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Hydrocycloning Thickening: Dewatering and Densification of Fine Particulates

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Abstract

The paper reviews integrated ore-dressing machines with particular reference to hydrocyclones and describes a new concept, the "cyclo-thick" apparatus, which combines features of the hydrocyclone and the thickener in a single machine. Field tests conducted with the "cyclo-thick" demonstrated that the unit is remarkably simple and clean in design, and can effectively separate, dewater, and densify fine particulates. This unit should be considered as a viable alternative when evaluating potential solutions to a given separation, thickening, or filtration problem. Various practical applications are proposed.

1. INTRODUCTION

Three main ways of reducing capital and production costs are well known in ore dressing. The first is to eliminate one or more of the operational steps in the production sequence; the second is to transform or modify the techniques or equipment applied; the third is to raise the grade of the material treated at an early stage in the process (preconcentration).

Three very important routes are often neglected (*1*):

(a) Concentration methods based on multifractionation in a single operation (*2, 3*)

*Presented in part at the 2nd International Conference on Hydrocyclones, Bath, England, 1984.

(b) Introduction of man-made properties by artificially modifying the bulk or surface identity of minerals (*4*) in order to adapt the properties of the mineral to the existing well-established separation devices (a concept already utilized in flotation, flocculation, etc.)
(c) Utilization of integrated processes (unification of unit operations)

The third of these concepts forms the subject of this paper.

Integrated Processes

Multistage processes are common practice in chemical and mineral engineering. The treatment of ores and other raw materials begins with comminution (crushing and grinding) combined with sorting, and it proceeds through concentration and enrichment to the final "polishing." Addition of extra stages to a process entails increased cost and intermediate means of handling while not necessarily ensuring improved efficiency. By contrast, integration (e.g., comminution combined into an independent unit operation with separation and concentration) opens the way for new technologies; e.g.,

Jaw-crushing in a heavy liquid, releasing desired matrix-locked components by simultaneous "float/sink" separation.

Electrical or mechanical crushing between the poles of a magnet (nonhomogeneous field) with a magnetic fluid as medium, thereby affecting comminution simultaneously with separation according to density and magnetic susceptibility.

Ball-milling in a liquid solvent, which simultaneously extracts one of the components (leaching or solvent extraction). Kopper's tower mill (capable of saving up to 60% power compared with ball mills in identical service) was first introduced in 1953 as an alternative to ball mills in regrind applications. (The tower mill was originally developed in Japan. The paddle mill, manufactured by Magstone Dev. Inc., Derbert, Canada, operates on principles similar to the tower mill.) Essentially a vertical ball mill with the medium agitated by an internal screw flight, it has been used in Japan for a wide variety of minerals (silica, limestone, coal, and copper). A unit intended for simultaneous grinding and leaching of gold tailings is being installed by the Langlea Mining Co. of Canada, Macassa, Ontario.

The main body of the mill can easily be lined with abrasion-resistant material or it can be made acid-proof. This latter feature has been adapted to the treatment of uranium ore in dilute sulfuric acid and to that of gold ore in potassium cyanide solution. Newly liberated minerals are chemically very active so that leaching is more rapid and more selective.

Three processing steps in one mill are offered by the MPS roller mill systems from Gebr. Pfeiffer (West Germany). They grind, separate, and dry materials with a moisture content of over 20% in a single unit. With this roller mill, fineness and particle-size distribution of the finished product can be adjusted over a wide range, maximum grain size being 0.03 to 1.5 mm. These units can reach outputs of over 500 t/h.

In most cases the MPS system requires fewer auxiliary machines and smaller buildings, resulting in lower investment costs. Energy savings of up to 30% can be achieved compared with other systems. For the grinding-drying process, this system utilizes large quantities of low-temperature gas, especially exhaust gases from suspension preheater kilns.

The usual practice with both metallic and nonmetallic ores is first to grind and then to float, and two separate successive processes are thus used. This leads to loss of values through slimes, unnecessary grinding of the gangue minerals, and other disadvantages. Conventional gradual grinding and flotation reduce these disadvantages but do not eliminate them. Almost complete elimination is, however, possible if grinding and flotation are integrated in one processing machine. This may be achieved (*5*) with comparative ease by using a vibrating vessel filled to a certain level with grinding balls. Pulp fed into the working cell at one end moves to the opposite end while undergoing continuous grinding. In the same cell, air is introduced continuously to form a source of bubbles. To give an example, flotation of barytes may be improved by combining the grinding and flotation processes into a single unit operation (*6*). Advantages accrue from the fact that, just after liberation, baryte particles are highly active chemically.

Cyclone/electrostatic unit. The method is based on frictional contact charging of particles in a lock-bottom cyclone and separation of the charge particles, which leave the cyclone at the bottom, using a static electric field (*7*).

The Tri-Flo separator is a two-stage dynamic dense-medium separator. The unit may be considered as a pair of Dyna Whirlpool separators in series (*8*).

Gravity sedimentation/electrokinetic (electric phenomena of electrophoresis and electroosmosis) densification. Particle sedimentation can be accelerated by imposing a properly oriented electrical field on a suspension. This method takes advantage of the surface charge on the solid particles in a water suspension.

Simultaneous grinding and sieving (*9*).

Mining with the aid of solution-extraction techniques (*in-situ* leaching).

2. HYDROCYCLONES

New Hydrocyclones

There are 30 major manufacturers of cyclones in the world today, supplying units with diameters ranging from 10 mm to 50 in. Attempts have been made in the last 10 years to increase their capacity and efficiency, to develop new designs with minimized operating difficulties or for specialized applications, and to develop mathematical models for simulating cyclone performance. Several design modifications have been applied to conventional hydrocyclones with a view to extending their range and improving their performance (*10*). Examples: A small unit with a resolving power down to 5 μm (Mozley type) used for classification or clarification of solid suspensions was developed in the UK; a self-cleaning device protects the narrow inlet and outlets against choking. A new device of the spiral-cone hydrocyclone type was developed in Sweden, investigations being concentrated on the design of the inlet nozzle and on an interesting concept relating to the cone shape. A high-throughput choking-free cyclone was developed in Japan (*11*) in which the concentrate fraction (underflow) is removed continuously through the bottom of the cone by means of a spiral. Krebs Engineers has introduced hydrocyclone apex control devices (the Auto Apex) which may be attached to standard hydrocyclones to enhance their performance; these devices serve to minimize the water content of the underflow product when a hydrocyclone is used for thickening or dewatering pulp.

One of the most interesting of the new model from AKW is the Circulating Bed Classifier (CBC) hydrocyclone. The CBC unit is reported to utilize two separating effects in one unit. The hydrocyclone is of cylindrical shape with a flat bottom. By overthrottling the underflow nozzle, a rotating slurry bed is formed in the lower section of the cyclone. The classification in this bed, together with the more conventional classification in the top section, represents the two stages of the process. The automatically controlled height of the bed determines the mesh of the separation.

Cyclones of a new type are used for processing iron ore, diamonds, and coal by the "heavy-medium" technique (with ferrosilicon or magnetite), again with a view to obtaining improved efficiency and product quality. Hydrocyclones used for density separation with water medium are only able to separate particles in the finer size ranges and at relatively low separation efficiencies. Even the specially designed water-only cyclones cannot separate coarse particles. Liller developed a cyclone which is said to separate 50 mm to zero coal according to specific gravity in the range of 1.2 to 1.7 SG cut points (*12*). In this hydrocyclone the feed inlet is designed to create criticially deflected flow through a narrow restriction, thereby facilitating proper circulation within the unit. The vortex finder, which has an internal sleeve, is long, so as to prevent short-circuiting of the middlings.

Electrocyclone

The separative performance of a cyclone can be enhanced if electric forces are used to supplement the inertial ones. By precharging the particles and applying a radial electric field within the cyclone, collection efficiency is improved (*13*).

Cyclone-Magnet Combination

A hydrocyclone for aqueous suspensions containing a heavy medium (ferromagnetic particles) is combined with an electromagnet having specific intensity and orientation with a view to controlling the particle trajectories. Sorting or separation is affected according as the magnetic fraction is shifted toward the lower or the upper outlet of the hydrocyclone. If successful on an industrial scale, this technique may replace the standard magnetic-drum type separators used for recycling magnetite or ferrosilicon in HMS processing of diamonds, iron ore, and coal, as well as for separation of magnetite or pyrrhotite in beneficiation processes. The simplicity and reliability of the technique promise rapid development and immediate applicability.

Boxmag-Rapid (UK) has developed a low-intensity magnetic hydrocyclone thickener (*14*) capable of inducing very fine magnetic particles to report to the cyclone underflow while nonmagnetic particles remain unaffected. The magnetic field is shaped so as to have a radial component—perpendicular to the axis of the cyclone—with an outward gradient. As a result, the net magnetic force acting on a particle is also directed radially outward. By this means the apparent specific gravity of the material is enhanced, so that the behavior of a particle in the cyclone resembles that of one of somewhat larger diameter.

In clay processing, degritting hydrocyclones can be replaced by magnetic hydrocyclones which also remove some of the fine magnetic impurities from the clay product.

Desliming of iron ores in a magnetic hydrocyclone of new design is described by Yurov et al. (*15*). The concept of a magnetic hydrocyclone for concentrating titanomagnetite iron sands of New Zealand has been explored and developed (*16*). A conventional hydrocyclone was constructed to fit between the concentric annular poles of an electromagnet connected at the upper end. The inner pole has a smaller area than the outer one, so the magnetic gradient is increased radially inward and therefore directs magnetic particles to the overflow. A product grade (% magnetics) and a recovery that both exceeded 95% were obtained readily from an artificial mixture of magnetite and quartz sand.

Air-sparged Hydrocyclone

Preliminary test results for an air-sparged hydrocyclone (*17*) indicated that it gives coal separation efficiencies similar to those of conventional flotation cells. The air-sparged hydrocyclone consists of a steel jacket containing a porous cylinder for the dispersion of air. Various configurations of the feed inlet and product outlets have been tested. The fine air bubbles sweep through the conditioned pulp and attach themselves to coal particles. Due to buoyancy, the coal/bubble aggregates are driven toward the cyclone axis and leave through the vortex finder. Nonfloating particles move radially outward and leave through a tangential outlet.

Since the particles and bubbles are subjected to centrifugal forces several times those of gravity, the separation is rapid. Retention time is only about 2 s. The generation of a large number of finer bubbles and the directional, rather than random, interactions of particles with freshly formed bubbles improve flotation conditions. The probability of particle–bubble collision and attachment, especially for fine particles, is said to be superior. The 150-mm diameter air-sparged cyclone used in the tests on a -0.59 mm coal feed, containing 50–70% finer than 38 μm, gave 0.9 t/h capacity with results equalling those from batch flotation. The separation was vastly superior to that obtained with water-only cyclones. Comparison of air-sparged cyclones with conventional flotation cells shows that they have about 30 times higher throughput per unit volume, one-third energy consumption, and cost about half.

Operation and Applications

The hydrocyclones are simple and versatile devices. The underflow may be open to the atmosphere or else discharge into a piping network and thus be isolated from the atmosphere. For this latter condition the air core usually does not develop at the center of the hydrocyclone. This is referred to as flooded underflow operation or close-bottom hydrocyclone.

The hydrocyclone operates as a mechanical separator, since mechanical separation is taken to involve the response of particles to gravitational, inertial, or centrifugal forces in the presence of at least one other force which is usually the viscous drag of water or air. The particle size, shape, and density, the fluid density and viscosity, and the solids concentration in the fluid suspension all have a bearing on mechanical separation.

Physical separation methods such as gravity thickeners, hydrocyclones, filters, and centrifuges all reduce water content or increase solids content of a given suspension. Figure 1 shows the relative capabilities of common unit operations of classical dewatering methods in terms of the slurry particle size.

In order to promote good solid–liquid separation efficiency in hydrocyclones:

(a) A strong vortex must be present so as to produce high centrifugal forces separating particles from the fluid flow
(b) Low turbulence levels are essential so as to minimize intermixing across the unit
(c) Particulates must be removed from the separation region as early as possible so as to reduce the possibility of reentrainment

Table 1 illustrates the versatility of conventional hydrocyclones in a variety of process categories (mineral and metallurgical processing, coolant fluids in machining operations, pulp and paper, drilling-mud treatment, food industry, and in the process industries generally).

For other design features, improvements, and fields of application for conventional hydrocyclones, see elsewhere (*11*).

3. LOCK-BOTTOM HYDROCYCLONES

A different example is the lock-bottom hydrocyclone with a single inlet and outlet. (The lock-bottom hydrocyclone is basically similar to the dust collecting cyclone.) It is used for solid–liquid separation processes or

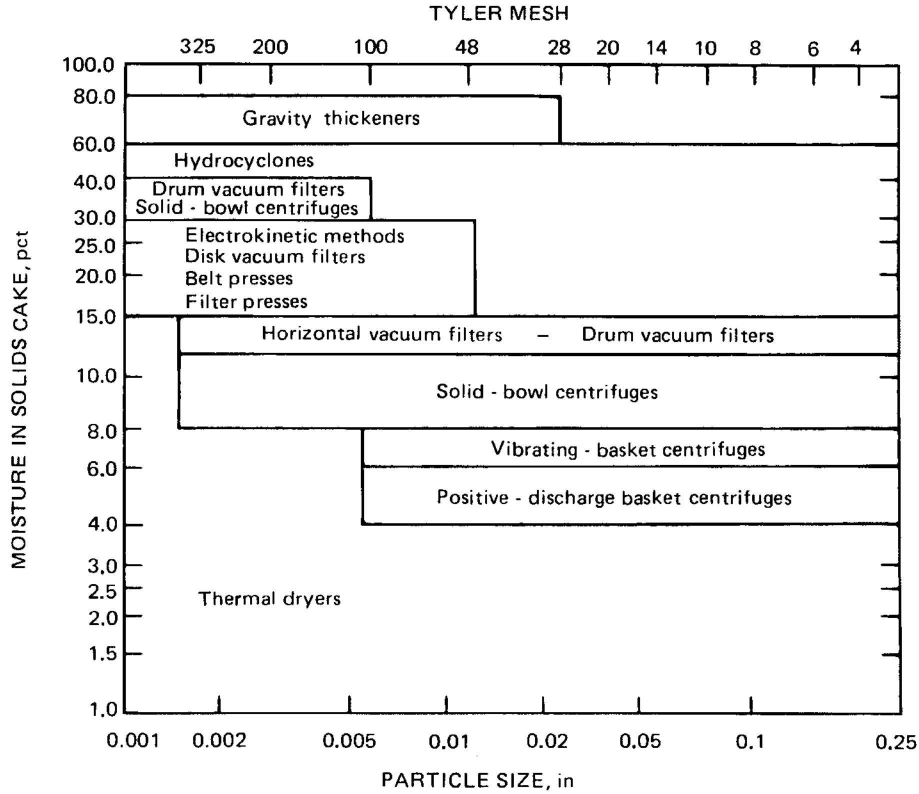


FIG. 1. Size limitations on S-L separation of wettable solids.

filtration-thickening unit operations, the solids bin serving as thickener; its use is in concentration and enrichment, classification, or clarification with a view to reducing the load on filters and centrifuges. These units (*18, 19*), single or in battery form, are employed in removal of suspended solids from well water, gas, and crude oil; for prefiltration in sprinkler and drip irrigation; for protection of liquid pipelines in industry and of domestic water piping, etc. Cleaning in special cases is effected by means of a flexible wire installed along the hydrocyclone axis.

Figure 2a is a schematic representation of a lock-bottom hydrocyclone (one entrance port and one exit port) made of Pyrex. The unit serves for laboratory experiments and tests, both for determination of particle paths and observation of the flow regime (in the cylindrical portion of the hydrocyclone and in the lower container) and for finding the efficiency of

TABLE 1
Generalized Hydrocyclone Application Categories

Classifying Desired Solids	
(a) Degritting and removal of oversized particles	Lime slaking, kaolin, ceramics, pollution wastes
(b) Fractionation of pigments and fillers	Calcium carbonate, mica
(c) Desliming slurries	Potash, coal, minerals
(d) Closed-circuit grinding operations	Calcite, taconite, copper
(e) Classifying tailings for backfill use or recovery	Phosphates, dredging wastes, underwater concentration of heavy mineral sands
(f) Processing for proper sizing	Crystallized salts, sand
(g) Product separation	Starch, minerals, waste plastic recycling
Thickening of Solids and Clarifying Fluids	
(a) Desanding and degritting water	Municipal and process waters
(b) Recovery of catalysts	Petroleum cracking, chemical reactions
(c) Thickening of slurries prior to deliquoring	Polymers, coal, urea
(d) Cleaning up fuel for engine consumption	Diesel oil, crude oil
(e) Thickening crystallized slurries	Adipic acid, ammonium sulfate
(f) Desanding fluids to gathering lines in order to reduce system maintenance	Water, crude oil, various slurries
(g) Removing solids from evaporation systems	Organic and inorganic crystals
(h) Cleaning up disposal well and injection fluids to maintain formation permeability	Waterflooding, solution wastes
Treating Slurries to Benefit Other Equipment	
(a) Removing oversized particles to reduce plugging	Spraying systems, nozzle centrifuges, coalescers
(b) Partial separation of solids to improve cycle	Basket centrifuge, cartridge/leaf filters
(c) Concentration of slurries to increase capacity and performance	Centrifuges, filters, crystallizers
(d) Removal of abrasive material to reduce maintenance	Centrifuges, pumps, flotation units, other equipment
(e) Cleaning up filtrates to improve performance	Screen centrifuges, filters
(f) Removing solids from process streams to minimize scaling	Piping, heat exchangers
(g) Processing bottoms to improve performance, eliminate cleanout	Storage vessels, settling tanks, lagoons

(*continued*)

TABLE 1 (*continued*)

Cleaning up Recirculating Fluids

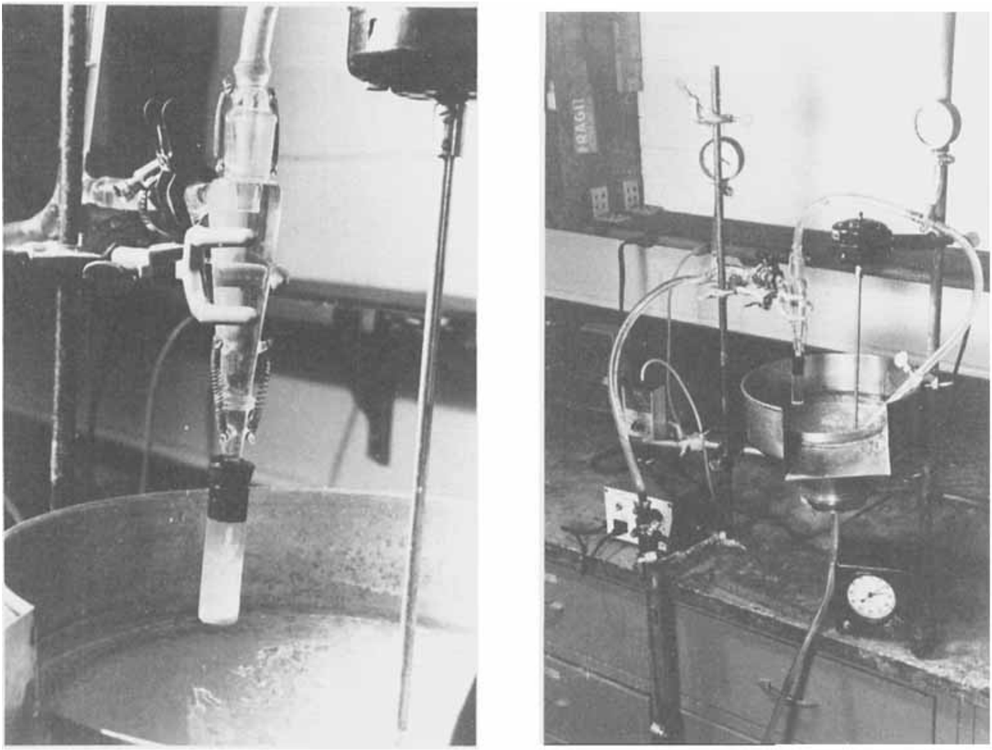
(a) Cleaning coolant fluids	Machining and grinding operations
(b) Separating oversized matter	Lapping and polishing systems
(c) Maintaining water quality	Cooling towers, air-conditioning systems
(d) Recovering soaps, detergents, solvents, and water	Washing operations
(e) Rejecting sands and silts	Drilling and treatment
(f) Cleaning up fluids used to cool or lubricate	Seals and bearings in pumps and other equipment
(g) Removing solids from oils and fluid baths	Heat treating

solid separation under different conditions of pressure and flow (Fig. 2b). The following were established: Classification, separation, and sharpness of cut of solids in the lock-bottom hydrocyclone are superior to those achieved in the conventional open-exit-port hydrocyclone; particle sedimentation in the container proceeds noiselessly with minimal turbulence (exchange of liquid between the pot and the hydrocyclone is from 4 to 8%); the sediment in the container undergoes a process of compaction; no liquid is lost in the system (the quantity of liquid entering the separator equals that issuing from it through the vortex finder); considerable saving in investment and energy costs seems possible with the new type unit.

Figure 3 describes the 4″/1″/1″/1″ hydrocyclone connected to a (transparent) container (underflow receiver) for collecting solids. The form of the sediment obtained and their consolidation can be observed, and the decision when to drain is facilitated.

Figure 4 shows a lock-bottom hydrocyclone forming an integral part of the outlet line of a water well and serving for continuous elimination of solids, thereby ensuring a clean water supply for the consumers. The separation capability of this particular unit is 50 μm (it functions efficiently with a head as low as 7 m, the separation capability increasing with the flow). Solid discharge is achieved by a manually or automatically operated purge value.

Figure 5 shows a bank of lock-bottom hydrocyclones (4 units of the type 8″/2″/2″/1″) operating in parallel to accommodate large flow rates in the drip-irrigation line of a cotton field. The units are installed on a common collection tank equipped with a bottom drain. This system serves for preliminary separation of particulates and is followed in series



(a) (b)

FIG. 2a. Transparent lock-bottom hydrocyclone laboratory test unit (30 mm diameter, small-cone-angle). Manufactured by Liquid–Solid Separations Ltd., UK.

FIG. 2b. Glass test rig for laboratory separation tests.

by a mechanical filter. Hydrocyclones of this type are used in agriculture, in Israel and elsewhere.

Another example: The Mining Research & Development Establishment of the National Coal Board, UK, has developed an efficient and low-cost lock-bottom hydrocyclone filter. The device is primarily intended to prevent blockage of water sprays by removing solid particles from the water (*20*).

Lock-bottom hydrocyclones can also be used as sand testers. Such a device, introduced into a liquid pipeline (see Fig. 6), enables the amounts of suspended particles present to be determined continuously and with maximum efficiency. The aggregate of solids collected in the sandmeter (the container is made of glass and shaped like a test tube) can be

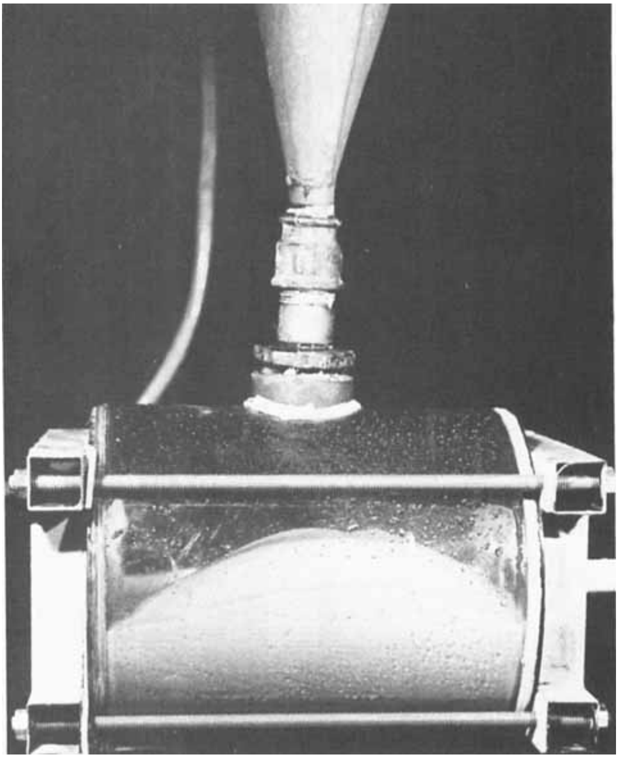


FIG. 3. Solids accumulation in the sand chamber (4″/1″/1″/1″ hydrocyclone).

estimated without delay. Mounting two sandmeters—one at the entry port, the other at the exit port—on a given hydrocyclone (as shown in Fig. 4) enables the efficiency of separation of a hydrocyclone or any other separation or classification device to be determined.

One serious limitation of the lock-bottom cyclone is that its feed may contain only minimal amounts of solids. The limiting factor in this type of equipment is handling of material removed from the liquid and stored in the collection vessel. Solids build up very rapidly, and it is extremely difficult to handle high loads (large tonnages) of solids as they are discharged from the sealed tank. Generally speaking, this type of equipment is thus limited to uses in which the solids in the feed are of the order of 0.1% by weight.

Despite the amount of knowledge we have concerning hydrocycloning, its practice is still an art.

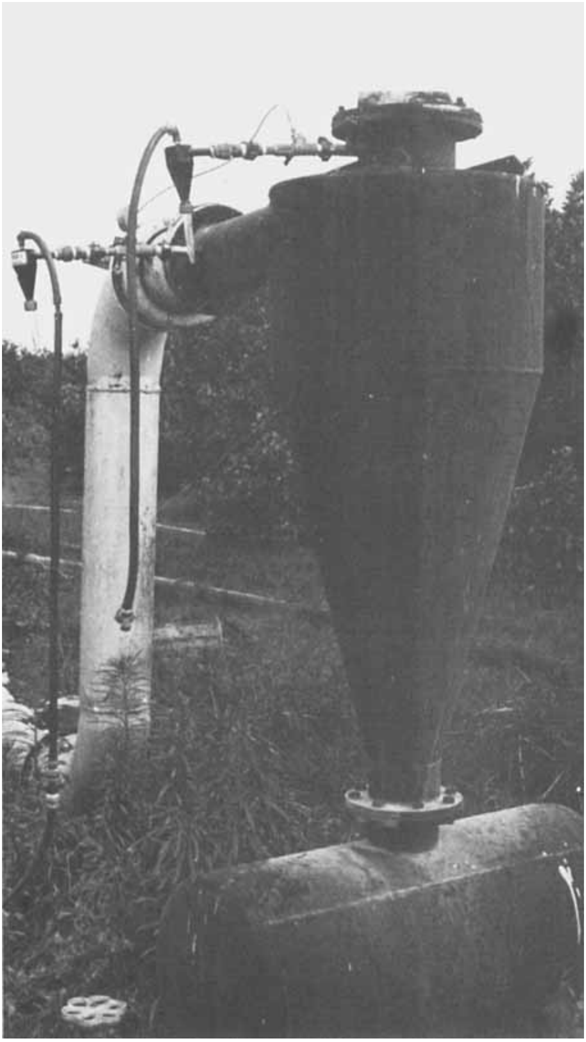


FIG. 4. Lock-bottom hydrocyclone for S-L separation in water well system. Manufactured by Mekorot Ltd.

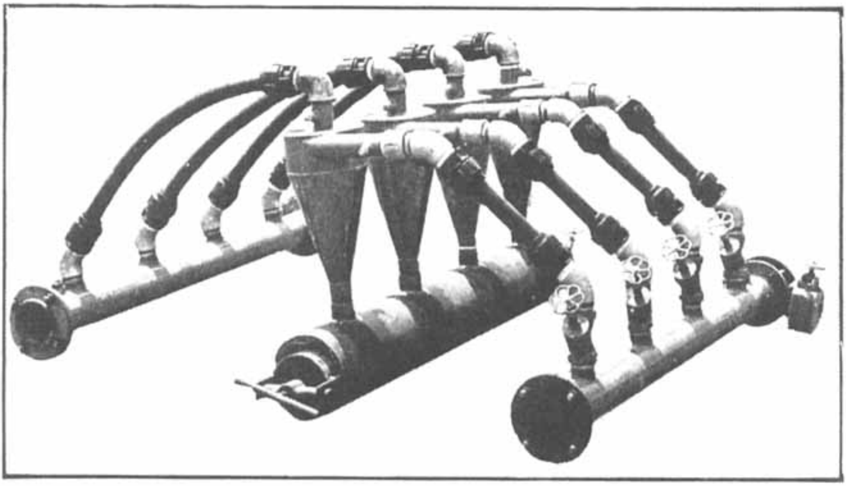


FIG. 5. Lock-bottom hydrocyclones (modular construction), 4 production units in parallel, utilized for prefiltration in a drip-irrigation system (single units are fed with fluid at the same pressure and flow rate). Manufactured by Netafim.

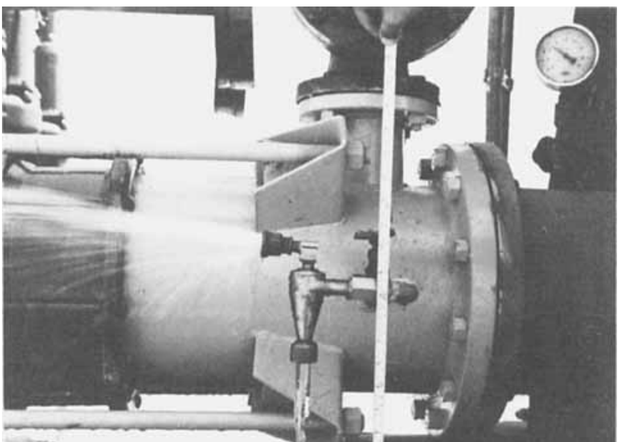


FIG. 6. Sand tester for on-line measurement of solids content.

4. CYCLO-THICK UNIT

Several methods were tried in the past in attempts at integration of processes, but most of them were never applied industrially. The importance of such integration lies in the simplification it brings as well as in the shorter time that integrated processes require. These, in turn, lead to savings in costs and equipment, higher process efficiency, and improved control.

The author's one-stage "cyclo-thick" unit combines the unique features of the hydrocyclone and of the thickener (high-rate or lamella thickener) in a single piece of equipment. Separation, classification, and washing of the solid particles take place in the hydrocyclone part, while settling and thickening occurs in the closed-pot part. Solids are discharged manually, automatically (cyclic operation), or continuously.

The proposed device includes a conventional hydrocyclone but with very smooth inner surfaces, to the base of which a settling tank is connected. A spiral mounted at the bottom of the tank serves to evacuate the solids in continuous operation. Different kinds of hydrocyclone (sizes, shapes, ordinary or magnetic, etc.) can be installed as well as different sizes and shapes of tanks. The spiral (screw conveyor) is rotated at the speed needed to achieve the desired rate of solids removal.

As regards classification, the coarser and heavier particles which have settled in the lower portion of the sand chamber are continuously removed by the spiral, removal capacity being governed by the geometry and rotation speed of the latter. If the settled sands are not removed at a suitable rate, pulp density and viscosity will build up in the settling zone. The build up starts in the lower depths of the sand chamber and works itself upward into the effective settling depths.

In dewatering operations, the sand discharge product should contain no free moisture but should be dry enough to be easily transported on sloping conveyor belts for proper handling or disposal.

The device (shown in Figs. 7 and 8) has the following advantages: It is simple, versatile, and inexpensive; it is equally efficient in solid–solid and solid–liquid separation; the space it occupies is modest; it functions continuously and at high flow rates and is capable of treating both concentrated and dispersed suspensions. A high solid-to-liquid ratio is achieved in the thickened product, and utilization of the centrifugal force makes the machine competitive with, and even superior to, ordinary gravitational settlers. It is easily controlled, energy-saving, and suitable for treatment of particles down to 1 μm. Finally, it reduces the feed load on the mechanical filter situated downstream, its initial cost is low, and its maintenance requirements are minimal. Other advantages of the

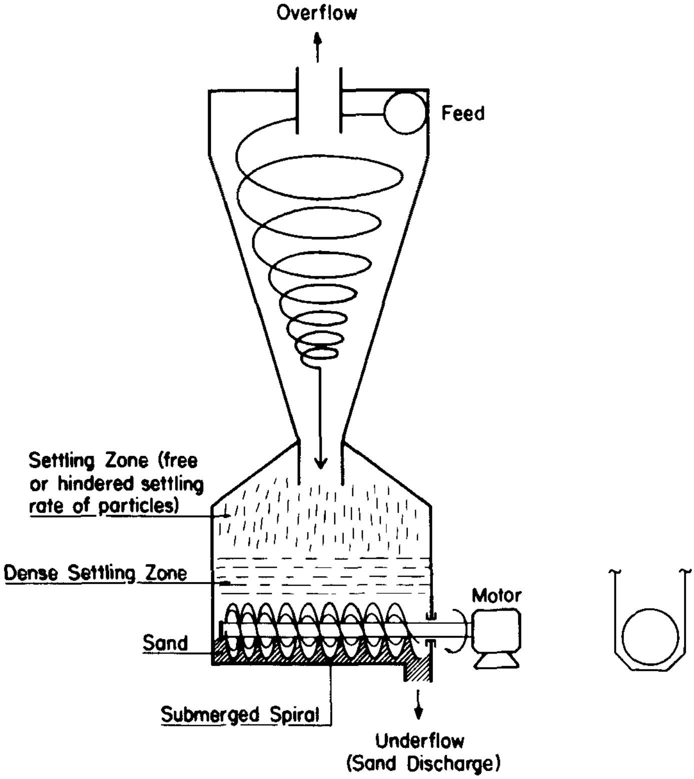


FIG. 7. Diagrammatic representation of cyclo-thick unit.

cyclo-thick system are the low mean retention time, the compactness of the unit, and its ability to withstand very high pressures. The transportable/modular units also have the advantage of being readily moveable.

Innovations have been introduced in reducing the space needed for gravity thickeners. First among these are the high-capacity or high-rate thickeners which have much smaller tanks than their conventional counterparts (5–10 ft^2 vs 0.3–0.6 ft^2 for each ton of solids per day). Second is the multiple-plate thickener which uses a series of uniformly spaced inclined plates positioned in a settling tank. The latter are in use by the mineral industry around the world for clarifying, classifying, and thickening. Both may function as thickening units as part of the cyclo-thick. Thus the cyclo-thick can reduce space requirements by as much as 90% compared with conventional thickeners.

Figure 9 shows the cross section of a cyclo-thick with the zonal pattern

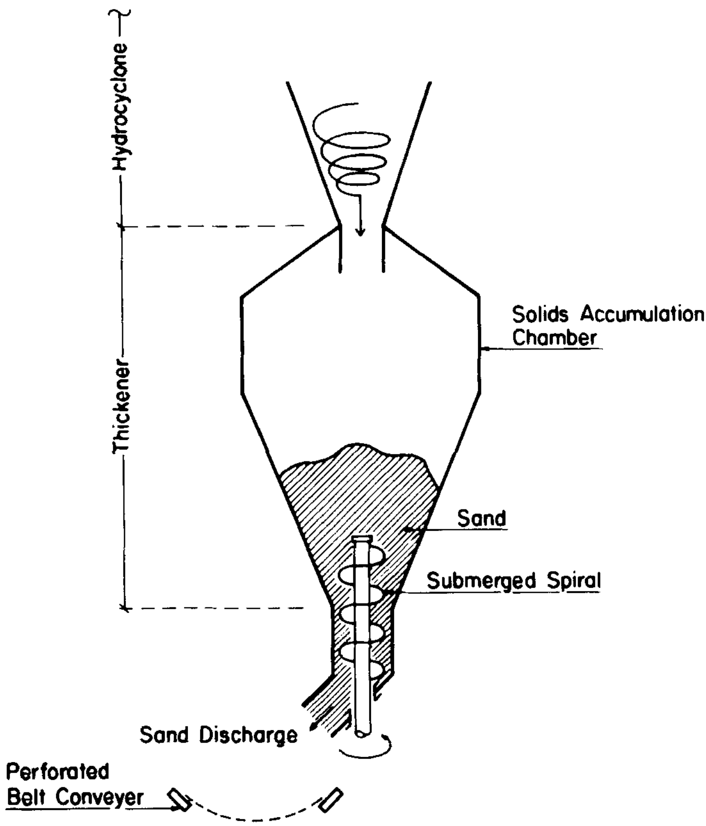


FIG. 8. Modified cyclo-thick unit.

of the sedimentation process. In the case of hard-to-treat solids, chemicals may be added either directly into the underflow well to aid settling (the efficiency of the flocculation depends on how thoroughly the flocculant and the slurry are mixed) or to the hydrocyclone feed to accelerate flocculation of particles that do not immediately separate from the liquid. The high degree of shearing and mixing within hydrocyclone generally necessitates large polymer doses to effect an increase in solids recovery. The unit shown in Fig. 9 has a smaller sand tank because it discharges the underflow stream directly into the bed of settled solids and uses chemical additives to accelerate flocculation of the sediments. Compression may be enhanced by means of a low amplitude vibrating pack mounted inside the sand tank. This vibration reduces the apparent

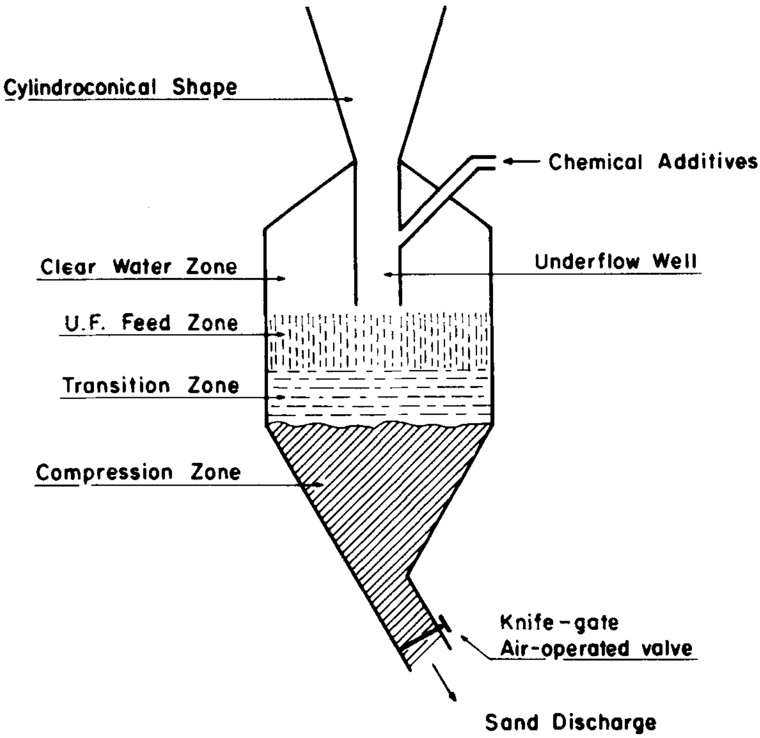


FIG. 9. Cross-section view of cyclo-thick showing zones of the sedimentation process.

viscosity, prevents hang-ups and "rat holing" effects, and ensures safe discharge.

Field experiments indicate that the "cyclo-thick" unit is not limited by the type of problems associated with the locked-bottom hydrocyclones. Its corrected cut size (the size at which the unit effects its separation, not accounting for the fraction of feed that by-passes the classification process) or cut point are superior compared with ordinary hydrocyclones; sharpness of size separation at different fineness is as for the normal cyclone of equal diameter; water-flow split between the U.F. and O.F. streams is zero (in practice, the volumetric flow rate of pulp that reports to the U.F., via the apex, is almost zero); the pressure drop profile across the unit differs from that of an ordinary hydrocyclone of similar geometry, and the design and operational parameters of the cyclo-thick also differ accordingly; underflow pulp density is always higher than in normal hydrocyclones; and operation is free of problems. The cyclo-thick is simple in design and operation, for the only item requiring operator attention is the sand-withdrawal spiral located at the sand discharge outlet and controlled by a variable-speed motor and/or a timer.

Hydrocyclones essentially effect volumetric partition while closed-pot hydrocyclones do not. Since the volumetric content of a cyclo-thick is very small relative to its throughput, the retention time is short, of the order of several seconds at most (quick product turnover). The cyclo-thick's output material is more uniform in its mineralogical constitution, chemical composition, and physical consistency, therefore most of the downstream unit operations processing this material could perform closer to their optima in terms of throughput capacity, attainment of target specification, and minimized specific power consumption.

The degree of classification or clarification of the fluid phase and thickening of the solid phase depend on optimal design of the cyclo-thick and on control of the operational variables. In solid–liquid separation, at small cutpoint sizes, batteries of multiple units must be installed with a common underflow pot.

As a vehicle for solid–liquid separation the cyclo-thick has a range of uses that range from dewatering and desliming to particle-size fractionation, and its designs vary accordingly. The following are some proposed industrial applications:

In mining: S-L separation in cooling water installations for deep-level mining operations; S-L separation in backfillings (preparation of underground mine fill material by hydrocycloning); suspension treatment in solution-mining activities; processing of soluble salts (sodium chloride and sulfate, trona, potash, etc.) and brines; and processing of drilling mud.

In chemical engineering: Treatment of slurries and effluents mainly for S-L separation; degritting; water clarification; S-L separation after hydraulic transport; solvent recovery; separation of immiscible liquids; and removal of scale from cooling water in open and closed systems (including cooling-tower blow downs).

In mineral dressing: Treatment of slurries and for classification, clarification, thickening (prethickening ahead of dumps, screens, filters, centrifuges, and thickeners; postthickening of the effluents of screens, centrifuges, and filters; rethickening of slurries), desliming, elutriation, or washing; treatment of dilute or thick suspensions when building tailing dumps; preconcentration.

In the oil industry: Separation of liquid droplets from gaseous or liquid media and solid particles from fluids; gas–oil separation for use in oil production operations, in cleaning of compressed air, etc.; separation of oil from water (removing contaminant oil up to a few percent from water); dewatering of oils (removal of water from oil); and separation of suspended solids from crude oil close to the well head.

In other industries: Petrochemicals, agriculture, food processing, pharmaceuticals, metal working, textiles, etc.

The cyclo-thick design philosophy proves that a unit operation can be made extremely compact by applying the principle of process integration. There are occasions where a highly compact layout is indispensable, such as when new equipment or a modification to the existing plant has to be housed within limited space in an existing building. Saving is usually effected in all areas of construction materials and power requirements. The cyclo-thick also has the advantage of being readily moved to other parts of a site. This should be a significant contribution to the art of plant design, e.g., process plant modularization.

5. CONCLUSION

The pressures under which the mineral industry operates call for higher efficiency, lower costs, and development of improved technologies for hitherto unfeasible tasks.

The use of centrifugal force instead of natural gravitational force and of closed settling tanks as thickening units probably represents the greatest opportunity for reducing the physical size of the equipment in processing plants.

Development of the cyclo-thick is still in full swing, and new fields of application will be created, especially those involving fine and very fine particles.

The cyclo-thick is not only remarkably simple and clean in design, but also uniquely efficient. This unit should be considered as a viable alternative when evaluating potential solutions to a given separation or filtration problem.

REFERENCES

1. I. J. Lin, "Technological Innovations in Separation of Particulates in S-L and S-S-L Systems," *Sep. Purif. Methods, 13*(1), 1–42 (1984).
2. I. J. Lin and A. Roisenberg, "Multifractionation of Minerals in a Single Operation," in *Proceedings of the XIIth International Mineral Processing Congress, Sao Paulo, Brazil, 1980,* Vol. 1, pp. 322–349.
3. I. J. Lin and T. B. Jones, "General Conditions for Dielectrophoretic and Magnetohydrostatic Levitation," *J. Electrost., 15,* 53–65 (1984).
4. I. J. Lin, "Manipulation of Mineral Properties by Reagents and Solid Additives in Relation to Beneficiation Processes," *Ind. Miner.,* pp. 43–51 (May 1985).

5. K. Schellinger and O. C. Shepard, *Trans. AIME, 183,* 219 (1949); S. Stoev, *World Min. Equip.,* p. 50 (November 1983).
6. S. Stoev, "Vibro-Acoustics—The Benefits to Industrial Minerals," *Ind. Miner.,* pp. 64–67 (January 1980).
7. J. Bouwma and B. H. M. Kuypers, "Coal Cleaning Using Electrostatic Separation," in *Proceedings of the International Symposium on Electrical and Magnetic Separation and Filtration Technology, Antwerp, Belgium,* May 1984, pp. 24–25.
8. G. Ferrara and H. J. Ruff, "Dynamic Dense Medium Separation Process," *Erzmetall, 35,* 294–299 (1982).
9. J. D. Brown and I. I. Inculet, "An Apparatus for Simultaneous Grinding and Sieving of Coal," *Can. Min. Metal. Bull.,* p. 40 (December 1975).
10. D. N. Hepbur, in *Proceedings of the International Conference on Hydrocyclones, Cambridge, UK,* October 1980, p. 1.
11. L. Svarovsky, *Hydrocyclones,* Technomic, London, 1984.
12. D. I. Liller, "Cyclone Separates Close Gravities," *Coal Age,* pp. 72–73 (January 1982).
13. P. W. Dietz, "Electrostatically Enhanced Cyclone Separators," *Powder Technol., 31,* 221–226 (1982).
14. *Magnetic Hydrocyclone Thickener,* Boxmag-Rapid, Ltd., Publication BR-14-C, February 1983.
15. P. P. Yurov and V. G. Pavlenko, "Desliming of Iron Ores in a Magnetic Hydrocyclone of New Design," *Cher. Metall., 7,* 35–37 (1984); *Chem. Abstr., 101*(24), 214437a.
16. A. G. Fricker, "Magnetic Hydrocyclone Separator," *IMM Trans., 94,* 158–163 (1985).
17. J. D. Miller and M. C. Van Camp, "Fine Coal Flotation in a Centrifugal Field with an Air-Sparged Hydrocyclone," *Min. Eng.,* pp. 1575–1580 (November 1982); J. D. Miller, U.S. Patent 4,279,743 (July 21, 1981).
18. I. J. Lin and Y. Riech, *Design of a Hydrocyclone Sand Separator for Purification of Water,* MERC Rep. 016-065, January 1973.
19. Y. Reich and I. J. Lin, *Production of Hydrocyclones in New Area,* MERC Rep. 016-107, April 1978.
20. Anon., "Highly Efficient, Low Cost Hydrocyclone Filter," *Min. J.,* p. 454 (June 1982).

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