (Ep Value).

In this study, SP is defined as used:

$$Set\ Point\ (SP)\% = 100 * \frac{P_{Set}}{P_{water}} - 100 \qquad (5.1)$$

P_{water} : Number read by the sensor when the device is filled with water only,

P_{set} : Number is set for the devices for opening and closing the valve.

Table 2. Statistically designed variables and their levels

Sl. no.	Variables	Low	Mid	High
1	Teeter water (lpm)	9	12	15
2	Set point (%)	11	28	44

5.1.1 Results and discussion

Statistically designed experiments were conducted with single replication and the obtained results are as in Table 3. The performance of the CrossFlow separator was evaluated in terms

Imperfection Index (I) and Ecart probable (Ep). They were calculated by using the following equations:

$$I = \frac{d_{75} - 7_{25}}{2d_{50}} \quad (5.2)$$

$$Ep = \frac{d_{75} - 7_{25}}{2} \quad (5.3)$$

It is observed that there is a significant change in performance with increase or decrease in all the studied parameters.

5.1.2 Effect of process variables on size separation/cut size (D50)

Effect of process variables on cut size of the CrossFlow density separator has been evaluated from the partition curve and the effect of teeter water and Set point has been given in figure 27.

a. Effect of Set point

Effect of set point on size separation at different teetered water has shown in figure 28. Figure 28 depicts the effect of set point at three teetered water rate (9, 12 and 15 lpm) on cut size (D50) which envisaged that with increase in the set point from 11% to 44%, there is an increase in the Size separation from 199 micron to 229 micron at lower teetered water rate (i.e.9 lpm), due to the increase in the bed height inside the column which shifts coarser material to the overflow fraction. At medium Teetered water rate (i.e.12 lpm), as there is an increase in the set point from 11% to 44%, the separation size shifts from 223 to253 micron which is shown in figure 28. At higher Teetered water rate (i.e.15 lpm), as there is an increase in the set point from 11% to 44%, the separation size shifts from 248 to 277 micron which is shown in figure 28. The shifting of the cut size with increase in the set point is due to the increase in the bed height (thickness of the bed formation) as well as bed pressure resulting in coarser particles reporting to the overflow stream thereby increasing the cut size of separation.

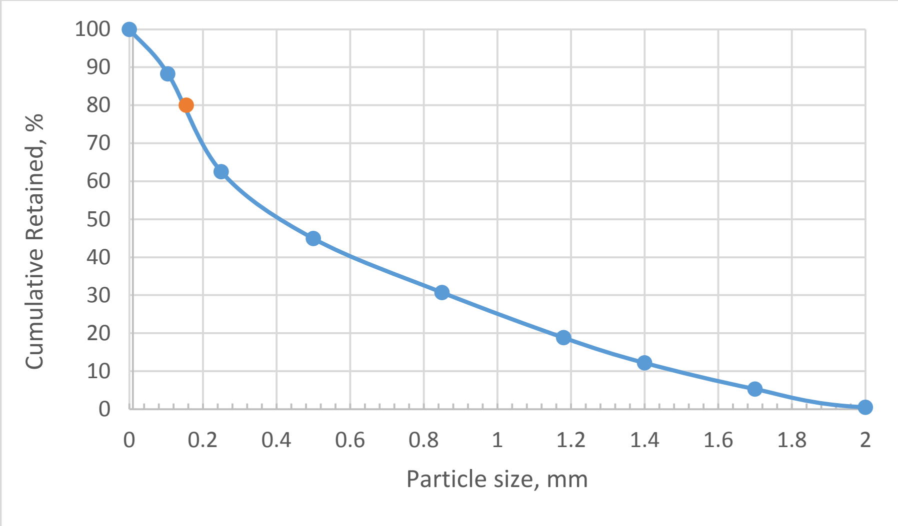

Figure 25. Size distribution of feed sample.

Table 3. Experimental results of CrossFlow density separator for calcite.

Test /No	TW(Lpm)	SP %	D50mm	D25mm	D75mm	I	EP
1	9	11	199.33	309.39	108.73	0.50334	*0.10033*
6	12	11	223.62	328.83	139.42	0.42352	0.09471
7	15	11	247.9	348.28	165.18	0.36931	0.09155
2	9	28	214.03	330.3	119.31	0.49289	0.10549
8	12	28	238.32	349.74	144.88	0.42981	0.10243
9	15	28	262.6	369.19	170.64	0.37805	0.09928
3	9	44	228.73	351.21	133.17	0.47662	0.10902
4	12	44	253.02	370.65	150.34	0.43537	0.11016
5	15	44	277.3	390.1	176.1	0.38587	0.107

b. Effect of teetered water

Effect of teetered water on size separation at different set point has shown in figure 28. Figure 28 depicts the effect of teetered water at three set point rate (11%, 28% and 44%) on cut size (D50) which envisaged that with increase in the teetered water from 9 to 15, there is an increase in the size separation from 199 micron to 248 micron. At lower set point rate (11%), due to the increase in the water velocity inside the column which shifts coarser material to the overflow fraction. At medium set point rate (i.e.28%), as there is an increase in the teetered water from 9 to 15 lpm, the separation size shifts from 214 to262 micron which is shown in figure 28. At higher set point rate (i.e.44%), as there is an increase in the set point from 9 to 15 lpm, the separation size shifts from 229 to 277 micron which is shown in figure 28.

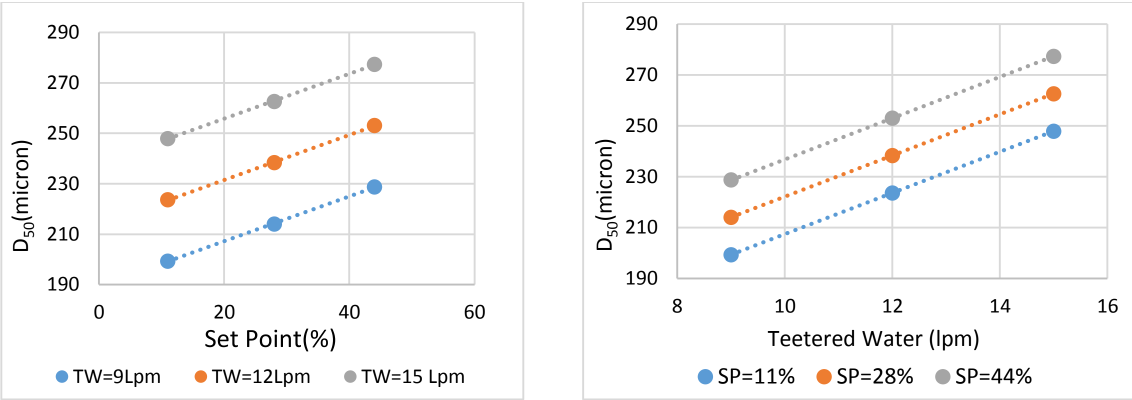

Figure 26. Effect of set point and teetered water flow rate on Cut Size for calcite

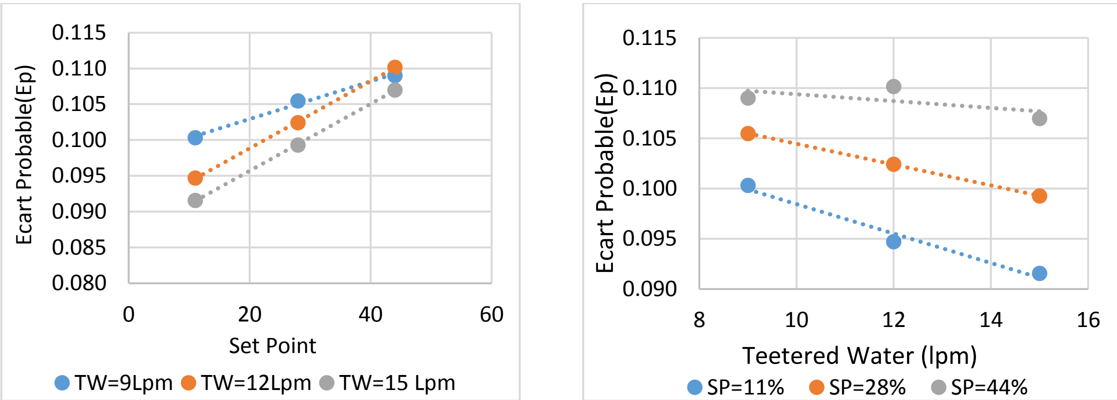

Figure 27. Effect of set point and teeter water flow rate on partition curve for calcite

5.1.3 Statistical analysis

The test results were analyzed to understand the effect of each variable, their interactional effects and the significant variables were ascertained through the use of statistics[13]. The results of the statistical analysis are presented in Table 3 and the main findings are described in the following sections.

a. Regression analysis

To predict and analyze the performance of FDS, multiple regression equations were developed by utilizing the obtained experimental results (Table 3). The equations for different responses are given below:

$$Cut\ Size\ (d_{50})\mu m = 117 + 0.891SP(\%) + 8.09TW(Lpm) \qquad (R^2{=}0.921) \qquad (5.4)$$

$$EP\ = 0.102 + 0.0004SP(\%) - 0.000945TW(Lpm) \qquad (R^2{=}0.908) \qquad (5.5)$$

It is observed that, the derived regression equations are in good agreement with the experimental value which is evident from the higher correlation coefficient (R^2).

b. Effect of main variables

From the ANOVA results (Table 4) it is observed that the teetered water has the maximum effect on separation size. By increasing the teetered water, superficial velocity increases at the separation zone due to which the coarser particle to report to over flow. From the ANOVA results (Table 5) it is observed that the set point has the maximum effect on EP.

Table 4. Two-way ANOVA: D50 versus SP, TW for calcite (single density materials).

SOURCE	DF	SUM OF SQAURE	MEAN SQAURE	F-VALUE	P
SP	2	0.0012965	0.0006483	2.71783E+14	0.000
TW	2	0.0035386	0.0017693	7.41762E+14	0.000
ERROR	4	0.0000000	0.0000000		
TOTAL	8	0.0048351			

Table 5. Two-way ANOVA: EP versus SP, TW for calcite (single density materials).

SOURCE	DF	SUM OF SQAURE	MEAN SQAURE	F- VALUE	P
SP	2	0.0002613	0.0001307	33.63	0.003
TW	2	0.0000484	0.0000242	6.23	0.059
ERROR	4	0.0000155	0.0000039		
TOTAL	8	0.0003253			

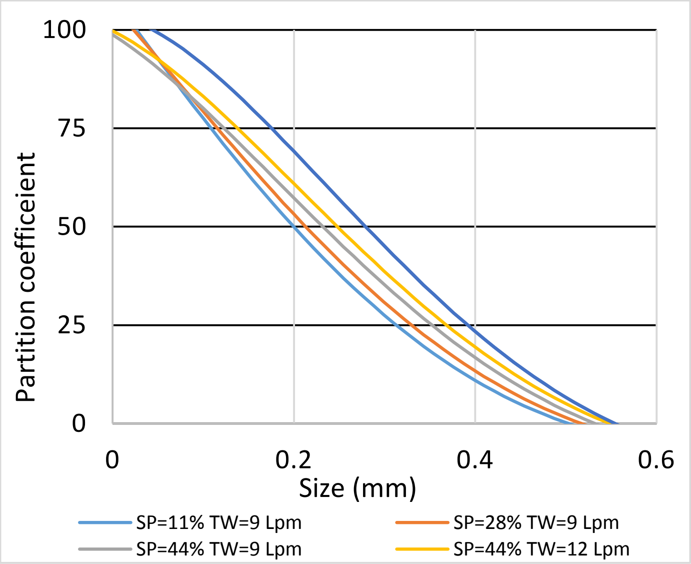

Figure 28. Performance curve for calcite (single density materials).

5.2 Tests at Dereköy Washing Plant in Soma Region

Initial field testing of the pilot-scale CrossFlow separator was conducted at Dereköy washing plant. This work involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the unit in order to predict the expected performance of a full- scale unit. Approximately 4 months of effort were allocated for field-testing.

5.2.1 Equipment Setup

With cooperation from the operators and mechanics at the plant, a 228.6x406.4mm pilot-scale CrossFlow separator was installed. A splitter-box was installed to collect the underflow of a hydrocyclone. This splitter was fully adjustable and allowed for the easy regulation of feed rates. The feed sample was conveyed by gravity through a 2 inch line to the CrossFlow separator that was positioned one level below the classifying cyclone. Underflow and overflow material from the separator was discharged to sizing screens in the plant, located on a level below the unit.

5.2.2 Shakedown Testing

After completing the installation of the test unit, preliminary shakedown testing was conducted to resolve any unexpected operational problems that could arise. These tests are normally necessary to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., are adequate. In addition, these tests provided an opportunity to establish approximate settings for the various process variables required to provide good separation performance based on visual inspections of the product streams.

5.2.3 Detailed Testing

Two series of detailed test programs were conducted using the pilot-scale CrossFlow. The first series of tests were performed to investigate the effects of the key design variables on separator performance. Important test variables included: feed injection depth and distributor design. In addition to determining the optimum operating variables, the first series of test simultaneously defined the overall grade and recovery curve for the process. The subsequent round of testing was used to investigate the effects of key operating parameters. The variables examined included: (i) fluidization water rate, (ii) solids mass feed rate, (iii) volumetric slurry feed rate, and (iv) teeter bed depth. A minimum of three settings were examined for each of the listed test parameters. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. Each sample was analyzed for ash and heating value (all cases on a size-by-size basis).

5.2.4 Feed characteristics

The samples were taken from Dereköy washing plant. These samples were nominally under 2.7 mm size. These were characterized in terms of their size distribution, size by size ash distribution table 6, washability, and release analyses. The size by size ash distributions of the average of 17 samples are shown in Table 7 and Figure 30.

Table 6. Feed size distribution, ash and heating value of size fractions for Soma coal.

Particle size (micron)	Weight (%)	Ash (%)	L.H.V.(kcal/kg)
+2000	2.91	38.82	3719
-2000 + 1000	11.75	27.89	4033
-1000 + 500	20.25	29.66	3813
-500 + 200	24.60	34.23	3343
-200 + 100	21.78	48.95	2573
-100	18.72	62.07	1555
Total	100.00	41.11	3027

Table 7. Size by Size Washabilities of Size Fractions for Soma

Density	200-500 (micron)			500-1000(micron)			1000-2000(micron)			+2000(micron)		
	Weight	Ash	LHV	Weight	Ash	LHV	Weight	Ash	LHV	Weight	Ash	LHV
(g/cm^3)	%	%	Kcal	%	%	Kcal	%	%	Kcal	%	%	Kcal
Float1.3	17.8	5.36	5314	28.57	4.51	5425	17.2	2.89	5811	17.5	4.09	5553
1.3×1.4	22.92	7.88	5091	16.3	6.64	5133	35.1	6.15	5282	16.5	7.66	5237
1.4×1.5	11.21	15.86	4556	8.72	12.7	4818	6.01	18.48	4753	5.42	23.8	3805
1.5×1.6	5.25	29.97	4016	4.22	21.5	4473	3.32	29.17	3828	3.31	31.7	2993
1.6×1.7	3.71	43.86	2756	3.83	34.2	3498	2.74	37.76	3183	3.96	52.4	1408
1.7×1.8	1.96	49.63	2001	3.01	41.3	2851	2.3	45.49	2749	2.9	43.9	2317
1.8×1.9	3.43	54.06	1893	3.62	50.7	2289	2.41	53.16	1809	3.42	52	1893
Sink1.9	33.73	70.14	235	31.73	65.8	344	31.4	62.94	366	47.1	62.4	260
T. Feed%	24.6	34.22		20.25	29.7		11.8	27.76		2.91	38.8	

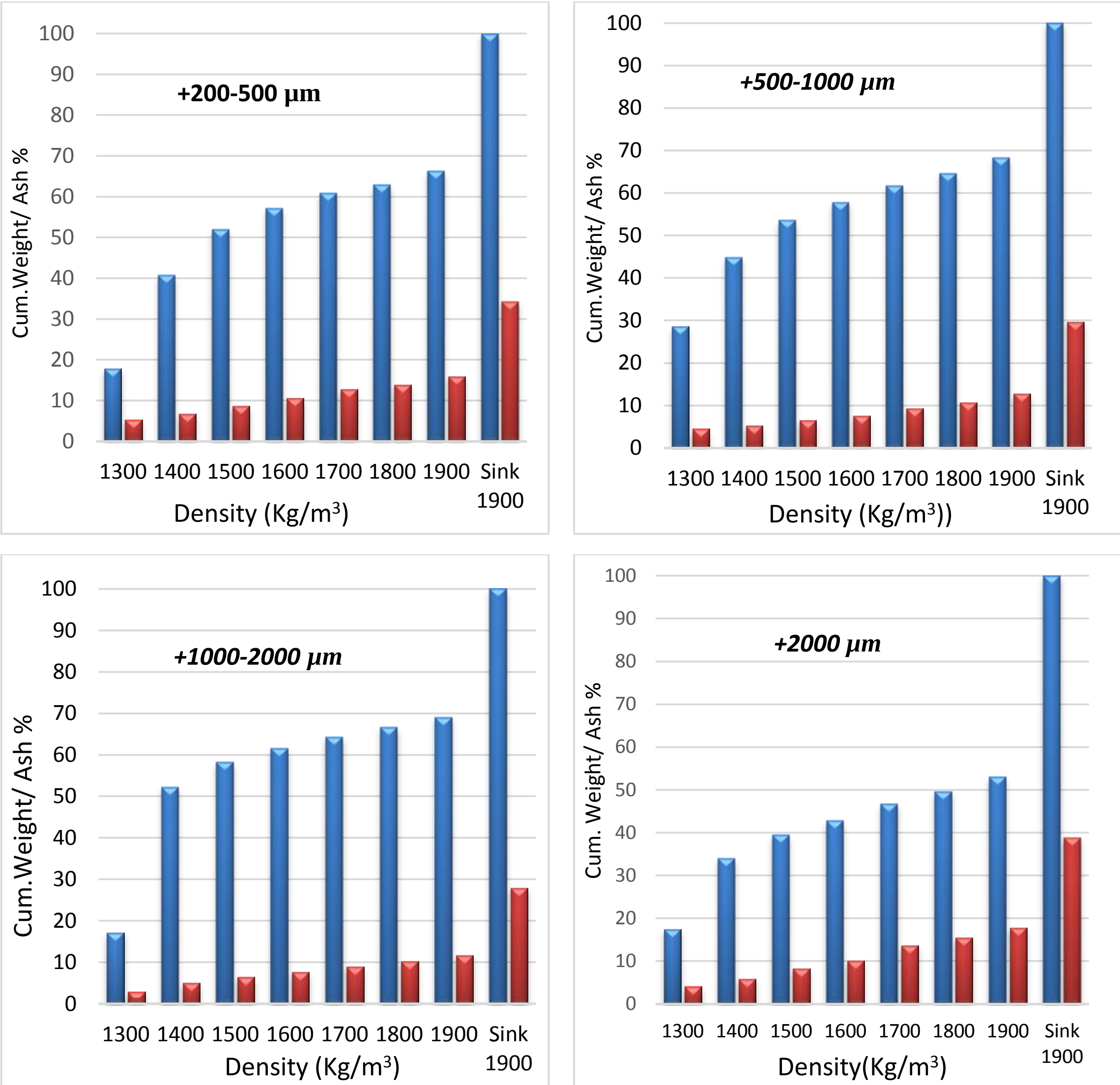

Figure 29. %Weight and Ash Contents of 200-500, *500-1000, 1000-2000 and +2000* µm Fractions (Soma Coal).

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5.2.5 Experimental Studies

Seventeen test campaigns were carried out using the pilot plant model crossflow at Soma washing plant as per the test conditions tabulated in Table 8. The operating conditions used involved a teeter water flow rate of 25-75 lpm, equivalent to a superficial velocity of 2.78-8.34 mm/s, and a set point relative density of 19%-52% were applied for the 2-4 hours. In addition the feed pulp density was around (25-32) % and clean coal (Overflow) pulp density was around 17.48w%. The size distributions of the samples are given in Appendices. Table 9 depicts the effect of different process variables on cut size (D50). The effect of set point and teeter water flow rate on EP value for each size shown in tables 10, 11. The effects of different variable on Yield to underflow, Recovery, Ash rejection and Efficiency for each size are shown in Tables 12, 13.

Table 8. Experimental conditions for Soma Tests

No	Bed pressure %	Teeter water flow rate lpm
T1	19	34
T2	23	34
T3	23	50
T4	29	50
T5	35	34
T6	35	50
T7	35	65
T8	41	25
T9	41	34
T10	41	50
T11	45	34
T12	45	75
T13	47	34
T14	50	25
T15	50	34
T16	50	42
T17	52	25

The performance of the CrossFlow separator was evaluated in terms of ash rejection and combustible recovery. They were calculated by using the following equations

$$Yield, Y\% = 100 * \frac{f-r}{c-r} \quad (5.1)$$

$$\text{Combustible Recovery, R}\ \% = 100\,\frac{(f-r)(100-c)}{(c-r)(100-f)} \quad (5.2)$$

$$Ash\ Rejection, J\% = 100 * \frac{(f-r)r}{(c-r)f} \quad (5.3)$$

$$Efficiency, \% = \frac{Y+J}{2} \quad (5.4)$$

Where, R represent the percentage of combustible matter in the feed that reports to clean coal, J represents the percentage of ash present in the feed that report to reject these important performance indicators can be calculated from the Ash content of the feed (f), clean coal (c) and refuse(r) streams using.

Table 9. Effect of different process variables on cut size (D_{50}) and Imperfection (I) for Soma tests

SP (%)	**TW (lpm)**	**D50** (micron)	**D75**(micron)	**D25**(micron)	**I**
35	42	2441	2480	2400	0.016
52	25	2376	2459	2130	0.069
47	34	2262	2421	1793	0.139
41	25	2241	2412	1776	0.142
29	50	2186	2395	1578	0.187
41	50	2071	2352	1359	0.240
45	75	2046	2346	1251	0.268
45	34	2043	2258	1703	0.136
23	34	1609	1900	1149	0.233
50	34	1441	2118	550	0.544
41	34	1383	1800	892	0.328
50	25	1250	1591	595	0.398
35	42	1229	2067	393	0.681
45	34	1177	2065	315	0.743
35	65	1047	1862	346	0.724
19	34	834	1614	318	0.777

Table 10. The effect of set point and teeter water flow rate on Yield, Recovery, Ash rejection and Efficiency for +200-500, +500-1000, 1000-2000 micron size(Soma coal).

SP (%)	TW (lpm)	SIZE (micron)	Feed		Over flow		Under flow		Yield %	Rec. %	Ash Rej. %	Efficiency %
			Ash	Kcal	Ash	Kcal	Ash	Kcal				
19	34	200-500	46.4	2942	41.1	3051	72.9	350	83.33	91.57	26.19	54.76
23	34	200-500	29.48	3721	26.06	4023	66.34	448	91.51	95.95	19.11	55.31
23	50	200-500	46.41	2623	40.22	3120	76.52	76	82.95	92.53	28.12	55.53
29	50	200-500	47.05	2378	38.77	3121	70.15	214	73.61	85.13	39.34	56.48
35	34	200-500	38.95	3252	32.21	3792	68.69	223	81.52	90.52	32.58	57.05
35	50	200-500	42.28	2825	33.66	3869	67.29	269	74.37	85.47	40.79	57.58
41	65	200-500	39.41	3177	31.57	3955	73.66	157	81.37	91.9	34.81	58.09
41	25	200-500	42.43	3016	37.41	3602	70.39	438	84.78	92.17	25.25	55.02
41	34	200-500	39.13	3179	37.3	3069	66.99	185	93.84	96.66	10.55	52.19
50	42	200-500	29.89	4085	26.01	4421	68.36	184	90.84	95.87	20.95	55.9
52	23	200-500	68.36	184	41.37	3003	74.54	117	18.63	34.52	88.72	53.68
19	34	500-1000	32.07	3663	29.66	3806	68.05	433	93.72	97.05	13.32	53.52
23	34	500-1000	26.41	3853	14.48	4943	55.67	1026	71.04	82.55	61.05	66.04
23	50	500-1000	37.84	3186	25.25	4303	64.85	363	68.21	82.02	54.49	61.35
29	50	500-1000	37.89	3017	23.6	4298	62.75	491	63.5	78.11	60.45	61.97
35	34	500-1000	28.71	4157	26.34	4429	62.18	469	93.39	96.49	14.32	53.85
35	50	500-1000	35.45	3377	22.8	4713	60.39	439	66.35	79.35	57.33	61.84
41	65	500-1000	36.23	3445	23.4	4781	63.4	359	67.93	81.59	56.13	62.03
41	25	500-1000	39.02	3203	29.45	4342	62.68	681	71.2	82.37	46.26	58.73
41	34	500-1000	42.92	2726	35.55	3417	61.08	404	71.13	80.32	41.08	56.11
45	75	500-1000	36.23	3445	32.48	3606	65.35	252	88.59	93.8	20.58	54.58
47	34	500-1000	31.7	4035	25.6	4604	66.82	207	85.2	92.81	31.19	58.2
50	25	500-1000	31.77	4143	17.87	5377	66.07	254	71.16	85.66	59.97	65.57
50	42	500-1000	27.2	4282	21.76	4822	61.39	215	86.27	92.72	30.98	58.63
19	34	1000-2000	41.57	4060	19.5	4583	45.19	2417	14.08	19.39	93.4	53.74
23	34	1000-2000	27.4	3801	13.46	5042	45.75	2057	56.83	67.74	72.08	64.46
23	50	1000-2000	30.65	3873	16.87	5024	60.41	584	68.35	81.93	62.38	65.37
29	50	1000-2000	33.87	3241	13.62	5040	57.8	1022	54.16	70.75	78.22	66.19
35	34	1000-2000	24.94	4522	18.23	5232	58.1	968	83.17	90.61	39.21	61.19
35	50	1000-2000	36.29	3348	25.19	4635	56.3	785	64.32	75.53	55.35	59.84
41	65	1000-2000	33.98	3641	21.5	5042	58.84	660	66.58	79.16	57.87	62.23
41	25	1000-2000	37.32	3250	19.27	5213	57.68	1173	53.01	68.27	72.63	62.82
41	34	1000-2000	45.16	2258	28.54	4059	59.89	463	46.99	61.23	70.31	58.65
45	34	1000-2000	37.32	3250	25.11	4069	61.84	445	66.76	79.76	55.08	60.92
45	75	1000-2000	45.16	25	25.35	4281	65.6	210	50.78	69.13	71.49	61.14
47	34	1000-2000	33.33	3923	23.07	4919	64.36	371	75.15	86.72	47.98	61.57
50	25	1000-2000	27.22	4584	11.51	5921	63.98	376	70.06	85.18	70.38	70.22
50	42	1000-2000	20.68	4945	14.74	5527	58.49	343	86.42	92.89	38.4	62.41

Table 11. The effect of set point and teeter water flow rate on Yield, Recovery, Ash Rejection and Efficiency for +2000mic size (Soma coal).

SP (%)	TW (lpm)	Size (micron)	Feed		Over flow		Under flow		Yield %	Rec. %	Ash Rej %	Efficiency %
			Ash%	Kcal	Ash%	Kcal	Ash%	Kcal				
19	34	+2000	31.93	3594	24.93	4204	39.71	2909	52.64	58.05	58.90	55.77
23	50	+2000	31.53	3597	9.05	5838	56.68	840	52.80	70.14	84.84	68.82
29	50	+2000	33.64	3267	7.15	5515	51.25	1650	39.93	55.87	91.51	65.72
35	34	+2000	29.75	3934	6.12	6409	52.64	1309	49.20	65.76	89.88	69.54
35	50	+2000	39.36	2889	10.51	5995	48.88	1433	24.81	36.62	93.37	59.09
41	65	+2000	27.83	4261	13.10	5799	55.56	870	65.31	78.64	69.26	67.28
41	25	+2000	38.74	3025	10.94	5872	57.41	1188	40.18	58.41	88.65	64.42
41	34	+2000	45.68	2235	10.39	5982	57.01	790	24.30	40.09	94.47	59.39
45	75	+2000	45.68	2235	21.66	4721	61.29	491	39.39	56.81	81.32	60.36
50	25	+2000	28.55	4341	9.49	6146	62.24	478	63.87	80.90	78.77	71.32
50	42	+2000	27.13	4359	8.87	6047	55.71	590	61.02	76.31	80.05	70.53
52	25	+2000	55.71	590	22.21	4331	62.25	356	16.33	28.69	93.49	54.91

Table 12. The effect of set point and teeter water flow rate on EP value for +200-500 and 500-1000 micron size (Soma)

SP (%)	TW(lpm)	SIZE(μm)	ρ_{50}(kg/cm^3)	ρ75(kg/cm^3)	ρ25(kg/cm^3)	Ep	O/f
19	34	200-500	1850	1911	1844	0.03	
23	34	200-500	1687	1780	1568	0.11	
23	50	200-500	2100	2300	1900	0.2	0.91
29	50	200-500	1884	1944	1772	0.09	0.83
35	34	200-500	2040	2280	1880	0.2	0.86
35	50	200-500	2120	2310	1925	0.19	0.93
35	65	200-500	1990	2240	1840	0.2	0.83
41	25	200-500	2080	2260	1850	0.21	0.92
41	34	200-500	1960	2220	1860	0.18	0.81
41	50	200-500	1940	2190	1840	0.18	0.76
45	34	200-500	2040	2260	1850	0.21	0.88
45	75	200-500	2000	2280	1880	0.2	0.93
47	34	200-500	2180	2200	2030	0.16	0.99
50	25	200-500	2180	2330	2040	0.15	0.99
50	34	200-500	1920	2180	1840	0.17	0.84
50	42	200-500	1960	2210	1840	0.19	0.98
52	25	200-500	2160	2320	1920	0.2	0.95
19	34	500-1000	1754	1908	1574	0.17	
23	34	500-1000	1631	1739	1501	0.12	
23	50	500-1000	1882	1896	1844	0.03	0.72
29	50	500-1000	1785	1900	1623	0.14	0.62
35	34	500-1000	1897	1912	1855	0.03	0.83
35	50	500-1000	1900	2180	1830	0.18	0.84
35	65	500-1000	1866	1899	1798	0.05	0.71
41	25	500-1000	1880	2160	1840	0.16	0.84
41	34	500-1000	1801	1899	1652	0.12	0.63
41	50	500-1000	1887	1896	1857	0.02	0.57
45	34	500-1000	1910	2180	1840	0.17	0.86
45	75	500-1000	1960	2240	1850	0.2	0.82
47	34	500-1000	1860	2060	1840	0.11	0.85
50	25	500-1000	1860	2040	1830	0.11	0.79
50	34	500-1000	1888	1896	1862	0.02	0.57
50	42	500-1000	1896	1908	1876	0.02	0.87
52	25	500-1000	2080	2280	1890	0.2	0.93

Table 13. The effect of set point and teeter water flow rate on EP value for +1000-2000 and +2000 micron size (Soma).

SP (%)	TW(lpm)	SIZE(μm)	ρ_{50}(kg/cm^3)	ρ75(kg/cm^3)	ρ25(kg/cm^3)	Ep	O/f
23	34	1000-2000	1422	1551	1317	0.12	
23	50	1000-2000	1622	1749	1484	0.13	0.59
29	50	1000-2000	1516	1650	1369	0.14	0.44
35	34	1000-2000	1649	1790	1491	0.15	0.53
35	50	1000-2000	1794	1863	1666	0.1	0.62
35	65	1000-2000	1666	1796	1520	0.14	0.63
41	25	1000-2000	1840	1890	1680	0.11	0.73
41	34	1000-2000	1614	1850	1442	0.2	0.48
41	50	1000-2000	1605	1751	1446	0.15	0.39
45	34	1000-2000	1843	1892	1738	0.08	0.76
45	75	1000-2000	1860	1880	1840	0.02	0.69
47	34	1000-2000	1840	1897	1830	0.03	0.78
50	25	1000-2000	1423	1567	1312	0.13	0.78
50	34	1000-2000	1857	1886	1785	0.05	0.56
50	42	1000-2000	1876	1894	1823	0.04	0.79
52	25	1000-2000	1841	1896	1734	0.08	0.88
29	50	+2000	1320	1432	1249	0.09	
41	50	+2000	1475	1544	1393	0.08	
52	25	+2000	1829	1881	1724	0.08	

5.3 Tests at Ömerler Washing Plant in Tunçbilek Region

Initial field testing of the pilot-scale CrossFlow separator was conducted at Ömerler washing plant. This work involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the unit in order to predict the expected performance of a full- scale unit. Approximately 3 months of effort were allocated for field-testing. Because the trial process was same at Dereköy washing plant repeat the steps(i) equipment setup, (ii) shakedown testing, and (iii) detailed testing described 5.2 section be avoided.

5.3.1 Feed characteristics

In the present study Kütahya coal is used as the raw material. For computational purpose, the required feed characteristics are in terms of size distribution and size by size density distribution of the particulate system. In order to compute the grade of the products, distribution of assay values is also required, which is simply the washability data. This assumption will be valid only if the intervals are narrow. However, in practice the data are evaluated only at a few widely spaced density values[4]. The generated set of data is then used as input data. Similarly, the additional intermediate grade distribution data, as a function of particle size and density, are generated using the interpolation.

To study the effect of size distribution on the performance of the CrossFlow, computations are performed for three types of feed: +1000 micron size, -1000+600 micron size and 600+250 micron size. Size distributions, size by size ash distributions and washability analysis of the above three types of feed were obtained experimentally and are presented in table 14, and figure 31 respectively.

Table 14. Float–Sink Test Results of Tuncbilek Coal +250-2000 micron.

Gravity range	250-600 (micron)		600-1000(micron)		+1000(micron)	
(g/cm^3)	Weight (%)	Ash (%)	Weight (%)	Ash (%)	Weight (%)	Ash (%)
Float 1.3	41.7	16	44.2	10.78	40.6	9.93
1.30x1.40	13.3	25.92	9.4	16.04	9.9	17.29
1.40x1.50	6.5	41.75	5.4	30.53	5.5	28.93
1.50x1.60	4.8	50.64	5.7	42.23	5.4	40.12
1.60x1.70	4.2	58.09	5.4	51.42	4.9	47.73
1.70x1.80	4.1	64.63	3.9	58.57	4.3	54.29
1.80x1.90	2.6	68.13	4.7	64.73	5.4	64.68
Sink 1.9	22.8	76.46	21.2	76.76	24	74.62

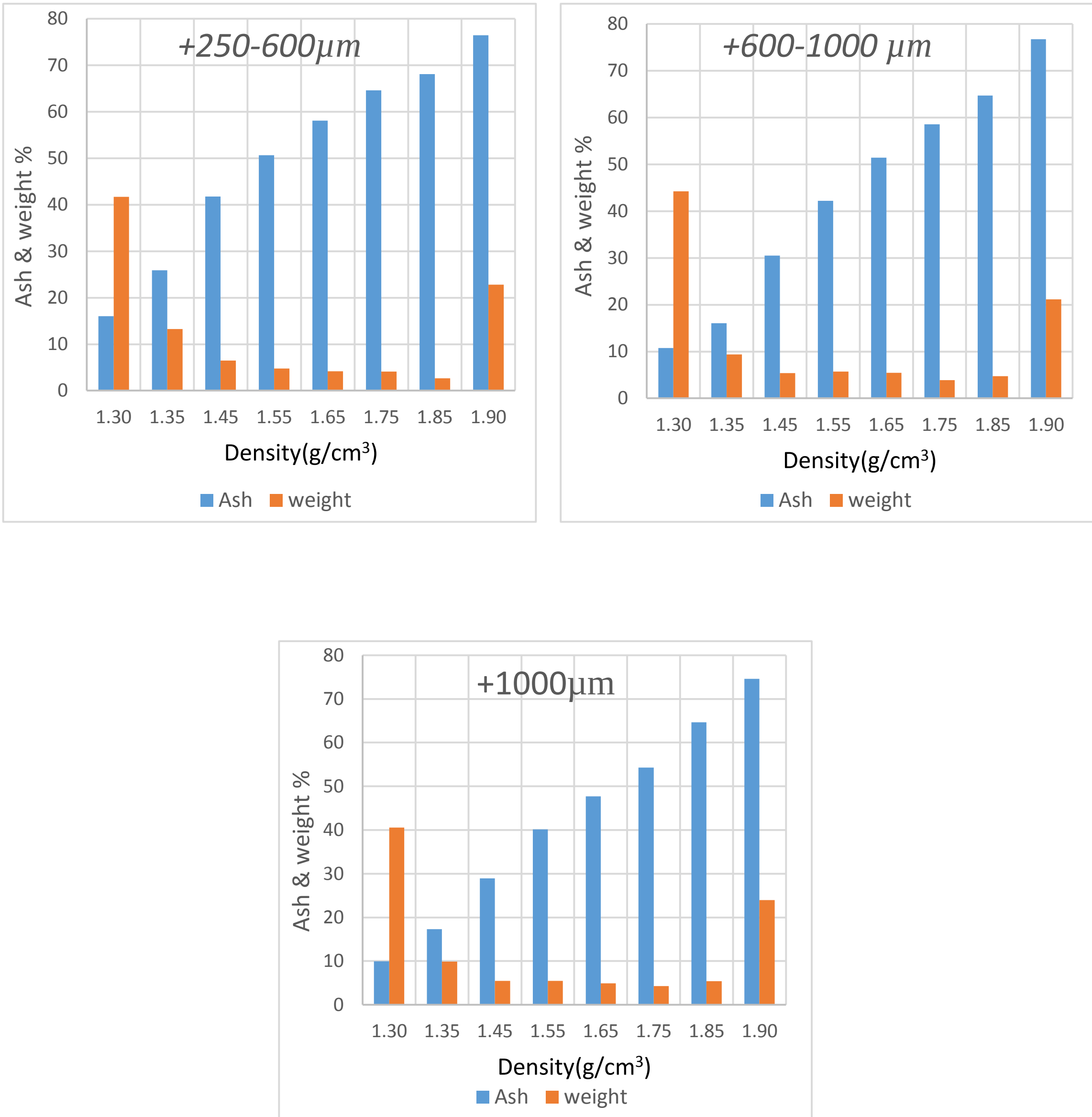

Figure 30 Ash Content & Lower Heating value (Kcal) Distribution for +250-600, +600-1000 and +1000 micron (Tunçbilek coal)

5.3.2 Experimental Studies

Nine test campaigns were carried out using the pilot plant model CrossFlow at Ömerler washing plant as per the test conditions tabulated in Table 15. The operating conditions used involved a teeter water flow rate of 17-41 lpm, equivalent to a superficial velocity of 2-4.6 mm/s, and a set point relative density of 19%-52% were applied for the 2-4 hours. In addition the feed pulp density was around (25-32) % and clean coal (Overflow) pulp density was around 17.48w%. The size distributions of the samples are given in Appendices. To study the effect of size distribution on the performance of the CrossFlow, computations are performed for three types of feed: +1000 micron size, -1000+600 micron size and 600+250 micron size. Size distributions, size by size Ash distributions and washability analysis of the above three types of feed were obtained experimentally and are presented in Table 16, and Table 17 respectively.

Table 15. Experimental conditions for Ömerler Tests

Test	NO	1	2	3	4	5	6	7	8	9
SP	%	34	28	23	23	44	34	40	34	28
TW	lpm	29	23	23	29	29	23	17	41	41

Table 16. The effect of set point and teeter water flow rate on Yield, Recovery, Ash rejection and Efficiency for +250-600, 600-1000 and +1000 micron (Tunçbilek coal).

SP	TW	Size	Ash %			Yield	Recovery	Ash Rej	Efficiency	S.E
%	lpm	micron	Feed	Overflow	Underflow	%	%	%	%	%
23	23	250-600	32.74	25.9	70.64	84.73	93.33	32.95	58.84	26.29
28	23	250-600	31.99	27.06	72.92	89.26	95.72	24.49	56.87	20.21
23	41	250-600	35.92	27.56	77.22	83.16	94.01	36.19	59.68	30.21
23	29	250-600	35.92	27.56	77.22	83.16	94.01	36.19	59.68	30.21
34	29	250-600	34.36	28.8	75.33	88.05	95.51	26.2	57.12	21.71
28	41	250-600	35.48	29.25	75.91	86.66	95.02	28.55	57.6	23.57
34	23	250-600	34.23	30.98	75.8	92.75	97.33	16.06	54.4	13.39
34	41	250-600	39.15	31.47	76.64	82.99	93.47	33.29	58.14	26.76
40	17	250-600	37.19	31.96	80.65	89.25	96.69	23.31	56.28	20
44	29	250-600	36.92	32.99	81.64	91.93	97.65	17.85	54.89	15.5
34	29	600-1000	31.26	19.54	64.46	73.9	86.5	53.83	63.86	40.33
23	23	600-1000	31.94	20.14	67.03	74.82	87.8	52.83	63.83	40.63
28	23	600-1000	30.03	20.5	67.09	79.54	90.37	45.71	62.62	36.09
23	29	600-1000	33.62	21.19	70.38	74.75	88.73	52.87	63.81	41.61
34	41	600-1000	36.16	22.6	71.43	72.23	87.57	54.86	63.54	42.43
40	17	600-1000	38.15	24.55	76.94	74.05	90.32	52.33	63.19	42.66
34	23	600-1000	32.01	25.22	72.75	85.72	94.28	32.45	59.09	26.73
44	29	600-1000	36.06	26.19	73.61	79.19	91.41	42.48	60.84	33.89
28	41	600-1000	36.84	27.65	66.7	76.47	87.59	42.61	59.54	30.2
34	29	1000	32.37	15.52	67.9	67.83	84.73	67.47	67.65	52.2
28	23	1000	29.47	15.63	63.06	70.82	84.72	62.44	66.63	47.16
23	23	1000	27.29	16.1	60.89	75.01	86.56	55.77	65.39	42.32
23	29	1000	29.7	17.14	70.78	76.6	90.27	55.79	66.19	46.06
44	29	1000	29	18.98	67.24	79.24	90.42	48.14	63.69	38.56
34	23	1000	28.83	20.74	69.97	83.57	93.07	39.88	61.73	32.95
40	17	1000	40.92	22.16	70.38	61.08	80.48	66.94	64.01	47.42
34	41	1000	35.12	22.85	67.25	72.36	86.04	52.93	62.64	38.97
28	41	1000	36.62	26.26	60.12	69.41	80.75	50.23	59.82	30.98

Table 17. The effect of set point and teeter water flow rate on EP value for +250-600, 600-1000 and +1000 micron(Tunçbilek coal).

SP	TW	Size	P50	P25	P75	EP	O/f	U/f
%	lpm	micron	Kg/m^3	Kg/m^3	Kg/m^3			
23	23	250-600	1760	1950	1505	0.22	0.85	0.15
23	29	250-600	1805	1985	1645	0.17	0.64	0.36
23	41	250-600	1850	2050	1600	0.23	0.7	0.3
28	23	250-600	1885	2050	1695	0.18	0.76	0.24
28	41	250-600	1915	2110	1650	0.23	0.71	0.29
34	23	250-600	1780	2120	1835	0.14	0.89	0.11
34	29	250-600	1860	1980	1725	0.13	0.87	0.13
34	41	250-600	1925	2080	1750	0.17	0.67	0.33
40	17	250-600	1900	2075	1700	0.19	0.77	0.23
44	29	250-600	1925	2020	1825	0.1	0.82	0.18
23	23	600-1000	1500	1690	1370	0.16	0.75	0.25
23	29	600-1000	1705	1845	1575	0.14	0.47	0.53
23	41	600-1000	1610	1860	1450	0.21	0.45	0.55
28	23	600-1000	1735	1890	1575	0.16	0.54	0.46
28	41	600-1000	1775	1970	1470	0.25	0.57	0.43
34	23	600-1000	1810	1935	1660	0.14	0.74	0.26
34	29	600-1000	1750	1860	1635	0.11	0.76	0.24
34	41	600-1000	1785	1915	1650	0.13	0.45	0.55
40	17	600-1000	1745	1890	1605	0.14	0.48	0.52
44	29	600-1000	1735	1960	1695	0.13	0.58	0.42
23	23	1000	1415	1625	1315	0.16	0.75	0.25
23	29	1000	1505	1665	1450	0.11	0.44	0.56
23	41	1000	1565	1760	1405	0.18	0.47	0.53
28	23	1000	1670	1415	128	0.38	0.62	0.62
28	41	1000	1565	1910	1370	0.27	0.5	0.5
34	23	1000	1580	1835	1410	0.21	0.61	0.39
34	29	1000	1525	1625	1420	0.1	0.69	0.31
34	41	1000	1695	1835	1555	0.14	0.47	0.53
40	17	1000	1620	1760	1495	0.13	0.33	0.67
44	29	1000	1690	1830	1545	0.14	0.52	0.48

6 DISCUSSION

6.1 Effect of Operating Parameters

a. The Effect of Particle Size

An example of partition curves of different size fractions for Soma coal is shown in Figure 32. As seen from the figure increasing size from 200 micron to +2000 micron decrease cut density (ρ50) from 1.72 to1.47.

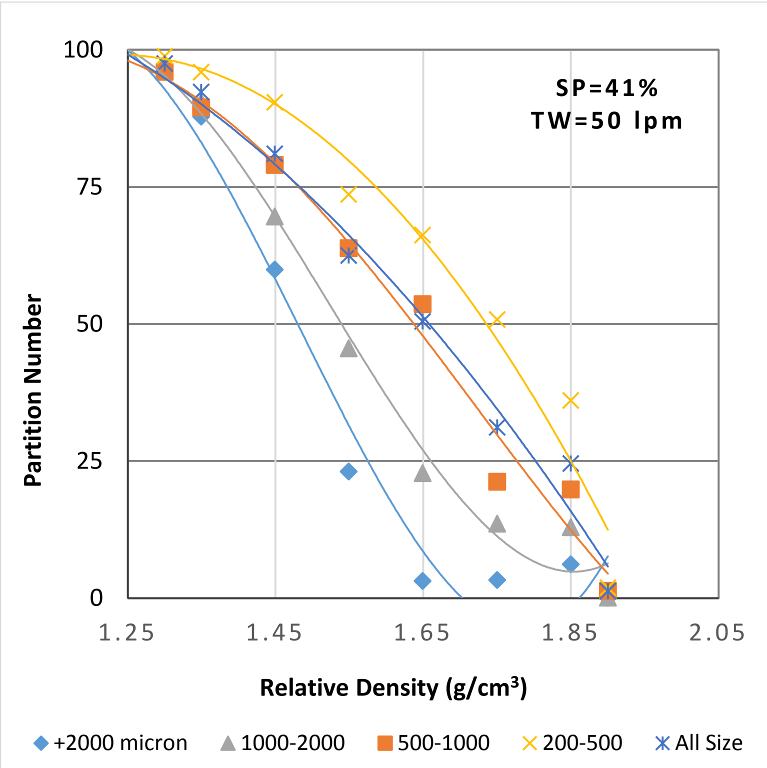

Figure 31. Partition curves for different size fractions (SP=41%, TW=50 lpm) , Soma

As somewhat expected, Ep decreased with increasing particle size. This is demonstrated in Figure 33. For the particles coarser than 2mm the Ep value was found be comparable with Dense Medium Cyclone (DMC).

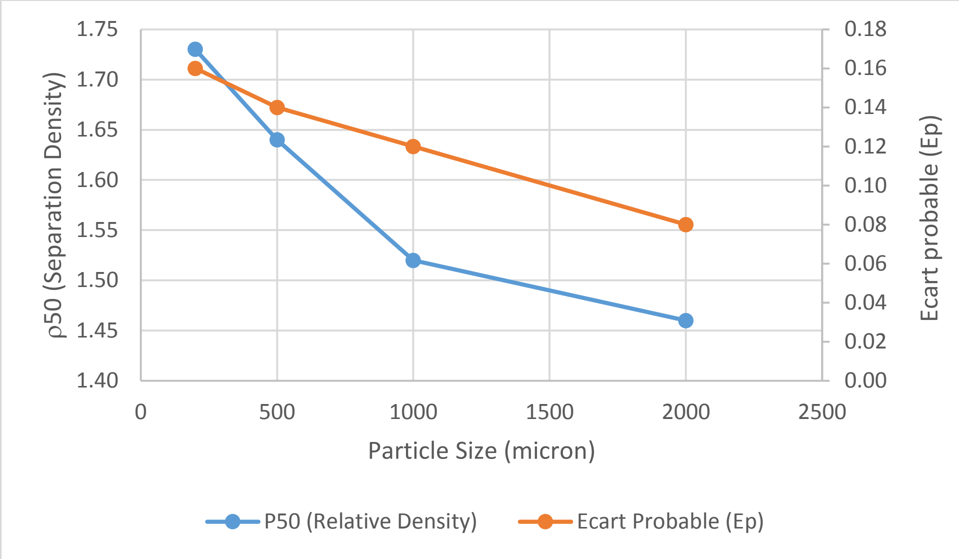

Figure 32. Variation of separation density and Ep with particle size (SP=41%, TW=50lpm) Soma.

Partition curves for different operating conditions are shown in Figures 34, 35 and 36 for Tunçbilek data. The curves of different size fractions followed the same order that the coarsest size fraction has the lowest curve. However, the absolute values change as SP and TW changes.

Considering dense media effects and teeter water contribution, the forces acting on individual particles is different, this is somewhat expected and observed by other researchers[1],[12] and[26]. Therefore, size distribution of the feed has an important effect on product quality. Any attempt to quantify density separation in TBS should be in size by size basis.

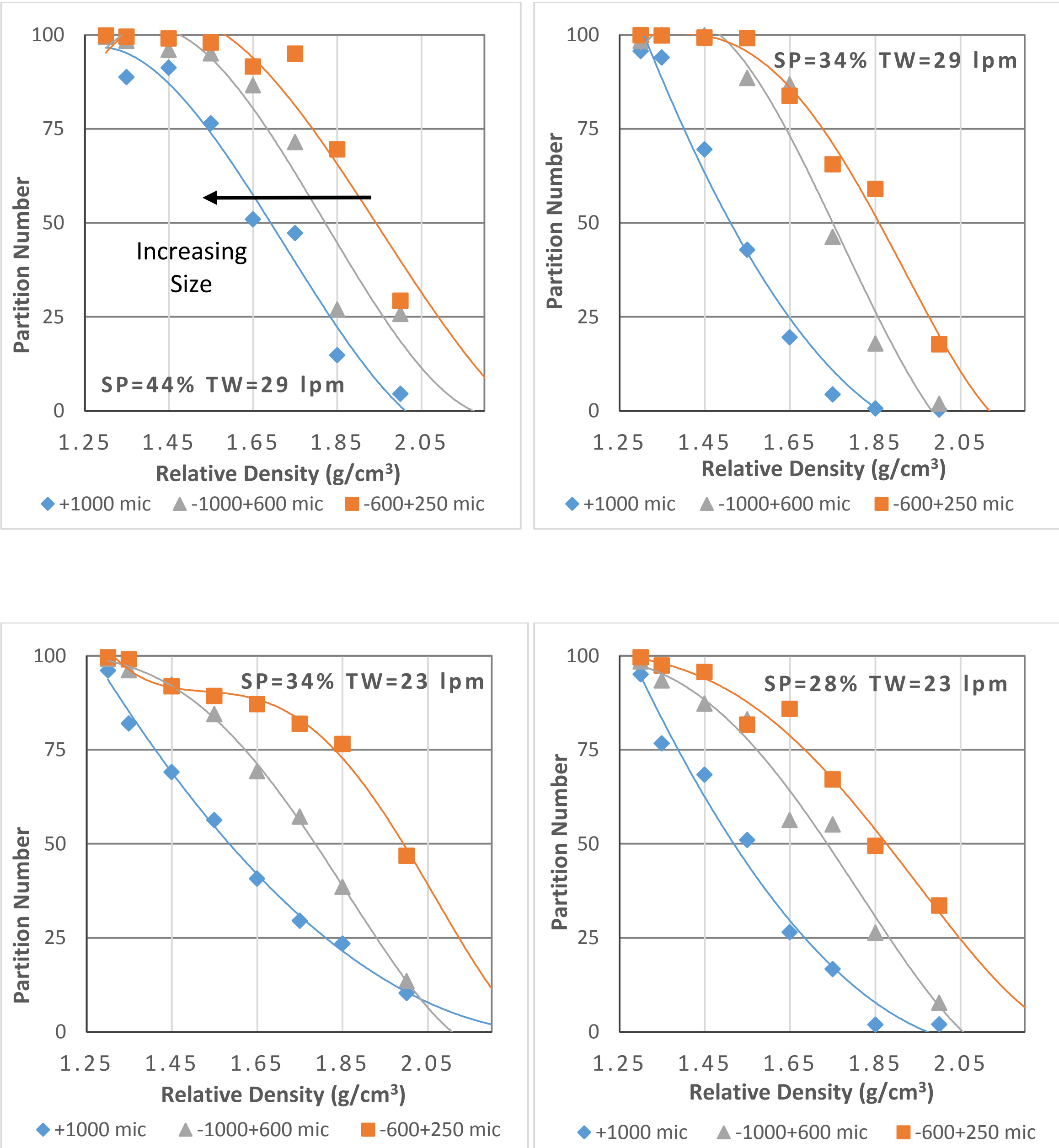

Figure 33. Partition curves for different size fractions (Tunçbilek data).

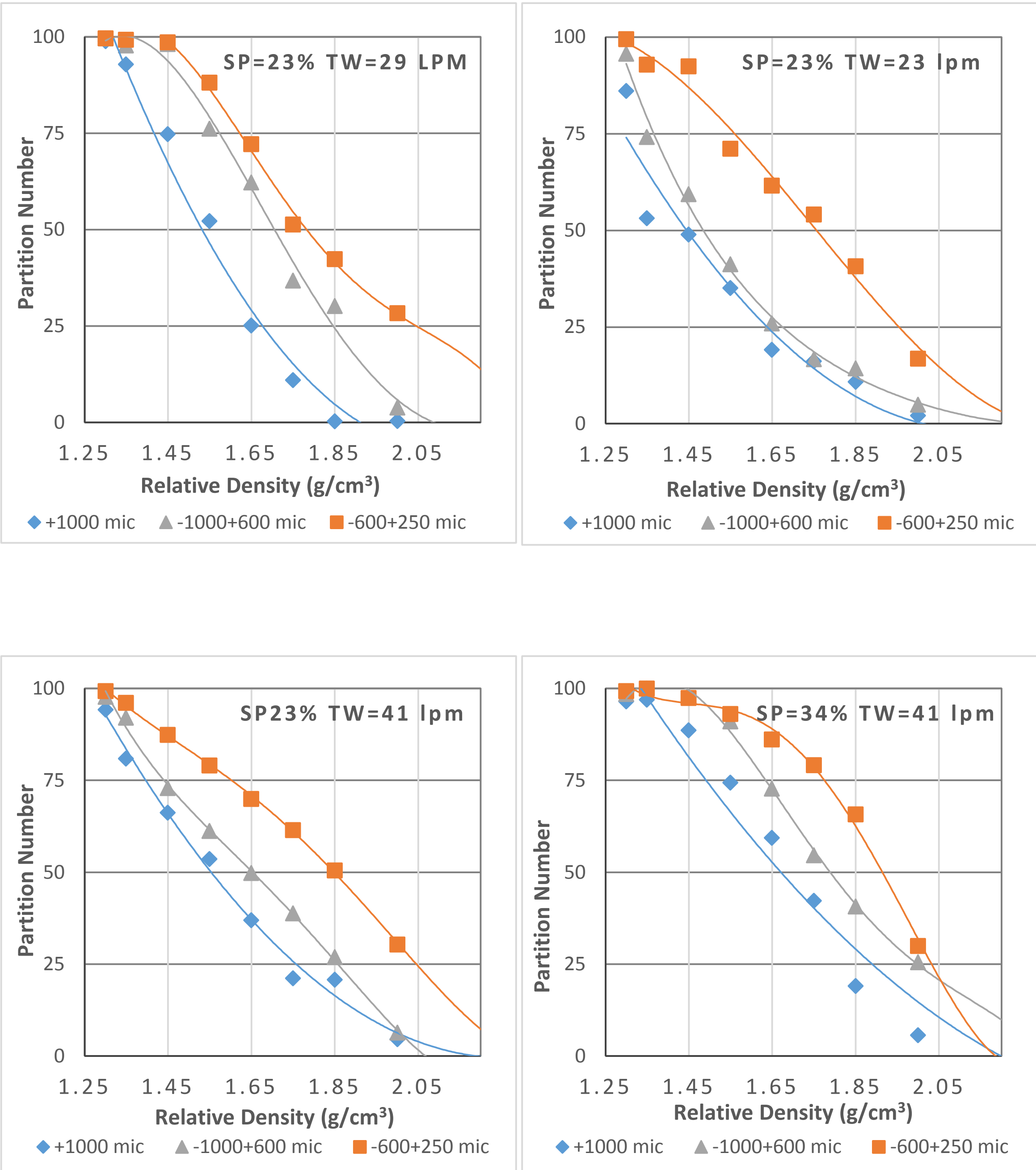

Figure 34. Partition curves for different size fractions (Tunçbilek data).

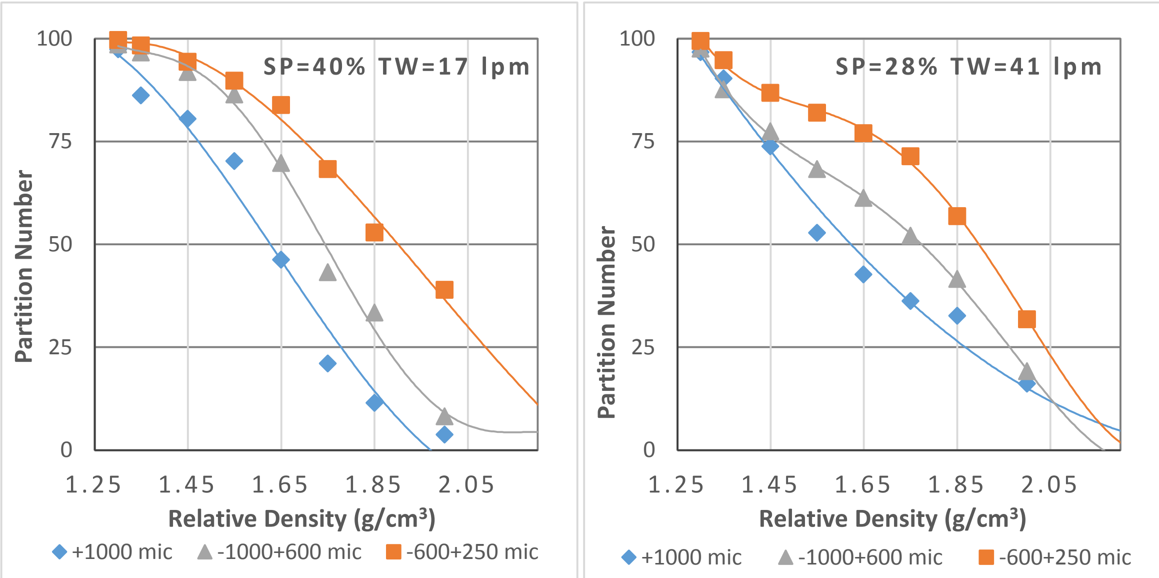

Figure 35. Partition curves for different size fractions (Tunçbilek data).

b. Set Point effect

Separation performance curves for the CrossFlow separator for various set points are shown in Figures. 37-39. Cut density (ρ_{50}) increases with increasing bed pressure as well as the teeter water flowrate. It is evident that there is an optimum bed pressure, feed size and an optimum teeter water rate for proper operation of the CrossFlow separator.

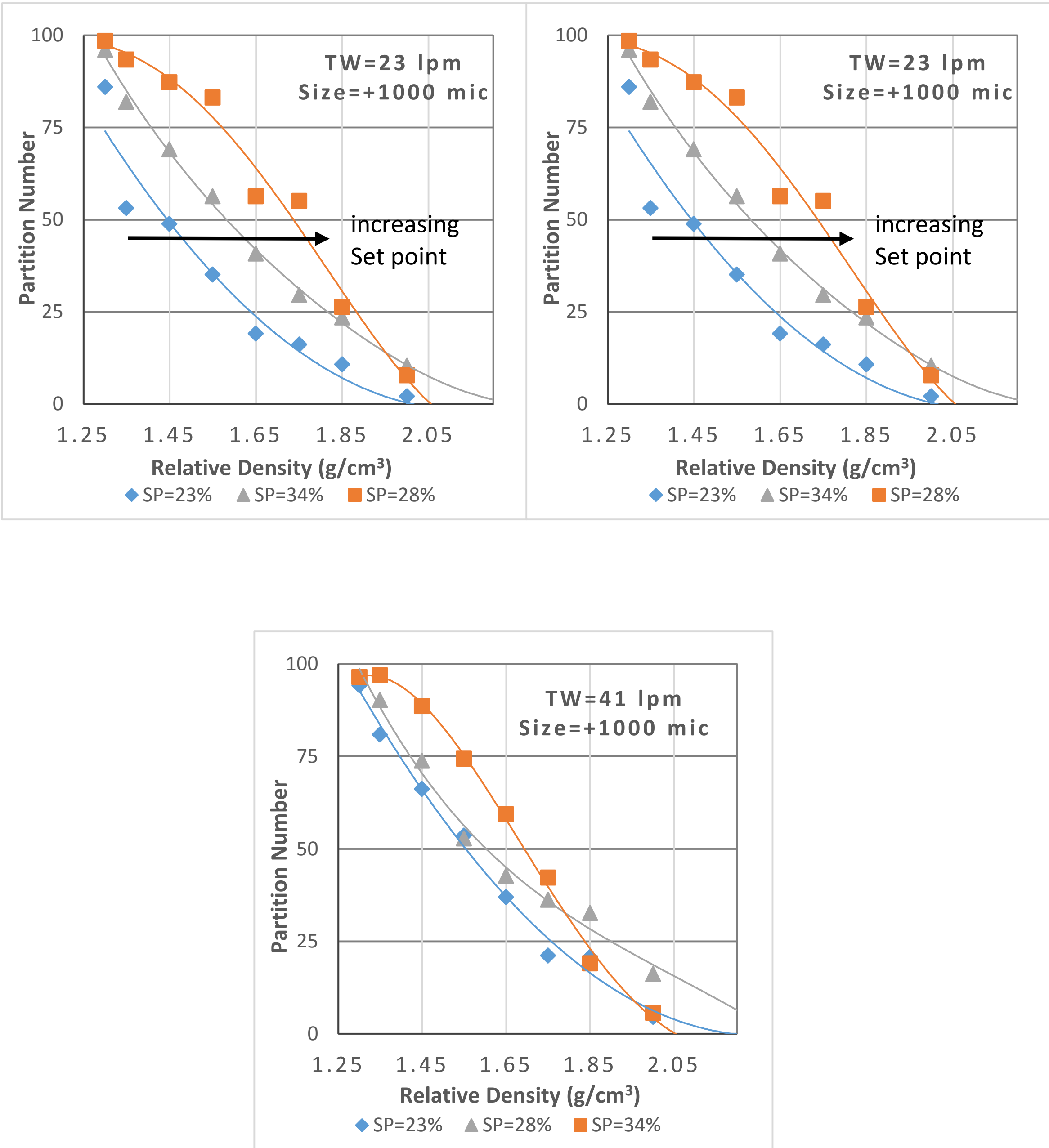

Figure 36. Partition curves for +1000 µm size fraction for varying TW (Tunçbilek).

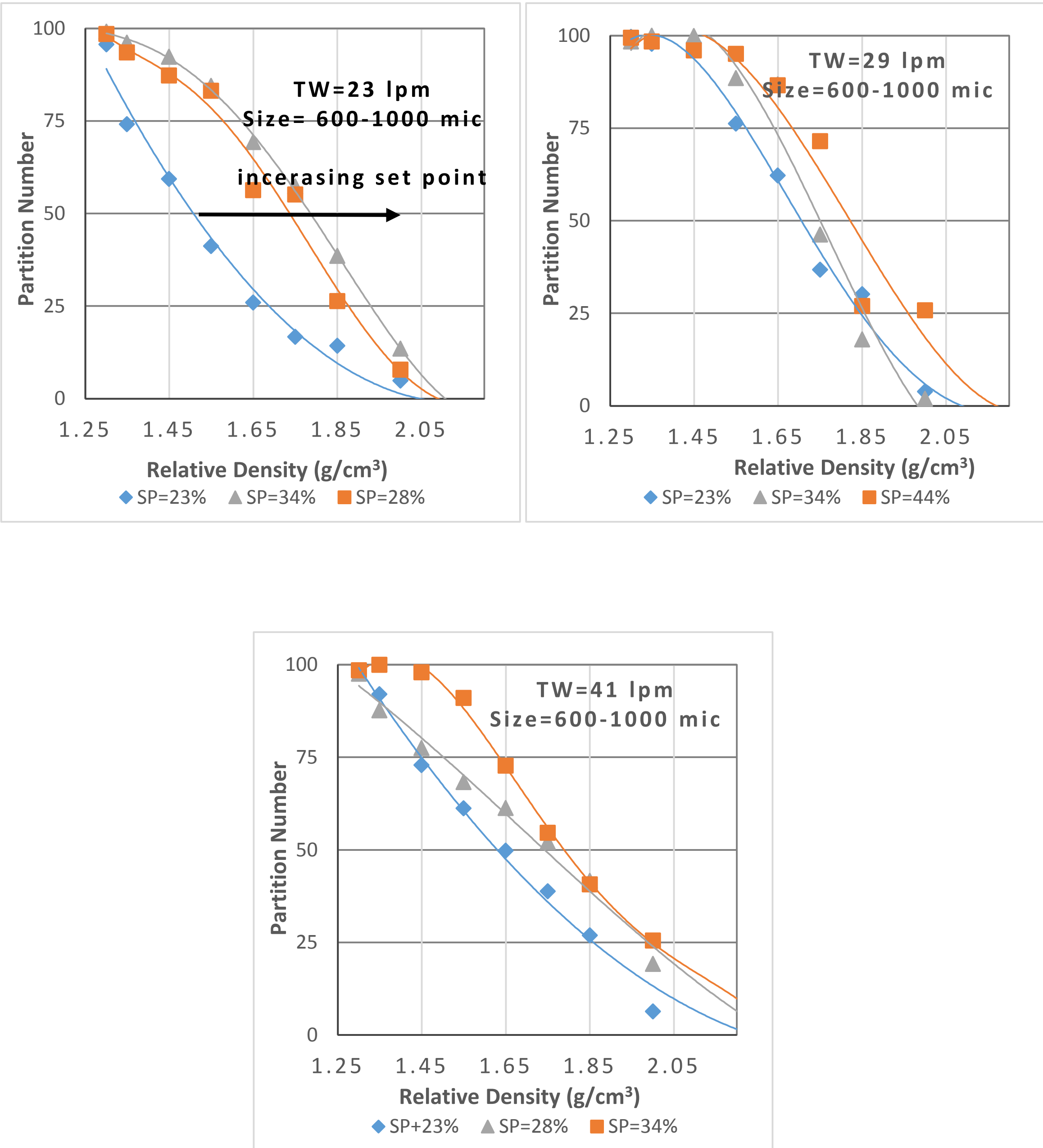

Figure 37. Partition curves for 1000-600 µm size fraction for varying TW (Tunçbilek).

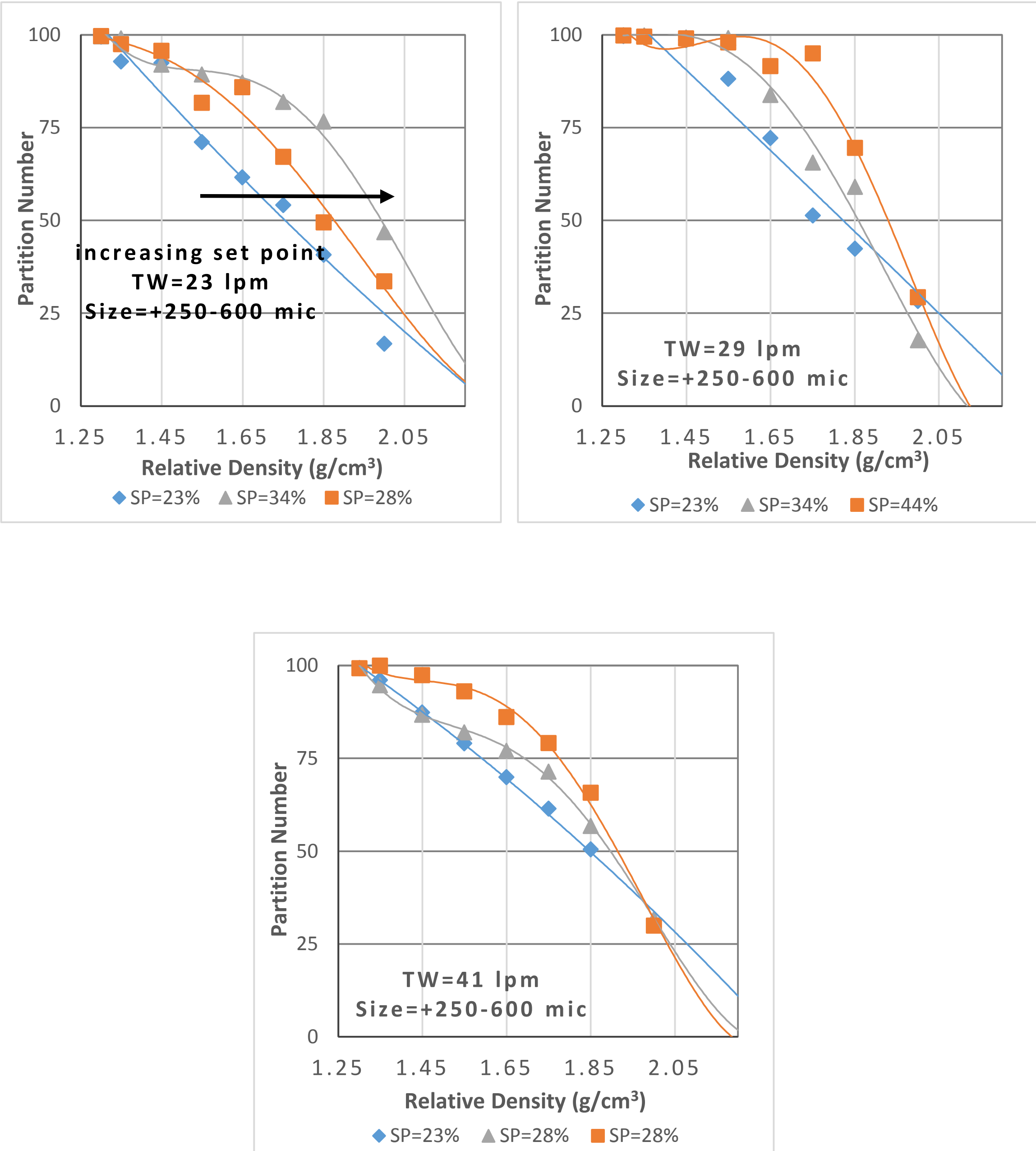

Figure 38. Partition curves for 600-250 μm size fraction for varying TW (Tunçbilek).

c. Effect of Teetered Water Flowrate

Figures. 40-42 depicts the effect of different teetered water flowrate on cut density (ρ50). In each of the figures cut density increases with the increase in teetered water flow rate.

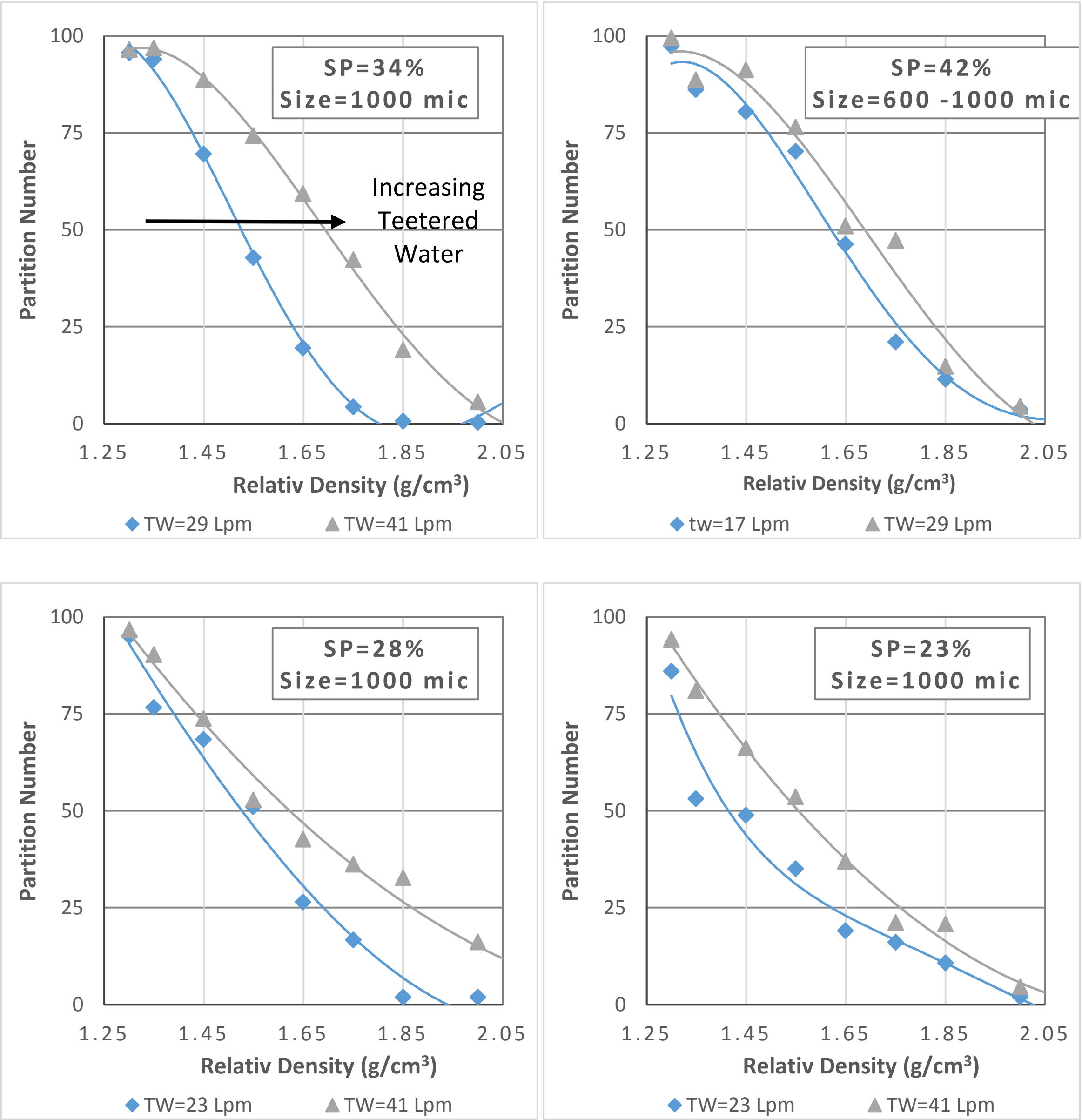

Figure 39. Partition curves for 1000 µm size fraction for varying SP (Tunçbilek).

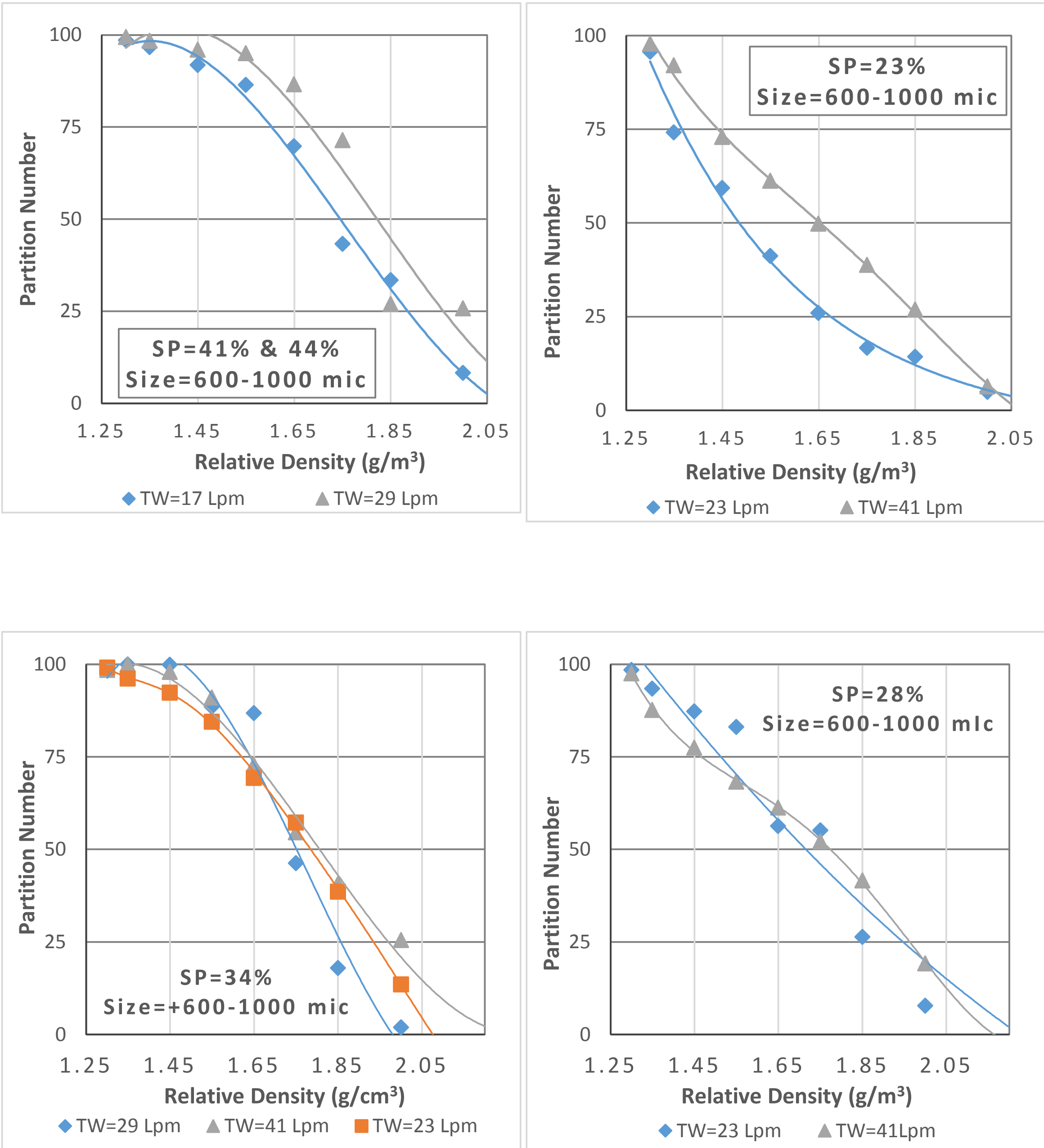

Figure 40. Partition curves for 1000-600 μm size fraction for varying SP (Tunçbilek).

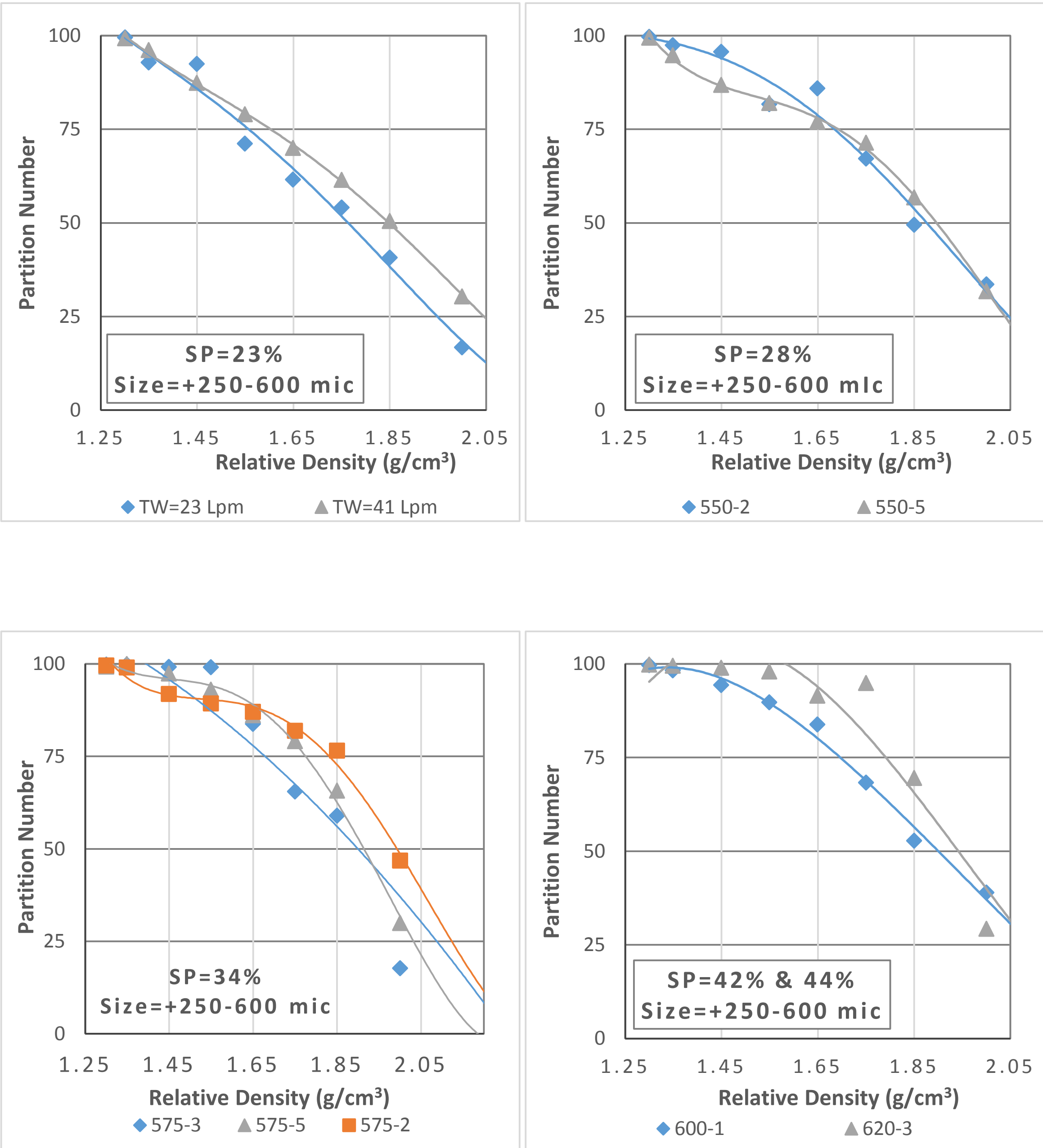

Figure 41. Partition curves for 600-250 μm size fraction for varying SP (Tunçbilek).

6.2 Statistical Evaluation of the Data

Using the data obtained from Soma and Tunçbilek coals, multiple regression analysis was performed for each set of the data. MINITAB V16 software was used in these analyses. A general form of the multiple regression equation is given below:

$$(\rho50, Ep, Y, AR, E) = A + B\times(TW) + C\times(SP) + D\times(SIZE)$$

Where,

ρ50	:	Separation density (g/cm^3)
Ep	:	Ecart probable (g/cm^3)
Y	:	Yield (%) –Eq. (5.1)
AR	:	Ash rejection (%)–Eq.(5.3)
E	:	Efficiency (%)–Eq.(5.4)
TW	:	Teetered water flowrate (lpm)
SP	:	Pressure Set Point (%)
SIZE	:	Average size of fraction (µm)
A,B,C,D	:	Regression coefficients

The regression coefficients and coefficient of determination (R^2) are given in Table 18.

Table 18. The regression coefficients and coefficient of determination

	A	B	C	D	R^2
ρ50 (soma)	1761	0.68	7.77	- 0.269	68.8%
ρ50 (Tunçbilek)	1611	3.31	7.66	- 0.369	82.0%
ρ50 (All)	1562	2.68	9.46	- 0.249	64.2%

	A	B	C	D	R^2
Ep (soma)	0.138	0.000228	0.000274	- 0.000039	11.7%
Ep (Tunçbilek)	0.242	0.000540	- 0.00303	0.000011	15.2%
Ep (All)	0.209	0.000097	- 0.00113	- 0.000040	12.9%

	A	B	C	D	R^2
Y (soma)	102	- 0.078	- 0.378	- 0.0178	26.4%
Y (Tunçbilek)	89.8	- 0.149	0.218	- 0.0206	59.0%
Y (All)	103	- 0.205	- 0.303	- 0.0152	25.7%

	A	B	C	D	R^2
R (soma)	105	- 0.115	- 0.208	- 0.0149	22.4%
R (Tunçbilek)	97.0	- 0.101	0.136	- 0.0125	65.7%
R (All)	109	- 0.220	- 0.194	- 0.0137	26.2%

	A	B	C	D	R^2
AR (soma)	4.3	- 0.074	+ 0.684	0.0254	35.1%
AR (Tunçbilek)	32.2	0.121	- 0.585	0.0404	65.1%
AR (All)	13.9	0.079	0.451	0.0189	23.0%

	A	B	C	D	R^2
E (soma)	53.2	- 0.0761	0.153	0.00382	18.9%
E (Tunçbilek)	61.0	- 0.0143	- 0.184	0.00990	64.8%
E (All)	58.2	- 0.0630	0.0737	0.00188	5.5%

It is seen that any of the multiple linear regression models are not suitable to explain the variation in particle size, TW and SP.

Although the effect of operating parameters are evident in individual data sets, the generalization or quantification of these effect was not possible. The plausible explanation of this phenomenon is that the dynamic nature of the teetered bed. Since the pressure is set and controlled at one point, there is gradual changes within the whole column. This may also suggest that a control system based on multiple pressure gauges can provide a better control for TBS separator. This point also deserves more experimental data.

6.3 Practical implications of the study

This study showed that the different sized particles will have different cut density. Therefore, for a given SP and TW some particles will be separated at the desired density, provide the desired quality product. It is not possible to make sharp separations as in dense medium processes. A second stage separation will improve the performance significantly. On the other hand, teetered bed separator produced much higher reject ash content than spiral concentrator. A comparison of ash contents of TBS and spiral rejects for Tunçbilek coal when processing exactly the same coal is given in Figure 42. The flowsheet suggested for fine Turkish lignite's coal washing are given in Figure 43.

First suggestion to modify the existing coal washing flowsheet would be to increase screen apertures from 0.5mm to 2mm. Since magnetite loss increases with decreasing particle size, increasing aperture will reduce magnetite losses and increase the screen efficiency. This is being applied unofficially in most of the washing plants. Then, -2mm is directly fed first stage TBS. The underflow will be final tailing and overflow is fed to 0.5 mm screen. Screen undersize is fed to the second stage TBS. The underflow of second stage TBS is sent to the tailings, while overflow is screened through 0.15mm high efficiency screens such as Derrick screens. Screen oversize will be the clean coal product. Screen overflow can be fed to a small diameter desliming cyclone battery to remove clays. Cyclone underflow will be a clean coal product and overflow will be sent to final tails. This flowsheet maximizes the clean coal product which can be used for industrial purposes. Alternatively, the overflow of the first stage product is dewatered and used as thermal power plant feed. The flowsheet has also another advantage over conventional cyclone-spiral circuit. The cyclones ahead of spirals are difficult to control and result in significant fine coal losses to final tailings. The performance of TBS in this duty would be much better and smooth-out any fluctuations in feed tonnage and solids content.

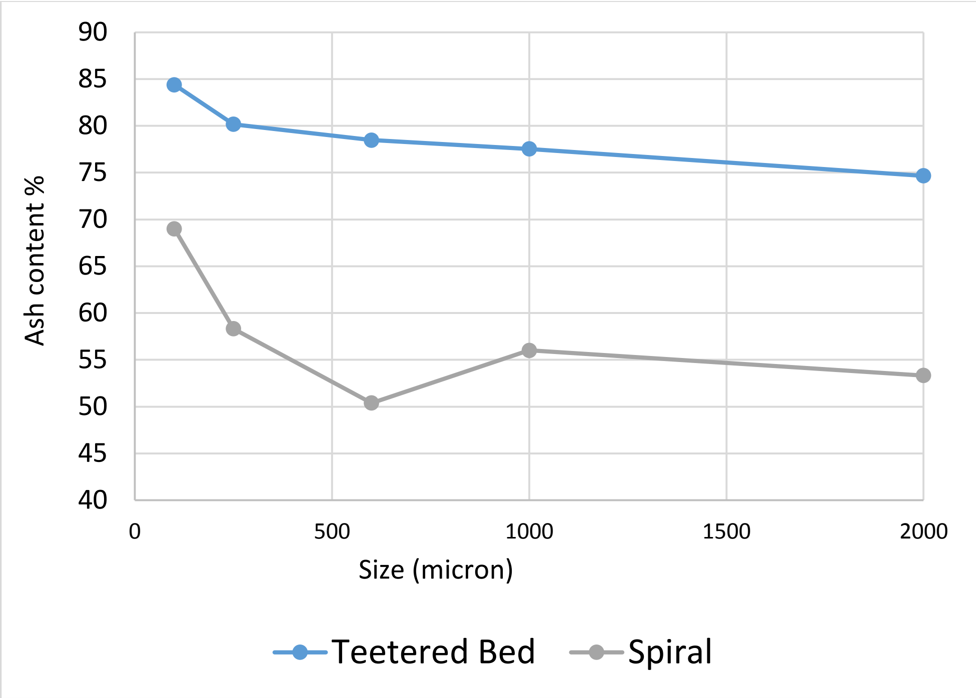

Figure 42. The comparison of ash content of spiral and TBS reject for Soma Coal

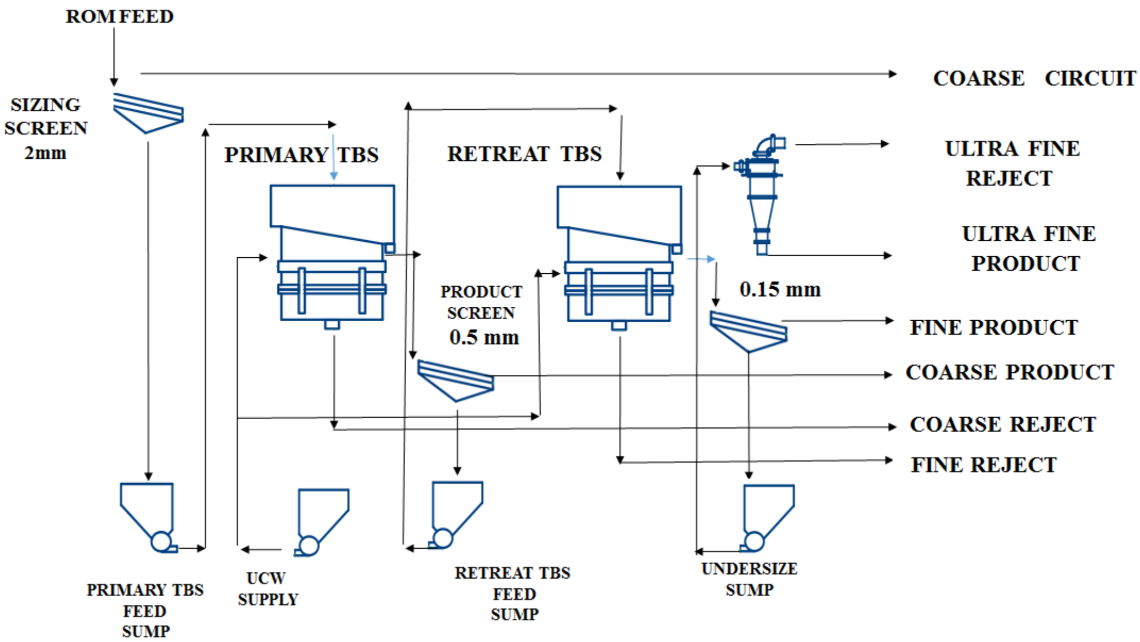

Figure 43. Suggested flowsheet for the beneficiation of fine lignite coals.

7 CONCLUSION

Tests with single density material showed that the teetered water has the maximum effect on separation size. By increasing the teetered water, superficial velocity increases at the separation zone due to which the coarser particle to report to over flow. From the ANOVA results it is observed that the set point has the maximum effect on EP.

The results show that acceptable separations were possible for fine lignite coal with teetered bed separators. Especially for coarser particles, which have lower probable errors (0.08) and lower densities of separation (1.45 g/cm^3). The fractional recoveries of fine particles were more sensitive to changes in operating variables than those of coarser particles. Ep decreased with increasing particle size, 0.08 for the particles coarser than 2mm, the Ep value was found be comparable with DMC.

It was found that the separation was greatly affected by the operating variables. In particular, the teeter water rate and the set point can be used to adjust the separation. Although both variables induce similar effects, the changes in set point generate much greater magnitudes of effects.

The separation performance for narrow size fraction is better than wider size fraction. It is not possible to make sharp separations as in dense medium processes. A second stage separation will improve the performance significantly.

A comparison of ash contents of TBS and spiral rejects for Tunçbilek coal when processing exactly the same coal revealed that TBS produced much higher reject ash content (75-85% Ash) than spiral concentrator (50-70% Ash).

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Appendices

1-TUNÇBILEK

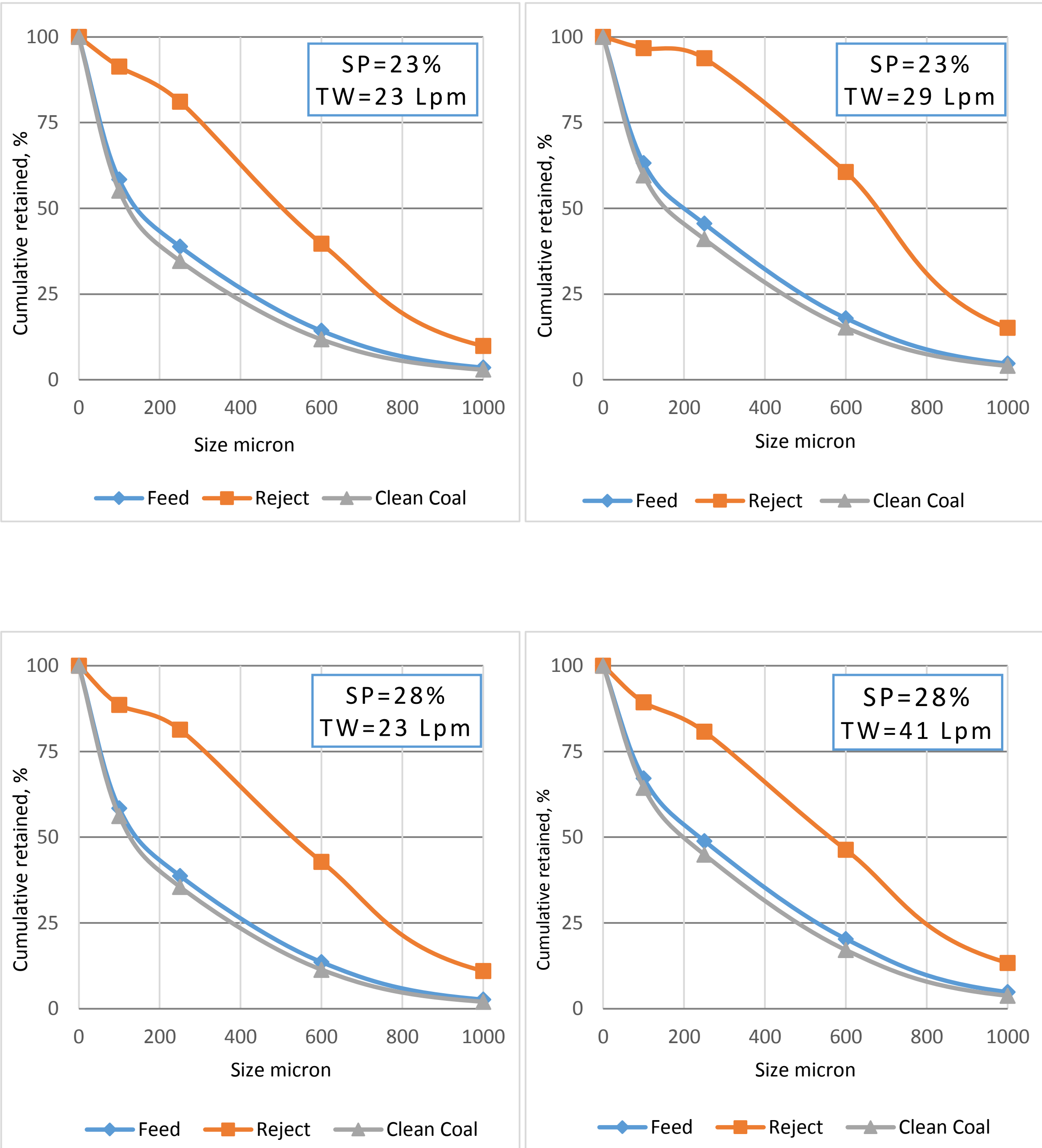

Figure 1. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Tuncbilek Coal

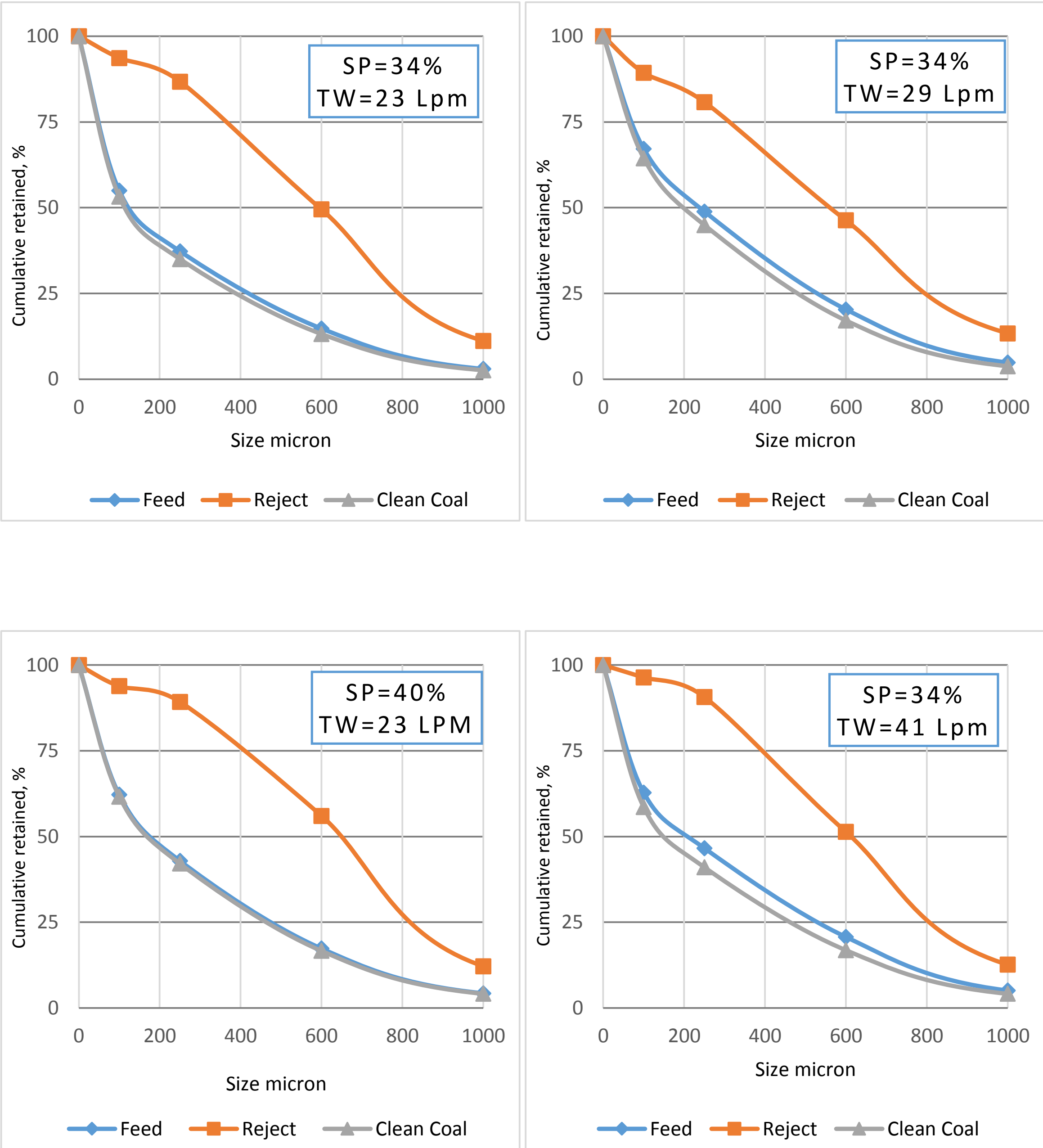

Figure 44. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Tuncbilek Coal

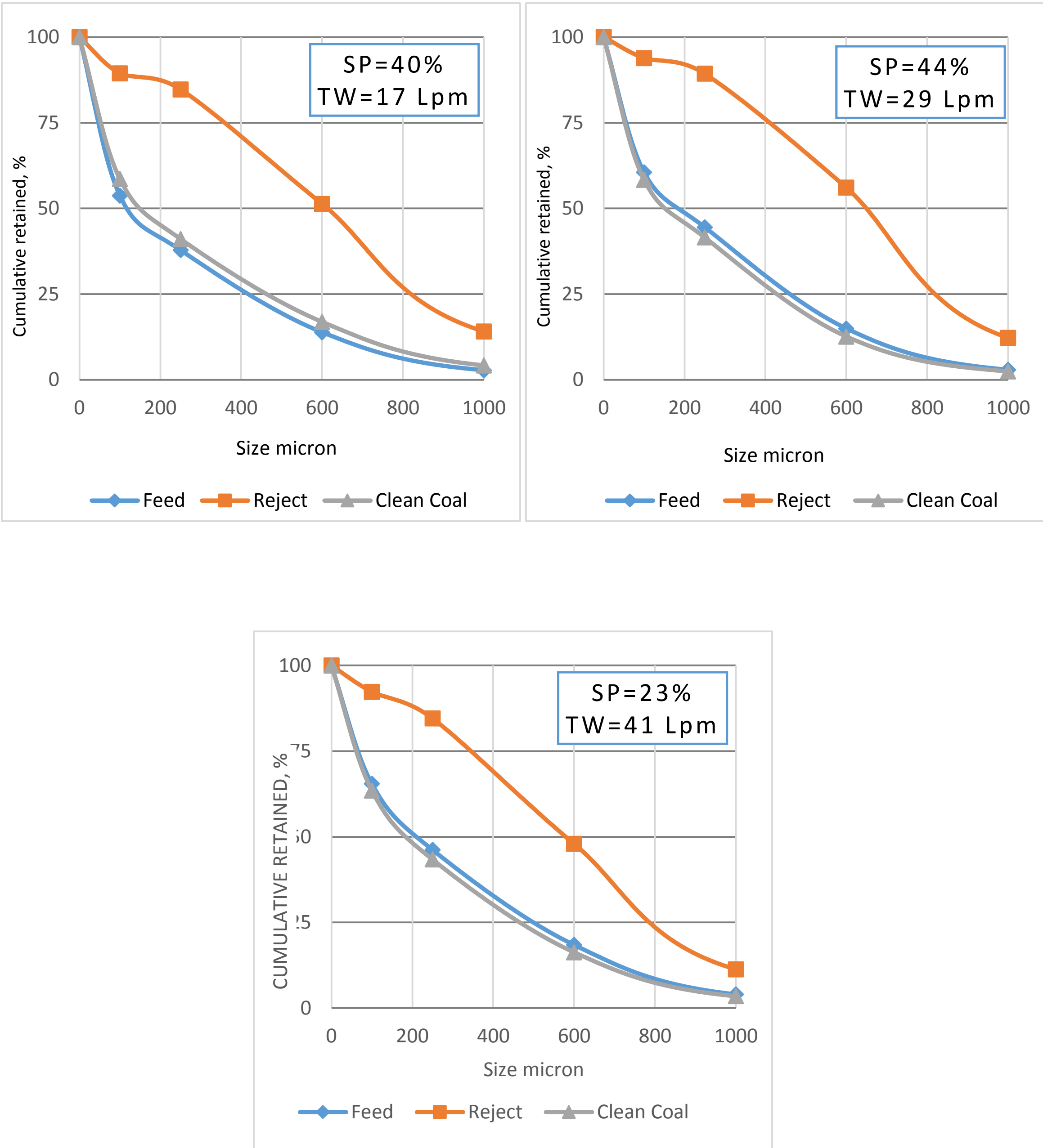

Figure 3. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Tuncbilek Coal

Table 19.The effect of set point and teeter water flow rate on Yield, Recovery, Ash rejection and Efficiency for +100-250micron

SP	TW	Size	Ash %			Yield	Recovery	Ash Rej	Efficiency	S.E
%	Lpm	micron	Feed	Overflow	Underflow	%	%	%	%	%
28	41	100-250	38.39	36.29	76.97	94.84	98.07	10.35	52.60	8.42
23	23	100-250	38.22	36.36	75.58	95.26	98.13	9.38	52.32	7.50
28	23	100-250	37.77	36.78	75.26	97.42	98.98	5.13	51.28	4.11
34	29	100-250	39.05	36.84	80.74	94.98	98.41	10.39	52.68	8.80
44	29	100-250	37.52	36.92	80.98	98.63	99.58	2.95	50.79	2.54
23	41	100-250	40.02	37.25	79.94	93.51	97.83	12.96	53.24	10.79
23	29	100-250	40.02	37.25	79.94	93.51	97.83	12.96	53.24	10.79
40	17	100-250	44.75	43.92	80.40	97.72	99.19	4.09	50.91	3.28
34	23	100-250	39.17	38.50	77.81	98.29	99.38	3.39	50.84	2.77
34	41	100-250	41.15	39.64	77.93	96.07	98.53	7.44	51.76	5.97

Table 20. The effect of set point and teeter water flow rate on Yield, Recovery, Ash rejection and Efficiency for 0-100micron

SP	TW	Size	Ash %			Yield	Recovery	Ash Rej	Efficiency	S.E
%	Lpm	micron	Feed	Overflow	Underflow	%	%	%	%	%
44	29	0-100	63.17	63.00	82.65	99.15	99.60	1.12	50.13	0.72
28	41	0-100	64.20	63.41	85.31	96.40	98.52	4.79	50.59	3.31
34	23	0-100	63.67	63.55	83.65	99.38	99.72	0.81	50.10	0.53
23	23	0-100	64.17	63.84	81.19	98.10	99.00	2.40	50.25	1.40
28	23	0-100	64.39	64.04	82.54	98.07	99.05	2.47	50.27	1.53
40	17	0-100	70.35	70.08	85.20	98.23	99.12	2.14	50.19	1.26
34	41	0-100	65.45	65.24	84.38	98.91	99.51	1.41	50.16	0.91
23	41	0-100	66.44	66.00	82.56	97.35	98.63	3.29	50.32	1.91
23	29	0-100	66.44	66.00	82.56	97.35	98.63	3.29	50.32	1.91
34	29	0-100	68.06	67.63	81.39	96.90	98.20	3.70	50.30	1.90

Table3. Partition factor data of +1000 micron Tuncbilek

Density	**Partition factor** (Set point (%) - Teetered Water Rate Lpm). (SP-TW)									
g/cm^3	**23-23**	**23-29**	**23-41**	**28-23**	**28-41**	**34-23**	**34-29**	**34-41**	**40-17**	**44-29**
1.30	86.06	98.91	94.22	95.06	96.74	96.13	95.69	96.54	97.40	99.54
1.35	53.13	92.92	80.97	76.69	90.30	82.00	94.03	96.97	86.20	88.75
1.45	48.90	74.81	66.23	68.41	73.84	69.12	69.57	88.63	80.49	91.25
1.55	35.11	52.22	53.59	51.05	52.82	56.34	42.88	74.39	70.28	76.51
1.65	19.13	25.12	36.98	26.52	42.72	40.81	19.60	59.40	46.31	50.98
1.75	16.13	10.95	21.17	16.74	36.26	29.55	4.37	42.28	21.09	47.32
1.85	10.80	0.28	20.78	1.95	32.69	23.48	0.65	19.05	11.49	14.84
2.00	2.09	0.32	4.58	1.99	16.20	10.36	0.35	5.67	3.78	4.53
2.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4. Partition factor data of +600-1000 micron Tuncbilek

Density	**Partition factor** (Set point (%) - Teetered Water Rate Lpm). (SP-TW)									
g/cm^3	**23-23**	**23-29**	**23-41**	**28-23**	**28-41**	**34-23**	**34-29**	**34-41**	**40-17**	**44-29**
1.30	95.68	99.67	97.78	98.52	97.57	99.15	98.43	98.50	98.54	99.41
1.35	74.16	97.81	92.03	93.49	87.68	96.18	100.00	100.00	96.66	98.41
1.45	59.35	98.14	72.94	87.33	77.50	92.35	99.88	97.95	91.87	95.98
1.55	41.21	76.21	61.28	83.14	68.34	84.51	88.58	91.05	86.47	95.04
1.65	25.96	62.25	49.80	56.34	61.31	69.33	86.83	72.80	69.82	86.57
1.75	16.68	36.75	38.82	55.16	52.16	57.30	46.27	54.65	43.25	71.47
1.85	14.33	30.20	26.91	26.39	41.60	38.58	17.93	40.72	33.45	26.96
2.00	4.92	3.86	6.37	7.81	19.22	13.55	1.94	25.49	8.25	25.80
2.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. Partition factor data of +250-600 micron Tuncbilek

Density	**Partition factor** (Set point (%) - Teetered Water Rate Lpm).(SP-TW)									
g/cm^3	**23-23**	**23-29**	**23-41**	**28-23**	**28-41**	**34-23**	**34-29**	**34-41**	**40-17**	**44-29**
1.30	99.48	99.67	99.29	99.64	99.41	99.62	99.88	99.31	99.68	99.86
1.35	92.85	99.30	96.13	97.46	94.74	99.06	99.86	100.00	98.34	99.55
1.45	92.42	98.59	87.38	95.71	86.81	91.93	99.25	97.44	94.40	99.02
1.55	71.14	88.15	79.04	81.69	82.04	89.32	99.16	93.06	89.76	97.97
1.65	61.60	72.20	69.98	85.92	77.02	87.12	83.78	86.17	83.85	91.54
1.75	54.14	51.33	61.51	67.17	71.42	81.95	65.56	79.18	68.32	94.97
1.85	40.73	42.36	50.53	49.48	56.84	76.61	59.02	65.77	52.87	69.55
2.00	16.79	28.34	30.35	33.60	31.78	46.86	17.72	29.97	38.98	29.33
2.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

2- S0MA

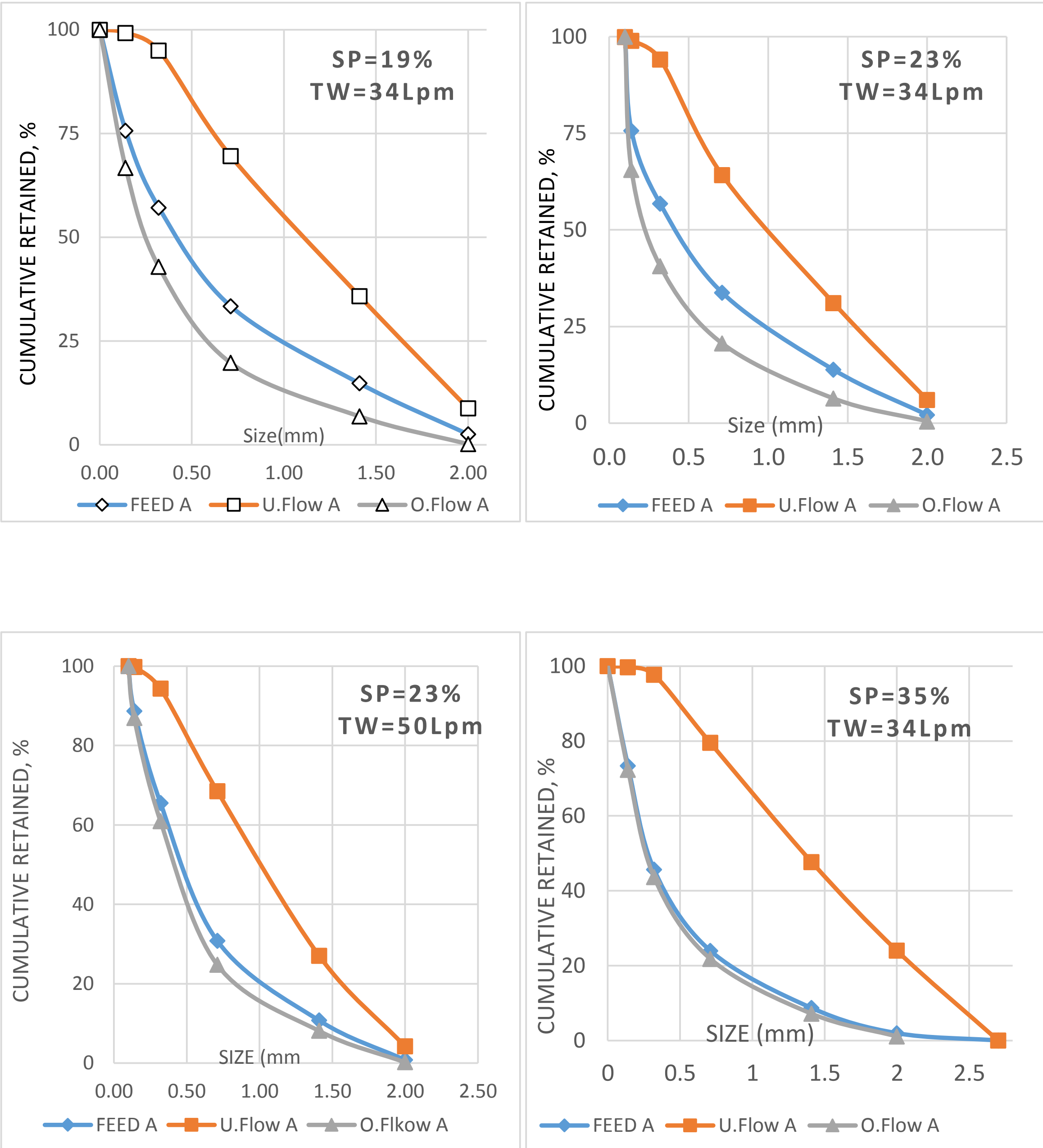

Figure 4. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Soma Coal.

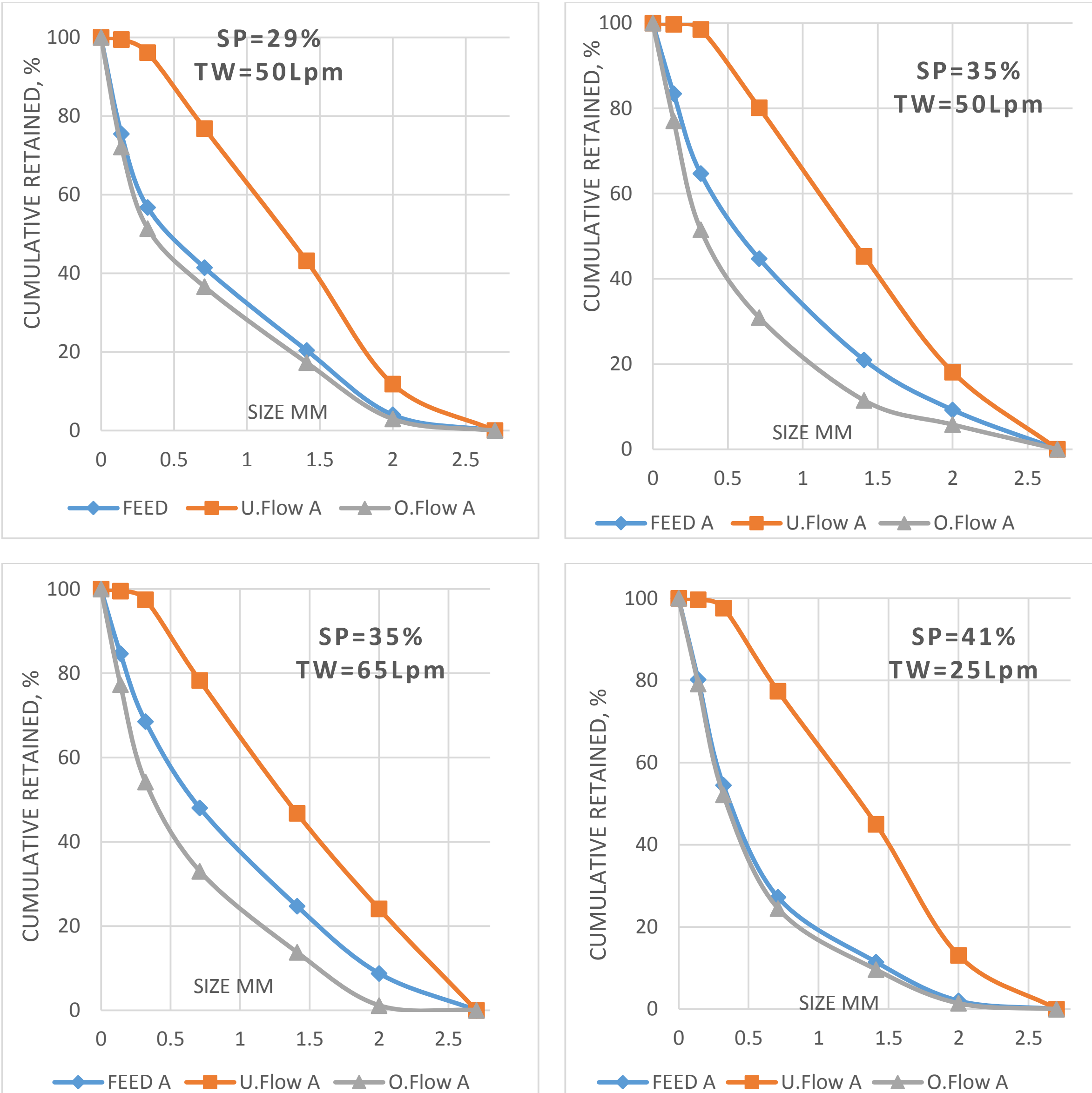

Figure 5. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Soma Coal.

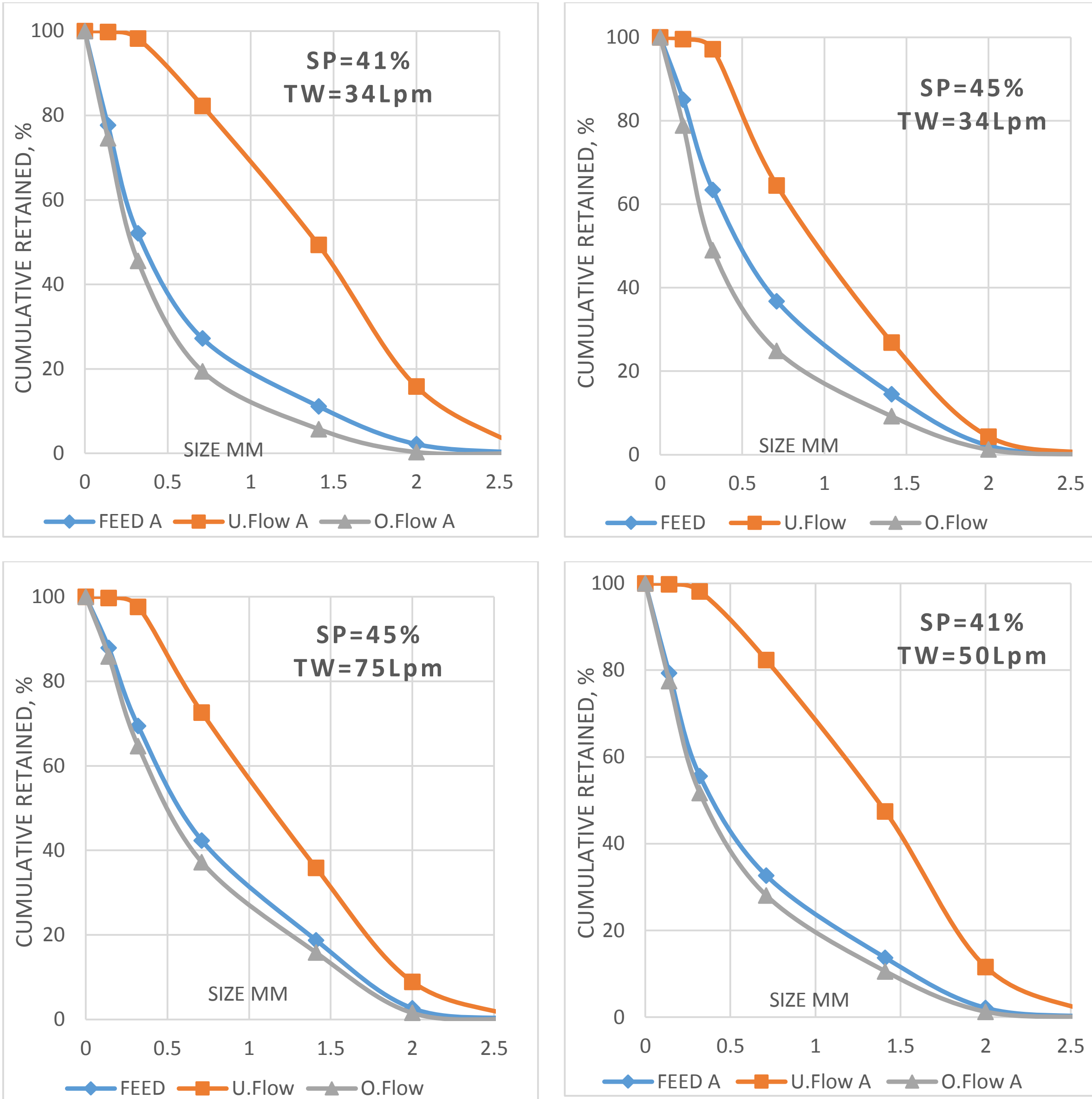

Figure 6. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Soma Coal.

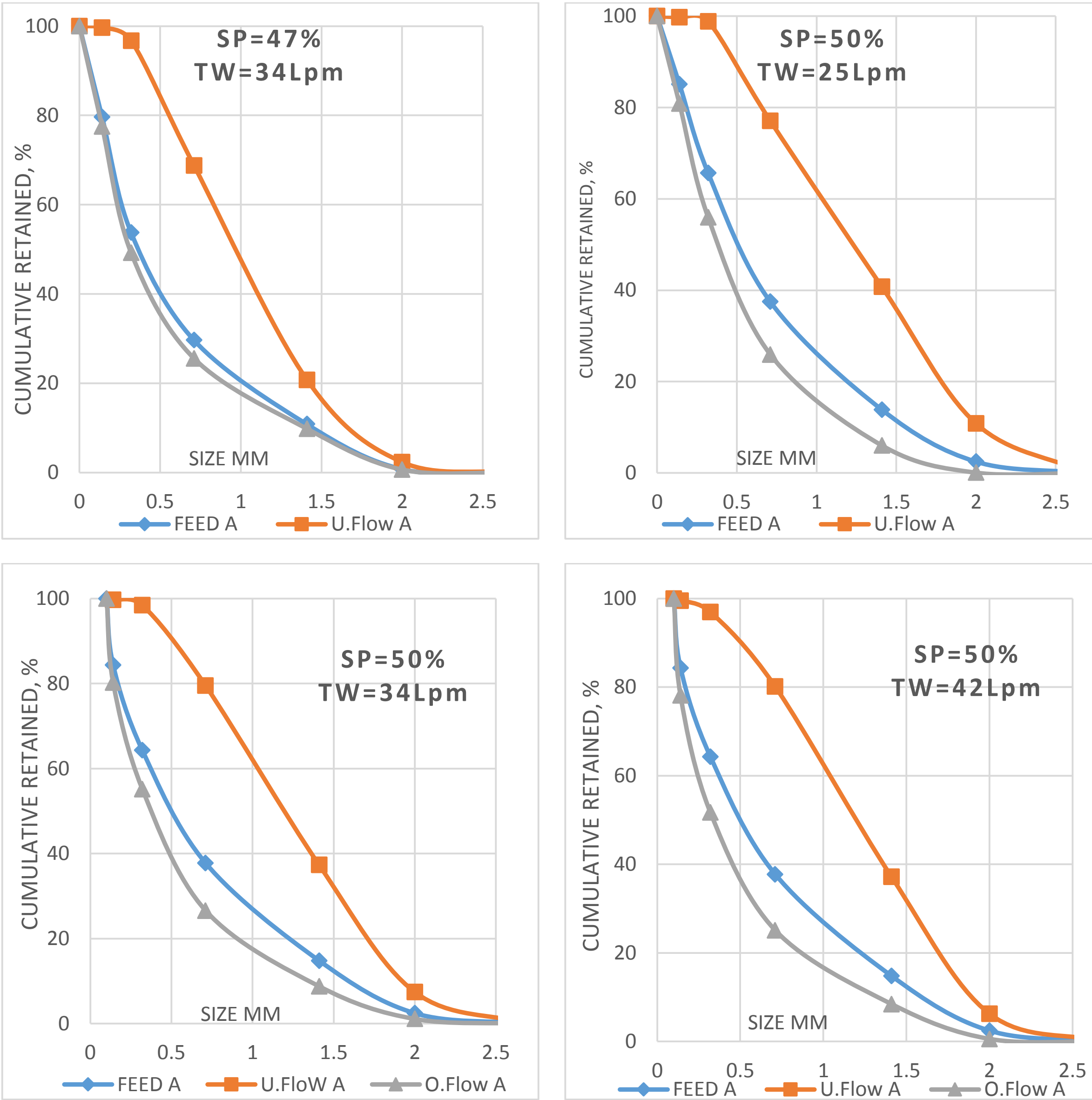

Figure 7. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Soma Coal.

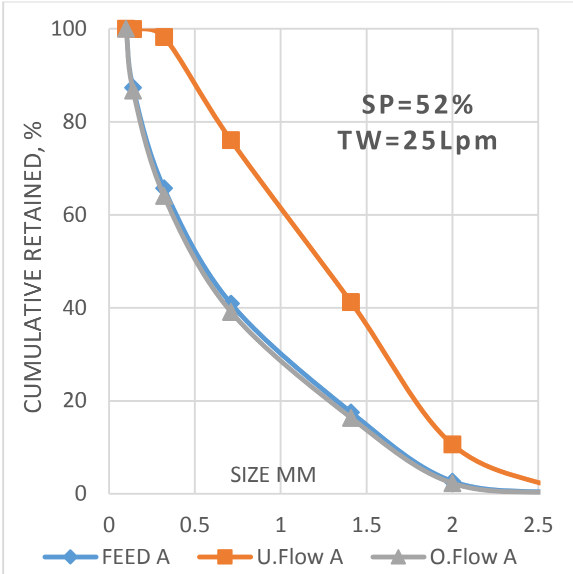

Figure 8. Size distribution of feed, Clean Coal and Reject samples of CrossFlow in different Setpoint and teetered water for Soma Coal.

Table 6. Size by Size Washabilities of Size Fractions in Setpoint =19% and teetered water=34 lpm (soma coal).

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30			0.54	2.21		79.79	1.77	0.87	19.82	9.09	2.25	0.38
1.3X1.4			24.00	21.74		11.51	38.56	38.34	19.08	10.63	2.67	0.67
1.4X1.5			28.00	21.61		3.30	30.79	17.06	10.07	8.94	2.79	0.77
1.5X1.6			6.51	7.94		1.92	8.04	7.87	6.13	6.05	3.73	0.87
1.6X1.7			4.88	5.08		1.50	6.81	7.00	4.19	7.83	3.87	1.54
1.7x1.8			1.36	2.86		0.81	2.04	2.77	3.08	5.52	2.23	2.21
1.8x1.9			6.64	4.56			4.22	5.69				
+1.90			28.07	33.98		1.19	7.77	20.41	37.64	51.94	82.46	93.56

Table 7. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =23% and teetered water=34 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30	18.67	24.73	31.00	27.69		48.99	46.97	46.43		7.03	4.92	0.17
1.3X1.4	15.91	23.73	20.58	18.94		43.63	31.51	31.39		9.21	2.72	0.66
1.4X1.5	4.58	5.19	8.70	7.58		5.30	12.83	12.68		5.12	1.95	0.08
1.5X1.6	3.08	3.87	5.08	4.33		1.40	6.30	6.45		5.67	3.08	1.20
1.6X1.7	3.97	2.59	2.85	2.12		0.59	2.37	2.51		4.04	3.64	1.53
1.7x1.8	2.86	3.06	2.31	0.68		0.00	0.01	0.11		5.29	6.08	1.51
1.8x1.9	3.16	2.31	1.19	2.87		0.00	0.00	0.30		4.00	3.14	6.63
+1.90	47.76	34.49	28.29	35.92		0.01	0.01	0.13		59.66	74.47	88.48

Table 8 Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =23% and teetered water=50 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30		24.96	32.24	9.90		47.39	47.52	10.47		5.46	2.91	0.72
1.3X1.4		30.62	10.29	27.84		33.82	10.37	31.63		8.22	2.32	1.09
1.4X1.5		7.10	11.24	10.56		8.92	11.70	11.10		2.36	2.46	0.79
1.5X1.6		3.32	5.05	6.45		3.47	6.67	6.85		2.10	0.68	0.42
1.6X1.7		2.36	3.79	4.64		1.42	4.40	5.47		3.57	1.38	0.41
1.7x1.8		1.72	3.58	1.89		0.76	3.34	1.54		3.28	2.85	0.76
1.8x1.9		2.26	6.24	4.01		0.72	6.57	3.39		3.23	2.28	2.01
+1.90		27.65	27.57	34.71		3.49	9.44	29.55		71.79	85.12	93.81

Table 9. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =35% and teetered water=34 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30		27.11	39.04	27.22		46.26	48.99	23.55		6.62	2.95	3.41
1.3X1.4		38.70	14.61	23.62		37.46	12.92	24.85		9.86	3.59	1.77
1.4X1.5		4.68	7.88	8.84		5.92	7.20	9.46		1.41	2.18	0.83
1.5X1.6		2.60	4.80	3.98		3.14	5.20	4.77		1.30	1.30	0.88
1.6X1.7		2.00	3.77	2.05		1.91	3.27	1.72		2.40	2.01	0.76
1.7x1.8		1.20	2.16	1.93		0.90	2.56	2.00		1.98	2.09	0.69
1.8x1.9		1.19	2.52	3.38		0.50	2.51	3.44		1.35	2.19	3.16
+1.90		22.51	25.22	28.97		3.91	17.33	30.21		75.09	83.69	88.50

Table 10. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =29% and teetered water=50 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30	16.51	29.44	29.85	22.69	50.81	61.60	49.16	33.29	13.44	3.74	0.21	0.02
1.3X1.4	24.23	9.40	9.61	17.05	21.95	20.00	17.38	22.21	13.38	5.83	2.26	0.14
1.4X1.5	5.81	6.85	4.93	4.78	3.58	8.96	7.81	6.40	7.43	3.54	1.20	0.29
1.5X1.6	4.06	2.66	2.89	4.06	0.38	2.01	4.11	4.11	5.31	3.27	1.94	0.95
1.6X1.7	4.24	4.56	4.99	2.56	0.41	3.39	5.17	3.35	5.71	5.31	3.05	1.23
1.7x1.8	3.38	3.77	3.36	1.84	0.53	0.90	2.88	2.88	4.75	4.67	2.96	1.27
1.8x1.9	3.67	3.25	4.31	2.44	0.59	0.37	3.35	2.68	5.17	4.37	4.11	2.94
+1.90	38.09	40.07	40.07	44.58	1.74	2.76	10.14	25.07	44.81	69.27	84.28	93.17

Table 11. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =35% and teetered water=50 lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		24.99	27.69	19.50		40.38	33.09	20.95		0.19	0.04	0.18
1.3X1.4		25.88	17.06	25.52		41.57	20.35	27.40		0.60	0.23	0.36
1.4X1.5		5.49	12.27	10.22		8.55	14.61	10.97		0.56	0.30	0.22
1.5X1.6		1.80	4.94	3.90		2.48	5.80	4.18		0.69	0.51	0.15
1.6X1.7		1.89	4.04	2.91		1.97	4.67	3.11		1.77	0.81	0.28
1.7x1.8		3.55	2.61	2.19		3.34	2.39	2.29		3.90	3.72	0.78
18x1.9		2.07	2.82	3.59		1.51	2.56	3.65		2.98	4.17	2.82
+1.90		34.32	28.57	32.16		0.20	16.53	27.45		89.29	90.22	95.20

Table 12. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =35% and teetered water=65 for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		33.77	25.91	16.16		58.38	33.68	16.83		3.13	1.72	2.12
1.3X1.4		23.58	18.79	21.50		26.01	27.27	27.21		6.36	0.70	1.34
1.4X1.5		5.14	8.70	10.61		7.48	12.69	12.76		1.16	0.38	0.17
1.5X1.6		2.67	3.36	5.64		2.38	4.77	6.54		2.37	0.47	0.24
1.6X1.7		2.10	3.87	2.20		2.39	5.64	2.63		2.96	0.17	0.34
1.7x1.8		1.48	2.40	2.51		0.57	2.79	2.81		3.09	2.53	0.22
1.8x1.9		2.03	2.52	2.18		0.88	1.67	2.59		3.85	3.73	1.51
+1.90		29.22	34.47	39.20		1.91	11.49	28.63		77.07	90.30	94.05

Table 13. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =41% and teetered water=25 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		4.16	24.38	25.85		4.72	29.44	26.65		0.89	0.34	0.40
1.3X1.4		47.37	20.38	20.42		66.44	24.06	21.51		0.50	0.29	0.20
1.4X1.5		8.85	11.09	8.59		10.81	13.16	9.02		1.64	0.16	0.06
1.5X1.6		5.02	4.72	7.53		5.91	5.34	7.87		2.77	0.39	0.09
1.6X1.7		2.98	3.39	2.72		3.23	3.54	2.84		2.61	0.58	0.09
1.7x1.8		2.33	2.70	2.89		2.30	3.16	3.03		2.69	1.46	0.09
1.8x1.9		4.66	4.90	3.61		5.00	5.25	3.63		3.79	3.46	3.32
+1.90		24.64	28.44	28.42		1.59	16.04	25.44		85.11	93.31	95.91

Table 14. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =41% and teetered water=34 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		5.04	29.61	18.44		7.61	50.50	23.91		5.21	1.45	1.15
1.3X1.4		38.29	8.36	23.20		72.72	8.68	27.41		1.62	2.66	1.15
1.4X1.5		4.73	8.35	8.80		6.63	11.22	10.32		1.99	2.25	0.51
1.5X1.6		3.18	3.97	2.93		4.01	5.41	3.50		1.89	1.21	0.15
1.6X1.7		2.27	3.74	2.52		1.82	3.86	3.16		2.97	3.53	0.97
1.7x1.8		2.06	3.52	2.60		1.35	3.60	2.96		2.44	3.50	0.28
1.8x1.9		2.19	4.17	3.44		1.88	2.95	3.26		3.47	4.17	3.77
+1.90		42.23	38.27	38.07		3.97	13.77	25.47		80.40	81.23	92.02

Table 15. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =45% and teetered water=34 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		18.72	25.32	22.88		63.58	29.54	26.09		1.31	0.28	0.05
1.3X1.4		26.86	27.03	22.13		18.90	31.52	25.23		0.75	0.37	0.15
1.4X1.5		6.04	7.10	7.04		10.22	8.18	8.02		0.84	0.69	0.07
1.5X1.6		4.11	4.83	4.92		2.94	5.47	5.58		0.96	1.06	0.23
1.6X1.7		3.27	3.46	3.47		2.45	3.84	3.92		2.82	1.21	0.23
1.7x1.8		3.37	3.62	3.02		0.86	3.64	3.44		3.11	3.53	0.03
1.8x1.9		3.21	2.27	2.13			2.31	2.14			2.02	2.07
+1.90		34.51	26.37	34.42		1.05	15.50	25.58		90.22	90.84	97.17

Table 16. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =45% and teetered water=75 lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		18.72	31.78	16.87		26.86	38.90	18.14		0.57	0.33	0.03
1.3X1.4		26.86	12.71	22.28		38.68	15.51	23.96		0.55	0.35	0.04
1.4X1.5		6.04	5.10	7.63		8.43	6.23	8.20		0.72	0.12	0.11
1.5X1.6		4.11	3.24	6.68		5.44	3.93	7.17		1.15	0.22	0.11
1.6X1.7		3.27	2.12	2.53		4.04	2.54	2.71		1.55	0.29	0.14
1.7x1.8		3.37	3.76	4.75		4.02	4.00	5.09		1.93	2.71	0.20
1.8x1.9		3.21	2.17	1.57		3.75	1.98	1.66		2.03	2.99	0.27
+1.90		34.51	39.12	37.69		8.74	26.93	33.07		91.92	92.98	99.10

Table 17. Size by Size Washabilities of Size Fractions in Setpoint =41% and teetered water=50 lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
F1.30	20.83	26.12	23.01	10.39	69.73	68.56	40.03	13.80	0.80	0.99	0.31	0.01
1.3X1.4	7.58	7.88	14.13	15.44	20.89	12.94	23.65	20.51	1.62	2.07	0.51	0.05
1.4X1.5	3.35	4.36	6.92	11.59	5.69	8.09	11.16	15.26	2.07	1.56	0.55	0.10
1.5X1.6	2.11	1.83	2.96	0.00	1.22	2.16	4.75	9.00	2.28	1.20	0.50	0.20
1.6X1.7	3.70	4.21	5.04	9.15	0.27	3.73	7.62	3.26	5.06	4.49	1.22	0.10
1.7x1.8	2.34	2.64	1.61	0.00	0.27	1.32	2.34	3.00	2.86	3.22	1.60	0.18
1.8x1.9	2.65	1.64	2.56	6.71	1.30	1.67	3.82	4.51	2.37	1.28	2.86	0.50
Sink1.90	57.44	51.32	43.76	46.71	0.63	1.52	6.62	30.65	82.93	85.19	92.47	98.86

Table 18. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =47% and teetered water=34lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30		15.33	30.03	28.98		19.92	40.55	29.46		0.15	0.29	0.32
1.3X1.4		40.41	15.44	24.95		51.81	19.71	24.72		0.48	0.79	0.57
1.4X1.5		7.65	7.28	10.96		9.64	9.30	11.21		0.59	0.66	0.19
1.5X1.6		4.34	3.36	5.06		5.40	4.61	4.98		0.59	0.11	0.42
1.6X1.7		2.48	3.32	3.29		3.03	4.37	3.35		0.67	0.22	0.26
1.7x1.8		2.59	1.89	2.87		2.88	2.47	2.76		1.51	0.38	0.33
1.8x1.9		2.76	3.26	1.43		2.76	3.87	1.47		2.80	1.88	1.99
+1.90		24.45	35.43	22.46		4.57	15.12	22.06		93.22	95.67	95.92

Table 19. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =50% and teetered water=25lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30		3.43	32.74			4.72	41.55			0.33	0.31	
1.3X1.4		59.97	21.83			78.75	28.59			1.84	1.10	
1.4X1.5		5.93	9.52			6.78	10.11			1.17	1.21	
1.5X1.6		3.96	4.12			4.00	4.54			1.72	0.49	
1.6X1.7		2.90	4.19			2.29	5.56			2.52	0.29	
1.7x1.8		2.02	2.69			1.17	2.65			2.59	1.19	
1.8x1.9		2.88	5.83			1.52	5.74			3.18	3.64	
+1.90		18.92	19.08			0.76	1.25			86.66	91.77	

Table 20. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =50% and teetered water=34 lpm for Soma Coal

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30		3.91	20.88	17.72		6.90	36.61	20.95		0.15	0.16	0.25
1.3X1.4		43.41	14.64	28.34		77.76	25.66	33.45		0.11	0.13	0.70
1.4X1.5		4.60	7.20	11.15		8.14	12.63	13.15		0.14	0.05	0.34
1.5X1.6		2.97	3.33	4.32		5.11	5.77	5.09		0.27	0.11	0.18
1.6X1.7		2.52	3.42	3.36		4.03	5.88	3.92		0.62	0.19	0.37
1.7x1.8		1.61	2.78	1.18		2.07	4.20	1.33		1.03	0.90	0.35
1.8x1.9		1.95	2.79	2.39		2.16	4.05	2.51		1.68	1.14	1.73
+1.90		45.00	44.95	31.55		4.55	5.30	19.60		96.01	97.43	96.09

Table 21. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =50% and teetered water=42 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)	+2 (mm)	-2x1 (mm)	-1x0.5 (mm)	0.2-0.5 (mm)
-1.30		5.60	32.94	18.54		8.32	36.95	17.46		1.28	1.10	1.52
1.3X1.4		56.48	19.71	34.78		70.18	21.12	35.46		1.15	0.35	0.16
1.4X1.5		6.74	7.82	12.74		7.69	8.52	14.46		1.10	0.23	1.53
1.5X1.6		4.05	5.21	5.12		4.63	5.61	5.03		1.17	0.13	0.69
1.6X1.7		2.54	3.28	4.30		2.62	3.43	3.83		1.28	0.35	0.83
1.7x1.8		1.92	9.32	1.11		1.76	8.52	1.03		1.44	1.88	0.93
1.8x1.9		1.58	3.15	2.22		1.35	3.46	2.49		2.58	2.01	0.24
+1.90		21.60	18.57	21.24		3.20	12.40	20.21		92.19	93.95	97.34

Table 22. Size by Size Washabilities of Size Fractions CrossFlow in Setpoint =52% and teetered water=25 lpm for Soma Coal.

S.G gr/cm3	Feed				Clean Coal				Reject			
Class	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)	**+2** (mm)	**-2x1** (mm)	**-1x0.5** (mm)	**0.2-0.5** (mm)
-1.30	13.76	11.85	3.21	2.52	20.74	13.81	2.62	2.23	2.34	0.33	0.37	0.02
1.3X1.4	21.13	45.01	21.84	13.19	43.81	49.35	16.72	13.13	0.91	1.71	3.04	1.58
1.4X1.5	5.87	6.84	29.28	23.45	12.30	8.21	25.96	20.05	0.39	0.44	0.14	0.80
1.5X1.6	3.74	4.25	11.09	13.28	7.43	5.22	12.61	10.81	0.83	0.39	2.84	1.31
1.6X1.7	3.55	2.99	3.71	4.47	4.81	3.59	3.26	3.56	2.01	1.10	0.10	0.44
1.7x1.8	2.61	2.30	5.17	3.40	2.13	2.64	4.77	3.62	2.94	1.79	0.22	0.65
1.8x1.9	2.30	2.99	8.13	5.31	3.42	3.19	7.93	4.96	0.40	4.62	0.76	0.31
+1.90	47.04	23.77	17.58	34.38	5.36	13.99	26.12	41.63	90.19	89.62	92.53	94.89

Table 23. Example (set point=40% teetered water= 17 lpm Size 600-1000micron) of details and calculations required for a partition curve

Relative Density		overflow *(Ypc=0.47)*		Underflow (1-Ypc=0.52)		Recent	Partition
CLASS	AVG	Fract.	Fract. Of. Total	Fract.	Fract. Of. Total	Feed	Factor
		yield *Acp*	*Ypc*Apc=Bbc*	yield *Ccp*	*(1-Ypc)*Apc=Dcp*	Bbc+Dcp=Epc	100*Bbc/Ecp
-1.30	1.30	55.13	26.28	0.74	0.39	26.67	98.54
1.30X1.40	1.35	12.57	5.99	0.40	0.21	6.20	96.66
1.40X1.50	1.45	6.57	3.13	0.53	0.28	3.41	91.87
1.50X1.60	1.55	6.22	2.96	0.89	0.46	3.43	86.47
1.60X1.70	1.65	5.16	2.46	2.03	1.06	3.52	69.83
1.70x1.80	1.75	2.50	1.19	2.98	1.56	2.75	43.25
180x1.90	1.85	3.32	1.58	6.01	3.14	4.72	33.45
+1.90	1.90	8.53	4.07	86.42	45.22	49.29	8.25

3-Single density material

Table *24.* Size distribution of feed and overflow and overflow calcite (single density materials).

	Feed %	Test 4		Test 3		Test1		Test 2		Test 5	
size mm		over %	under %	over %	under %	over %	under %	over %	under %	over %	under %
2	0.52	0.00	0.88	0.00	0.91	0.00	0.88	0.00	0.88	0.00	0.97
1.7	4.80	0.00	8.13	0.09	8.35	0.00	8.17	0.00	8.12	0.00	9.01
1.4	6.87	0.00	11.63	0.05	12.00	0.00	11.69	0.12	11.53	0.00	12.89
1.18	6.64	0.00	11.74	0.06	11.58	0.19	11.15	0.36	10.97	0.00	12.44
0.85	11.89	0.00	20.13	0.10	20.75	0.13	20.14	0.45	19.79	0.00	22.30
0.5	14.22	0.00	24.07	0.10	24.82	0.13	24.09	0.71	23.54	0.00	26.66
0.25	17.59	16.39	18.40	18.39	16.99	13.23	20.65	8.43	23.92	20.59	14.96
0.105	25.79	57.31	3.70	55.29	3.62	57.96	3.23	61.34	1.24	54.40	0.74
0	11.69	26.30	1.32	25.93	0.98	28.36	0.00	28.59	0.02	25.01	0.03

4-Spiral

Table 25 Spiral sample (600-1000) details and calculations required for a partition curve

Relative Density		overflow *(Ypc=0.3236)*		Underflow (1-Ypc=0.3236)		Recent	Prtition
CLASS	AVG	fract.	fract. Of.total	fract.	fract. Of.total	Feed	Factor
		yield *Acp*	*Ypc*Apc=Bbc*	yield *Ccp*	*(1-Ypc)*Apc=Dcp*	Bbc+Dcp=Epc	100*Dbc/Ecp
-1.30	1.30	44.30	14.34	8.40	5.68	20.02	28.38
1.30X1.40	1.35	28.97	9.37	7.20	4.87	14.24	34.18
1.40X1.50	1.45	12.76	4.13	8.07	5.46	9.59	56.94
1.50X1.60	1.55	7.65	2.48	9.27	6.27	8.75	71.68
1.60X1.70	1.65	3.40	1.10	10.47	7.08	8.18	86.54
1.70x1.80	1.75	1.46	0.47	12.87	8.70	9.18	94.86
180x1.90	1.85	0.85	0.28	9.81	6.64	6.91	96.02
+1.90	1.90	0.61	0.20	33.91	22.94	23.14	99.15

Table 26. Spiral (25-600 micron) details and calculations required for a partition curve

Relative Density		overflow *(Ypc=0.2163)*		Underflow (1-Ypc=0.52)		Recent	Prtition
CLASS	AVG	fract.	fract. Of.total	fract.	fract. Of.total	Feed	Factor
		yield *Acp*	*Ypc*Apc=Bbc*	yield *Ccp*	*(1-Ypc)*Apc=Dcp*	Bbc+Dcp=Epc	100*Dbc/Ecp
-1.30	1.30	75.68	16.37	17.31	13.56	29.93	45.31
1.30X1.40	1.35	13.51	2.92	14.78	11.58	14.51	79.85
1.40X1.50	1.45	4.65	1.01	10.76	8.43	9.44	89.34
1.50X1.60	1.55	3.46	0.75	11.88	9.31	10.06	92.56
1.60X1.70	1.65	1.19	0.26	8.79	6.89	7.15	96.40
1.70x1.80	1.75	0.65	0.14	6.92	5.43	5.57	97.48
180x1.90	1.85	0.32	0.07	5.43	4.25	4.32	98.38
+1.90	1.90	0.54	0.12	24.13	18.91	19.03	99.39

Table 27 Yield, Recovery, Ash rejection and Efficiency for spirals 0-2000 micron size

Size	Ash %			Yield	Recovery	Ash Rej	Efficiency	S.E	%O/F
micron	Feed	Overflow	Underflow	%	%	%	%	%	%
1000-2000	29.70	22.31	53.32	76.18	84.19	42.77	59.47	26.95	57.23
600-1000	33.62	18.31	56.01	59.40	73.10	67.64	63.52	40.74	32.36
250-600	35.92	17.61	50.38	44.12	56.72	78.37	61.24	35.10	21.63
100-250	40.02	24.61	58.31	54.27	68.21	66.63	60.45	34.84	33.37
0-100	66.44	65.46	69.00	72.26	74.37	28.81	50.53	3.18	71.19

Table 28. Partition factor data of Spirals in Tuncbilek

Size(micron)	ρ_{50}(g/cm^3)	ρ_{75}(g/cm^3)	ρ_{25}(g/cm^3)	EP
600-1000	1.420	1.580	1.290	0.145
250-600	1.310	1.340	1.270	0.035

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