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DEVELOPMENT OF A MAGNETIC HYDROCYCLONE SEPARATION FOR THE RECOVERY OF TITANIUM FROM BEACH SANDS

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The recovery of titanium from very fine particles of beach sand of Sri Lanka has been investigated using conventional hydrocyclone and novel magnetic hydrocyclone separation methods. A new design for a magnetic hydrocyclone has been developed using a permanent rare earth neodymium–iron–boron (Nd–Fe–B) magnet. Compared to the conventional hydrocyclone, this magnetic hydrocyclone was 5% more efficient in the recovery of titanium from the beach sand deposit with a commercial standard concentrate. It was also found that, for very fine particles, the titanium grade increased significantly (up to 56% TiO_2) when titanium-bearing minerals were separated using the novel magnetic hydrocyclone separation technique. Therefore, this type of magnetic hydrocyclone has potential to produce significant reduction in the processing time, thus saving energy and the running cost in an appropriate industrial application economically and efficiently.

Keywords: Beach sand; Titanium; Permanent magnet; Magnetic hydrocyclone

1. INTRODUCTION

Hydrocyclones have become a standard method of separating dispersed solids from liquids throughout the chemical and mineral industries. The devices use centrifugal forces to separate two minerals of different densities or to de-water one mineral. The devices have high capacity and low capital, maintenance and operating costs [1,2].

The feed slurry enters through a tangential inlet at the top of the hydrocyclone. The circular flow of the fluid directs the heavier particles towards the outer wall under the action of a centrifugal force. Radial movement is hindered by the drag force as the particles move through the carrying fluid. As the flow descends in the hydrocyclone, the layer adjacent to the hydrocyclone wall becomes loaded with heavy particles, which exit the device through the underflow (Fig. 1). The underflow diameter, however, is smaller than the inlet, so not all of the fluid can exit. A secondary,

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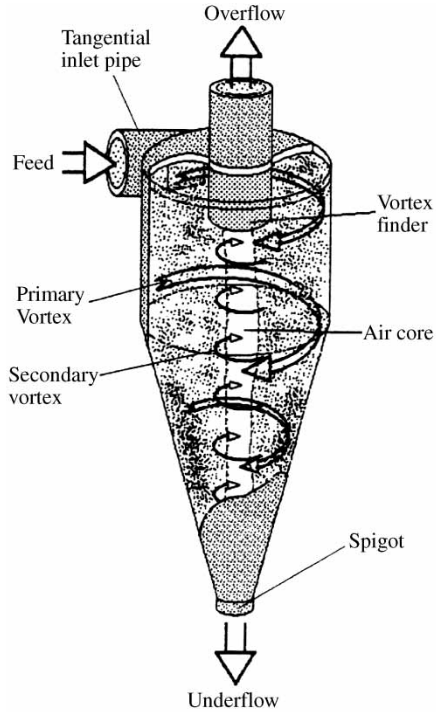

FIGURE 1 Hydrocyclone separator.

inner vortex is created when the fluid, still spinning in the same direction, rises up the length of the hydrocyclone and leaves through the overflow [1,2].

The magnetic hydrocyclone was developed as a natural extension of a conventional hydrocyclone with the aim of providing additional external magnetic force to supplement the gravitational and centrifugal forces that cause classification and separation. By providing such an external force, it is possible to manipulate the separation more efficiently under a wide spectrum of experimental conditions [2–4].

A number of designs have been manufactured, which fall into two design criteria. The first type was designed to attract a magnetic component to the overflow. The system used an electromagnet, where the inner pole formed the vortex finder with the overflow exiting through the centre of the inner pole, and the outer pole surrounded the hydrocyclone body. The second type has the magnets on the outside of the hydrocyclone body, attracting magnetic components to the underflow [2,5]. The magnet arrangements which have been developed include a dipole electromagnet, a quadrupole electromagnet and quadrupole permanent magnets [2].

All of these devices had varying degrees of success in improving the recovery of magnetite (Fe_3O_4) particles. The permanent magnet-based hydrocyclone was applied to beneficiation of the roasted magnetite ore and was reported to have removed fine low-grade material efficiently into the tailings [2]. Some studies showed that the application of the magnetic field in the hydrocyclone separation improved the recovery of ferrimagnetic magnetite by 6% from a magnetite suspension and paramagnetic ilmenite ($FeTiO_3$) by 1.5% from an ilmenite suspension [2].

The objective of this investigation was to study the application and optimisation of conventional hydrocyclone for the recovery of titanium-bearing minerals from very fine particles of beach sand deposits of Sri Lanka. This investigation was also intended to have improved efficiently the recovery of titanium from the deposit using a novel method of magnetic hydrocyclone.

2. EXPERIMENTAL PROCEDURE

2.1. Mineralogical and Chemical Analysis

The heavy mineral beach sand sample from Pulmoddai deposit in Sri Lanka, which was supplied by Lanka Mineral Sand Ltd, was used. Detailed mineralogical and chemical analysis of the deposit has been carried out in our previous published experimental work [6].

2.2. Hydrocyclone Separation

The experiments were carried out with a Mozley C 700 rig, using a 50 mm hydrocyclone (vortex finder size was 14.3 mm and diameter of the spigot was 4.5 mm), which is illustrated in Fig. 1. The applied feed pressure of the unit was varied from 34.5 to 172.5 kPa in this study. Representative fractions were riffled from raw beach sand samples of particle size less than 355 μm and ground down to particle size less than 63 μm using a Siebtechnik Tema mill. Approximately 100 g of finely ground (−63 μm) representative sample of beach sands was mixed in the rig with 10 L of water to a concentration of 10 g/L in each test run. After a 10 min equilibrium, the hydrocyclone underflow and overflow were sampled for a set period, normally 8 s. Underflow and overflow volumes were measured. The solid split was determined by filtering and drying the products.

Mineral samples were decomposed by fusion with $KHSO_4$ at 800°C and the melt was dissolved in 20% H_2SO_4 acid [7]. Titanium analysis was carried out in a UV/Visible spectrophotometer based on the yellow complex formed by titanium and H_2O_2 [8]. Total iron was analysed using an atomic absorption spectrophotometer. The relative errors of analysis of titanium and iron were ± 3.5 and $\pm 2.0\%$ respectively. Each experiment was carried out four times to check reproducibility.

2.3. Magnetic Hydrocyclone Separation

The second technique employed in this study was magnetic hydrocyclone separation for the beneficiation of titanium-bearing minerals from the deposit. A magnetic coupling was added to the outside of the hydrocyclone. A permanent rare earth magnet, which was made from neodymium–iron–boron (Nd–Fe–B) with maximum field strength of 0.6 T, was employed in this test work. The magnet rings were made of sintered Nd–Fe–B and mild steel was used for pole pieces. A cross section of the magnet coupling surrounding the cyclone body is shown in Fig. 2.

The experiments were carried out according to the same experimental procedure given previously. Dense magnetically susceptible titanium mineral particles were

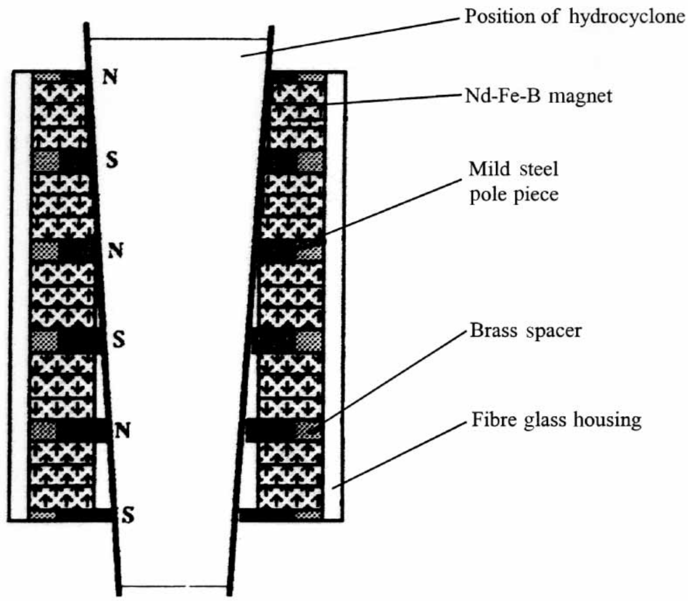

FIGURE 2 Cross section of the magnet coupling for the magnetic hydrocyclone.

separated into the underflow and the lighter gangue minerals were concentrated into the overflow.

3. RESULTS AND DISCUSSION

Figures 3 and 4 present the recovery and the grade of titanium and iron in different underflows, when titanium-bearing minerals were separated from beach sand using standard hydrocyclone separation technique. In this test work, reproducibilities of titanium grade and recovery were within ± 0.7 and $\pm 0.6\%$ respectively whereas reproducibilities of iron grade and recovery were found to be within ± 2.3 and $\pm 0.6\%$ respectively. The titanium grade in the underflow was increased from 28.2 to 32.9% by varying the feed pressure from 34.5 to 172.5 kPa, whereas there was no obvious variation in the grade of iron in the underflow with the increased feed pressure. However, there was a remarkable increase in the recovery of titanium and iron in the underflow with the feed pressure increased to 138.0 kPa. The recovery and the grade of titanium in the underflow increased slightly from 138.0 to 172.5 kPa feed pressure.

The titanium recovery was 44.2% with a grade of 28.2% at a feed pressure of 34.5 kPa. There was a significant increase in the recovery of titanium and iron in the underflow at a feed pressure of 138.0 kPa, giving 63.0% titanium recovery with a grade of 32.6 and 64.4% iron recovery with a grade of 16.0%.

Experimental results (Figs. 3 and 4) showed that using the hydrocyclone separation at its maximum experimental feed pressure of 172.5 kPa, the maximum recovery of titanium was 63.8% with a grade of 32.9% and the maximum recovery of iron was 64.6% with a grade of 15.6%.

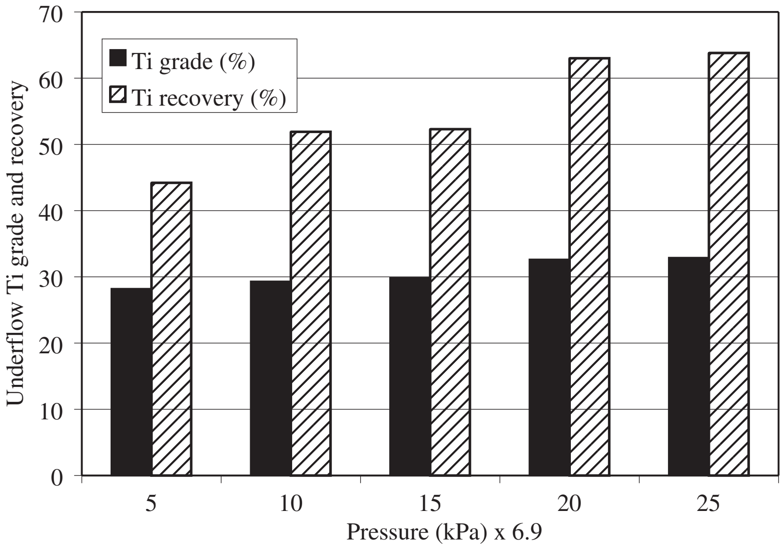

FIGURE 3 Titanium grade and recovery from the underflow from the hydrocyclone.

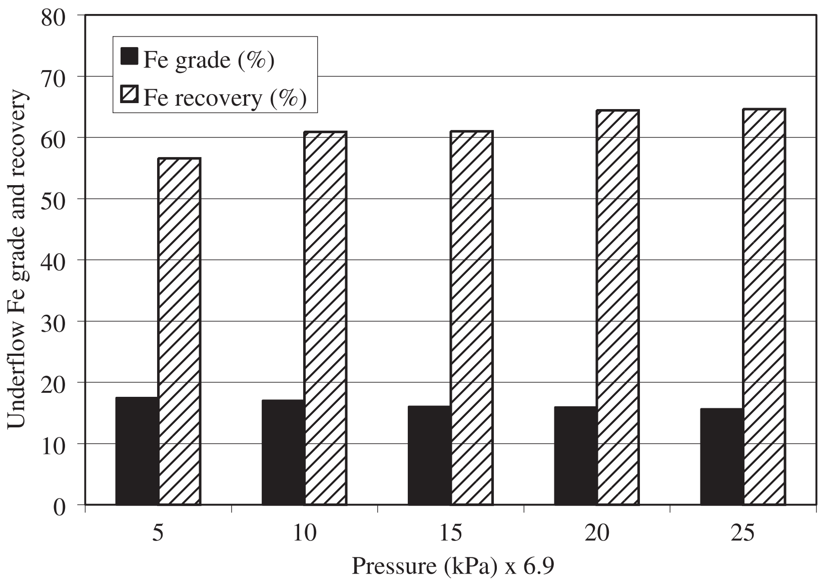

FIGURE 4 Iron grade and recovery from the underflow from the hydrocyclone.

Figures 5 and 6 show the recovery and the grade of titanium and iron in different underflows, when titanium-bearing minerals were separated from the deposit using the magnetic hydrocyclone. In this experimental work, reproducibilities of titanium grade and recovery were found to be within ± 0.8 and $\pm 1.0\%$ respectively whereas reproducibilities of iron grade and recovery were within ± 2.1 and $\pm 1.1\%$ respectively.

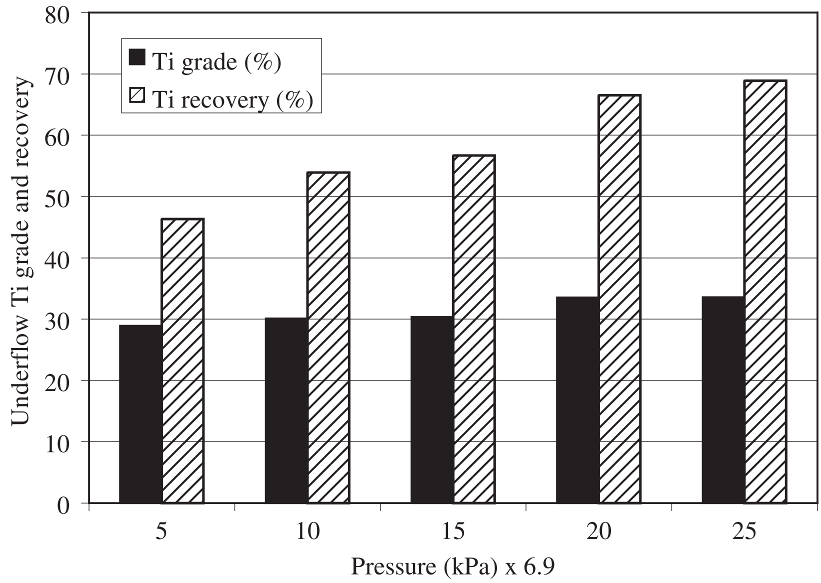

FIGURE 5 Titanium grade and recovery from the underflow from the magnetic hydrocyclone.

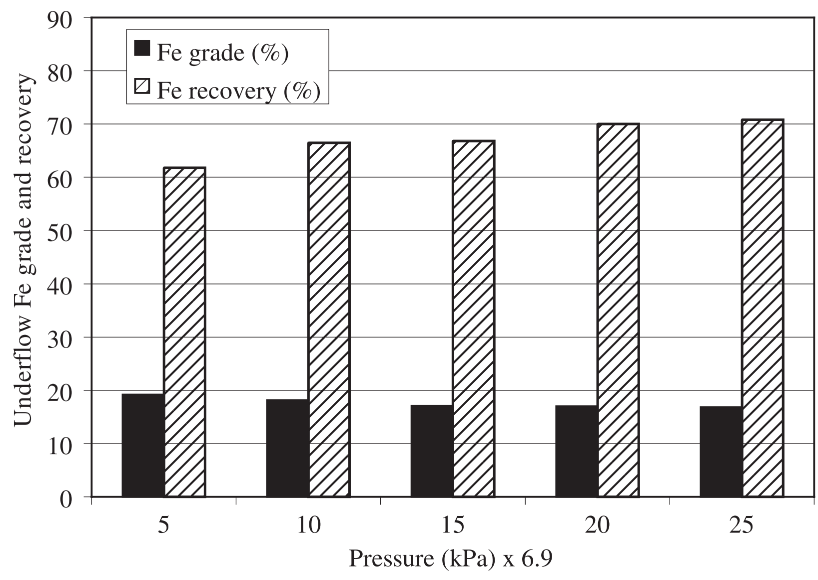

FIGURE 6 Iron grade and recovery from the underflow from the magnetic hydrocyclone.

In this test work, the titanium grade in the underflow was increased from 28.9 to 33.6% with the feed pressure increased from 34.5 to 172.5 kPa. However, iron grade in the underflow decreased slightly with the increased feed pressure. The recovery of titanium and iron in the underflow increased with the feed pressure increased up to 138.0 kPa, and there was no significant increase in the recovery of titanium and iron in the underflow above this feed pressure. The recovery of titanium was 66.5% with a grade of 33.5% and a recovery of 70.0% iron with a grade of 17.0% could be achieved at a feed pressure of 138.0 kPa. Experimental results showed that using the magnetic hydrocyclone separation method at its maximum feed pressure of 172.5 kPa, the maximum recovery of titanium was 68.9% with a grade of 33.6% (56.0% TiO_2) and the recovery of iron was 70.8% with a grade of 16.8%.

Therefore, a feed pressure of 138.0 kPa can be considered as the optimum condition for the recovery of titanium from very fine particles (−63 μm) of beach sand using the magnetic hydrocyclone separation technique.

According to experimental data, titanium recovery could be improved by more than 5% with a commercial grade concentrate (up to 56.0% TiO_2) using a magnetic hydrocyclone at its maximum feed pressure of 172.5 kPa compared to that from a conventional hydrocyclone separation method. Therefore, using a magnetic hydrocyclone is more effective and efficient for the recovery of titanium from very fine particles (−63 μm) of beach sand.

In general, a particle anywhere in the hydrocyclone is subjected to two opposing forces: an outward centrifugal force, F_c, and an inward drag force, F_d, according to Eqs. (1) and (2) [9].

$$F_c = \frac{\pi d_v^3}{6}(\rho_s - \rho_l) \cdot \varpi^2 r \tag{1}$$

where, F_c is the centrifugal force (kg m s^{-2}), d_v is the particle diameter (m), ρ_s is the density of the particle (kg m^{-3}), ρ_l is the density of the liquid (kg m^{-3}), ω is the angular velocity of the particle (rad/s) and r is the positional radius of the particle (m).

$$F_d = 3\pi d_v \mu \cdot v_r \tag{2}$$

where, F_d is the drag force (kg m s^{-2}), d_v is the particle diameter (m), μ is the viscosity of the liquid (kg m^{-1} s^{-1}), v_r is the relative radial velocity between the liquid and the particle (m s^{-1}).

When the centrifugal force exceeds the drag force, the particle moves outward, and may leave through the underflow. If the centrifugal force is less than the drag force, the particle moves inward and may leave through the overflow [9].

The presence of the novel design of magnetic coupling appeared to enhance the separation of titanium-bearing minerals from fine particles of beach sand. With the magnetic hydrocyclone, however, the maximum recovery from all of the experiments was achieved with the highest pressure. High pressure and the magnetic force (Eq. (3)) [10] enhance the separating forces acting on the particles and that could lead to an enhanced recovery of titanium from beach sands:

$$F_m = \mu_o \kappa V H \nabla H \tag{3}$$

where, F_m is the magnetic force (kg m s^{-2}), μ_o is the permeability of vacuum (kg m s^{-2} A^{-2}), κ is the volumetric magnetic susceptibility (dimensionless), V is the particle volume (m^3), H is the field strength (A m^{-1}) and ∇H is the magnetic field gradient (A m^{-2}).

Compared with a conventional hydrocyclone, the novel design of a magnetic hydrocyclone incorporating Nd–Fe–B magnets appears more efficient in the recovery of titanium from the beach sand deposit, with no change to the liquid content of the product. In an appropriate industrial application, the use of this type of magnetic hydrocyclone could produce significant reductions in the size of the installation and processing time.

4. CONCLUSIONS

Hydrocyclone and magnetic hydrocyclone experiments showed that the novel design of a magnetic hydrocyclone using Nd–Fe–B magnets was a successful method for the recovery of titanium-bearing minerals from very fine particles ($-63\,\mu m$) of beach sand. Using the magnetic hydrocyclone method, the maximum recovery of titanium was 68.9% with a grade of 33.6% in the underflow from a 10 g/L feed, at a feed pressure of 172.5 kPa. The iron grade was 16.8% with a recovery of 70.8% in this underflow fraction. The best results obtained from a standard hydrocyclone was 63.8% titanium recovery with a grade of 32.9% in the underflow. Compared to a conventional hydrocyclone, this magnetic hydrocyclone was 5% more efficient in the recovery of titanium from the deposit, while increasing the titanium grade. Therefore, this type of magnetic hydrocyclone has the potential to produce significant reduction in the processing time thus saving energy and the running cost in an appropriate industrial application economically and efficiently.

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