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THE PROGRESS OF THE MAGNETIC HYDROCYCLONE

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Abstract A discussion is presented, describing the published designs of magnetic of hydrocyclones and the outcome of using them to separate magnetite–sand mixtures. The designs fall into two groups: first, where magnetic–susceptible particles are attracted to the centre of the cyclone and are discharged through the overflow and secondly, where particles are attracted to the outer cyclone wall from where they exit via the underflow. This report also covers theoretical assessments of magnetic hydrocyclones; included is a modelling study, detailing how the resultant force experienced by the particles would vary with the number of magnetic poles incorporated in the hydrocyclone design. At the end of the paper, a new project is introduced, based on the conclusions of the above studies. This will use powerful rare–earth–type permanent magnets to provide high field values and gradients. With this approach it is hoped to overcome the difficulties encountered with previous designs.

INTRODUCTION

Hydrocyclones have become a standard method of separating dispersed solids from liquids throughout the chemical and minerals industries, since their initial development in the early 1950's. Interest has arisen in producing a magnetic hydrocyclone, with the aim to improve the separation of magnetically susceptible particles from a carrying fluid.

The designs of magnetic hydrocyclones fall into two groups. The first is where an electromagnet provides a field pattern, attracting the magnetically susceptible particles to the centre of the cyclone and then through the overflow. The second set of designs has electromagnets set on the outside of the cyclone, providing a field to attract particles to the side wall of the cyclone, from where the flow takes them through the underflow.

OVERFLOW MAGNETIC HYDROCYCLONES

An overflow design of magnetic hydrocyclone has been developed by Fricker [1], in order to concentrate titano–magnetite from iron–sands. The overflow design was chosen because it was thought that by control of the inlet pressure and the current to the electromagnet, greater selectivity could be achieved in the separation of locked particles. These locked particles were composites of titano–magnetite and augite. The design is illustrated in Fig. 1.

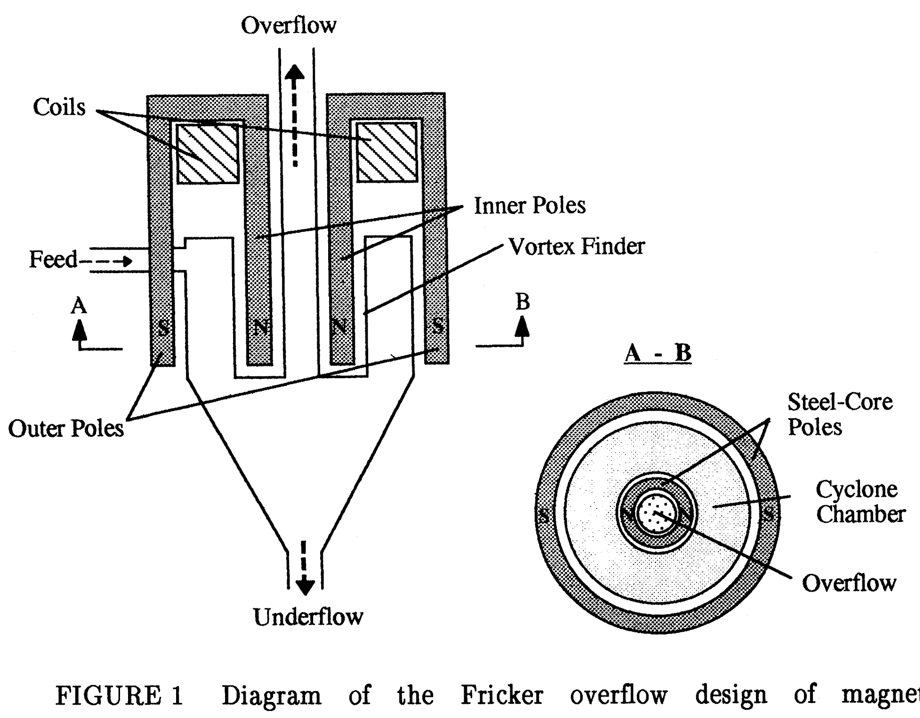

FIGURE 1 Diagram of the Fricker overflow design of magnetic hydrocyclone

The hydrocyclone chamber fits between the two poles of the magnet. The inner pole forms the vortex finder and the overflow exits through the centre of the inner pole. The outer pole surrounds the hydrocyclone. Since the outer pole has a greater surface area than the inner pole, a radial, inward magnetic field is created.

Preliminary studies were conducted using an artificial mixture of quartz sand and magnetite; the magnetite providing 20% of the mixture. With a field strength of 0.5 T half way between the two poles, a recovery of 98% was achieved and a commercial–grade constraint was surpassed.

With the naturally–occurring iron–sand samples, however, these results could not be reproduced. It was found that the commercial grade could be produced by increasing the inlet pressure to ≈ 70 kPa, using a 200 mm diameter hydrocyclone. This, however, was at the detriment to the recovery of the titano–magnetite which fell to 20%. Increasing the current improved both parameters but not to a sufficiently high degree. The proportion of solids in the liquid was also varied, without any significant result. Fricker concluded that the high proportion of locked particles was responsible for the low grade level.

UNDERFLOW MAGNETIC HYDROCYCLONES

The magnetic hydrocyclone produced by Watson and Amoako–Gyampah [2] followed the second set of designs. It utilised a twin–pole electromagnet to attract magnetically susceptible particles to the cyclone wall. A diagram of this arrangement is shown in Fig. 2.

A sand–magnetite mixture was used to test the performance of the system. While the magnetic field was increased, the variation in the recovery to the underflow, of both the magnetic and non–magnetic components, was studied. It was found that the recovery of the magnetite improved until the field reached 0.1 T. after which the recovery fell. The deduction from this observation was that there was a build–up of magnetite inside the cyclone at the higher field levels, which then caused distortion of the fluid flow.

An interesting result, from this hydrocyclone, was the relationship between the applied magnetic field and the non–magnetic component. Theory suggests that the sand would remain unaffected but its recovery roughly followed the same trend as the magnetite. This could be explained by the entrapment of the non–magnetic particles by the magnetic particles, which would also cause an increase in disruption of the flow patterns within the magnetic hydrocyclone.

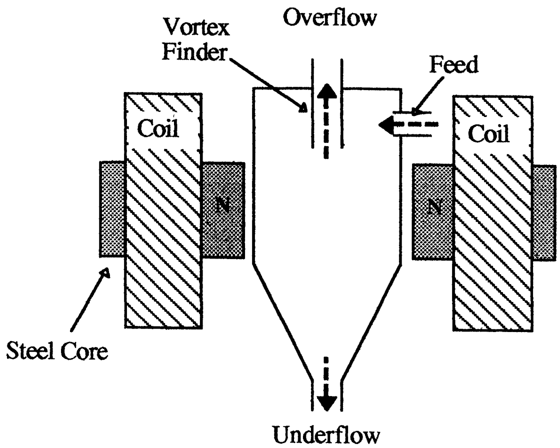

FIGURE 2 Diagram of the Watson underfow design of magnetic hydrocyclone

A British magnetic–devices manufacturer, Boxmag–Rapid Limited, have also researched into the design and application of magnetic hydrocyclones. They selected a design similar to that of Watson, but used a quadrupole–electromagnet arrangement [3]. This had the advantage of supplying a larger field gradient than Watson's design, leading to greater attraction of particles. Experiments were conducted using chalk and magnetite, which provided a simple visual analysis of the separation to be made. The variation of recovery with solids concentration, inlet pressure and field were studied.

The recovery of magnetite increased with concentration up to the value of 16 gl^{-1}; after this, the recovery was constant up to 130 gl^{-1}. At higher concentrations, the flow pattern inside the hydrocyclone broke down, leading to a 'rope'–type discharge from the underflow, instead of the normal spray. The inlet pressure was varied from 30 kPa to 70 kPa over a 200 mm diameter hydrocyclone but this did not have a significant effect on the magnetite recovery. The relationship between the magnetic field strength and recovery was more positive. There was an inverse–exponential–type increase with applied magnetic field, leading to a 'saturation' level of ≈ 99% (the magnetic–feed concentration was set at ≈ 30 gl^{-1}).

Anderson et al. [4] also evaluated a Boxmag–Rapid magnetic hydrocyclone. The electromagnetic circuit supplied a maximum magnetic field of 0.03 T to a half–radius position (halfway between the centre and the cyclone wall). In order for there to be a direct comparison with the Fricker and Watson and Amoako–Gyampah results, a sand and magnetite mixture was again used to test the equipment. As well as studying the effect of applied field on the recovery of the magnetic component, Anderson et al. also monitored the proportions of non–magnetics and of liquid discharging through underflow.

As before, recovery of the magnetic particles was found to improve in an exponential–type relationship with increasing field. It was also discovered that the amount of liquid going through the underflow varied with changing field. There did not seem, however, to be any simple trend between these two factors. The non–magnetics remained unaffected, unlike the data reported by Watson and Amoako–Gyampah and it was concluded that this was due to subtle differences between the two designs of hydrocyclone. A study of particle–size distribution revealed that, by applying a magnetic field, over 90% of the magnetite particles, across the complete range of sizes, were recovered.

In further experiments, Anderson [5] investigated the liquid–entrapment problem by using a solely magnetite–water suspension. Similar trends were produced, with the entrapment becoming significantly worse with field strengths greater than ≈ 6 mT, at the half–radius position. This was equivalent to to a current of 0.5 A being supplied to the cyclone's electromagnet. These tests suggest that, within the cyclone, the slight remanent magnetization of the magnetite was causing the magnetite particles to flocculate. The presence of these flocs then disrupted the liquid flow inside the hydrocyclone. With the flow destroyed, more liquid went through the underflow, forming a rope–type discharge. At low–field values, however, the magnetite did not form the flocs, which destroyed the flow.

THEORETICAL ASPECTS OF MAGNETIC HYDROCYCLONES

These studies, reported so far, have dealt with the experimental aspects of magnetic hydrocyclones. In contrast, there have been two papers reporting on theoretical analyses of multipole designs. The first [6] assessed the forces acting on magnetically susceptible particles in a hydrocyclone. By equating the three forces (centrifugal, magnetic and hydrodynamic drag) for equilibrium conditions, the following equations were derived for the radial velocity and limiting size for particles in an underflow–type magnetic hydrocyclone:

$$u_r = \frac{d^2}{18\mu}\left[\chi H_0^{\,2}\,\frac{(p-1)}{r}\left(\frac{r}{R}\right)^{2(p-1)} + \frac{(\rho-\rho_0)\,u_t^{\,2}}{r}\right]$$

and

$$d_{lim} = \sqrt[3]{\frac{2\mu u_r r}{\chi H_0^{\,2}\,(p-1)\left(\frac{r}{R}\right)^{2(p-1)} + (\rho-\rho_0)\,u_t^{\,2}}}$$

The nomenclature used in these equations is as follows:

d	article diameter
d_{lim}	limiting particle diameter
H_0	magnetic field strength at pole–tip surface
p	number of pole pairs
r	radius (equations are a function of r)
R	radius of hydrocyclone
u_r	radial velocity
u_t	tangential velocity
μ	viscosity of the medium
ρ	density of the particles
ρ_0	density of the medium
χ	magnetic susceptibility of the particles.

When these equations were calculated using experimental data, it was found that the magnetic field had a significant influence on the radial velocity, and, therefore, it improved separation. This effect peaked when the velocity of the fluid in the hydrocyclone inlet reached 5 ms^{-1}. At higher speeds, the influence of the magnetic field diminished The authors concluded that magnetic hydrocyclones were suitable for separating "large volumes of dilute suspensions of finely dispersed ferromagnetic materials at moderate feed pressures (low entry velocities)".

In the second theoretical paper, Gang Shen and Finch [7] studied the magnetic field pattern produced by multi–magnetic pole arrangements and derived the effect that they would have on the hydrocyclone separation. In particular, they compared Fricker's overflow design with Watson's underflow cyclone, with the view to upgrading the Watson design by increasing the number of electromagnet poles.

They defined a number of parameters, including the average force factor; the product of the field strength and the field gradient ($H.\nabla H$). These were solved both in the radial (average radial factor, ARF) and tangential (ATF) directions. The ideal case would have the ARF very high, to attract particles to the cyclone wall, and the ATF zero, so not to waste the field in accelerating or decelerating particles around the cyclone. The parameters were calculated by computer using a finite difference method. The forces acting on the particles were also analysed. It was discovered that for magnetic forces to overcome the drag forces, with particles $\geq$ 5 μm, the ARF had to be greater than 8 T^2m^{-1}. Under the same cyclone conditions, the centrifugal forces would match the drag forces with 35 μm particles.

It was found that ATF was zero for the Fricker design and very small, if not negligible, for the underflow designs. The results for the ARF of the various designs are displayed in Table I. They show that there is a significant improvement of the quadrupole design (as used by Boxmag–Rapid) over the two–pole design (Watson and Amoako–Gyampah). An eight–pole design, however, was required for the ARF to challenge the 8 T^2m^{-1} threshold. The overflow design readily surpassed the ARF requirement The authors, however, felt that the underflow designs had a processing advantage. Since magnetic particles are generally more dense than non–magnetic ones, the magnetic particles tend to be sent towards the cyclone wall, under the action of the centrifugal force. The underflow designs encourage this tendency while the overflow design oppose it.

The effect of altering the hydrocyclone diameter was also studied. There proved to be a linear relationship between diameter and the ARF; that is when the diameter was doubled, the ARF halved.

Type	Average Radial Factor (T^2m^{-1})
Overflow Design	16.20
Underflow Designs	
2 pole	0.17
4 pole	4.83
8 pole	7.31
12 pole	8.61
16 pole	9.35

Conditions : cyclone diameter = 0.1m : max B field = 1T

TABLE I Table of the calculated average radial factors for the different cyclone designs

Gang Shen and Finch concluded that an underflow design was preferential to an overflow design of magnetic hydrocyclone. Also, the optimum magnetic circuit should incorporate eight magnetic poles. This was despite separation being improved with designs utilising more poles.

GENERAL CONCLUSIONS AND FUTURE AREAS OF STUDY

From the preceding published studies a number of general conclusions may be drawn. The first concerns the nature of the test material. All the magnetic hydrocyclones were tested with magnetite, a ferromagnetic material. The researchers, however, found that undesirable effects occurred at maximum–field values. These values were significantly less than those proposed by Gang Shen and Finch for "strongly magnetic particles". The optimum results were achieved at field levels much less than the maximum. Large fields and field gradients, however, would a requirement for treating paramagnetic materials with small magnetic susceptibilities.

It is with the aim of extending the possible use of the magnetic hydrocyclone to the separation of paramagnetic minerals, that a new research project has been established which involves the use of high–performance permanent magnets based on Nd–Fe–B type material. These magnets provide high field levels with remanence values in excess of 1.1 T and as there is a considerable space saving over conventional electromagnets, the magnets can be packed closer together. As it is relatively simple to use a large number of permanent magnet poles, compared with the bulk of electromagnets, it may be beneficial to examine magnetic–hydrocyclone designs incorporating more poles than the optimum eight which Gang Shen and Finch suggested.

The second general conclusion that can be made is that there is evidence of material accumulating in the cyclone, especially near the underflow. It is intended that the design of the high–intensity magnetic hydrocyclone would concentrate the magnetic coupling near the top of the hydrocyclone. The swirling action of the liquid, down the length of the cyclone, should then break up any undesirable agglomerates to enable the flow pattern inside the hydrocyclone to be preserved.

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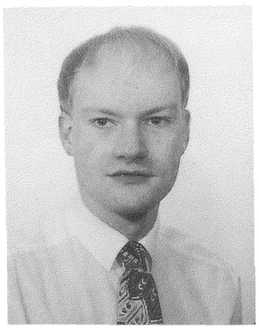

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