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Experiments with CRUD Simulants for Development of the Magnetic Filter using Rotation of Permanent Magnets

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ABSTRACT

Although radioactive corrosion products (CRUD) are not a kind of high level waste, they are very important products because they are the major source of occupational radiation exposure and can lead to AOA(axial offset anomaly) at a long term fuel cycle. Most of the insoluble radioactive corrosion products have the characteristic of showing strong ferrimagnetism. Therefore, new type of magnetic filter that can separate radioactive corrosion products and eventually reduce the radiation exposure of the personnel at a nuclear power plant is suggested. This new type of separator with novel geometry consists of an inner and an outer magnet assembly, a coolant channel and a container surrounding the outer magnet assembly. The particulates are separated from the coolant by the alternating magnetic fields that are generated by shift arrangement of permanent magnets. This study describes of experimental results performed with the different flow rates, rotation velocities of magnet assemblies, particle size and various material. The efficiency of magnetic filter tends to increase as the flow rate is lower, and particle size is bigger. The rotating velocity of magnet assembly has also some influences on the separation efficiency. This new magnetic filter shows good performance results in filtering magnetite, cobalt ferrite and nickel ferrite except hematite, which is a kind of anti-ferromagnetic material, from aqueous coolant simulation.

Introduction

The reduction and removal of crud from reactor coolant systems is very important because crud are the major source of occupational radiation in nuclear power plants. The ICRP 60 (International

Commission on Radiological Protection publication 60) for the radiation protection of the public is now requiring much stricter reduction of the occupational radiation exposure. Requirements to reduce the build-up of CRUD radioactivity and to increase the removal rate of CRUD in the primary coolant system for the radiation exposure reduction are becoming more demanding. Initially, magnetite (iron ferrite: $FeOFe_2O_3 \Rightarrow Fe_3O_4$) was suspected as the main corrosion product. However, further research confirmed that corrosion products more likely consisted of nickel-ferrites ($Ni_xFe_{3-x}O_4$). The ferrites have strong magnetic properties in contrast to other corrosion products that have show much weaker magnetic properties.

To reduce exposure to radiation, the requirements for reducing the build-up of crud radioactivity and for increasing the removal rate of crud in the primary coolant system of nuclear power plants are becoming more demanding. There are several ways to reduce the radiation levels around the primary water system. For example, improving the coolant purification system, operating at high pH, the adopting materials with low levels of cobalt in the primary coolant system and decontaminating the primary system more frequently [1]. By the mid 1980s, although the technology based on electromagnetic fields for particulate removal in crud had been studied widely, the studies could not continue due to problems such as the backflushing of electromagnetic filters. In recent years, the manufacturing technology of permanent magnets, especially rare earth magnets, has developed greatly: the new types of permanent magnets can inexpensively generate a stronger magnetic field than a conventional magnet. Thus, a new magnetic filter that uses these magnets has been proposed.

Magnetic Filter using Permanent Magnets

Most crud elements (nickel ferrite, magnetite and so on) are strongly ferrimagnetic. A magnetic filter that uses permanent magnets can be applied efficiently under extreme conditions such as high temperature and high pressure [2]. The system we have developed comprises two main parts: a separator and a driving motor. The separator consists of an inner assembly and an outer magnet assembly, a fluid channel and a container surrounding the outer magnet assembly. The fluid channel is located between the inner and outer permanent magnet assemblies. As corrosion products in the fluid pass through the channel between the magnet assemblies, they move toward nearby magnets became of the strong magnetic field. They then move toward the rotating direction of permanent magnets, which are rotated by a driving motor connected to the separator.

The rotation of the permanent magnet assembly and the shifted arrangement (S-N pole) of the permanent magnets generate the alternating magnetic field. The crud elements in the magnetic field such as magnetite and nickel ferrite are then magnetized. The crud that move toward the rotating direction of the magnet assemblies are separated from the coolant at the boundary wall of the vessel (Fig. 1) ; they are then collected in the corner of the fluid vessel near the outlet of the crud. The effectiveness of the magnetic filter in separating particles in a fluid stream strongly depends on the magnitude of the magnetic force. In general, the competing forces are due to the hydrodynamic drag and inertial effects on the particle.

In a cross-sectional top and side views of the separator, Fig. 2 shows the inner and outer magnet assemblies and the fluid channel. To maximize the magnetic field, magnetic circuits are constructed with irons that strengthen the magnetic field between the inner and outer magnet assemblies. Each magnet faces an opposite polar magnet respectively. Located between the inner and the outer assembly, the fluid channel is influenced by the strong magnetic field produced by the coupled magnets.

The crud in the coolant are captured by the magnetic field and moves to the rotating direction of the two magnet assemblies. Arriving at the boundary wall, the crud accumulate at the bottom corner of the fluid channel. The crud can be separated with an appropriate batch operation.

Theoretical approach

The analysis of the movement of CRUD (magnetic particle) under moving alternating magnetic field is performed as follows. First, when the particle moves under the magnetic field, the particle is influenced by both magnetic force and viscous drag force [3,4,5,6].

The magnetic force is assumed to be directed only in the x-direction (refer the right figure in Fig. 1) and can be described by

$$F_m = V_0 \mu_0 \chi H \frac{dH}{dx} \quad , \qquad \text{(Eq.1)}$$

where

F_m is the magnetic force (N), V_0 is the particle volume (m^3), μ_0 is the magnetic permeability of free space (T$\cdot$m/A), χ is the volumetric susceptibility, H is the magnetic field (A/m), x is the axial distance (m).

The strength of the moving alternative magnetic field H can be expressed by the following equation [7]

$$H = H_0 \sin(kx - wt), \qquad \text{(Eq.2)}$$

where

k is the frequency of magnetic field (m^{-1}), w is angular frequency (sec^{-1}), t is time (sec),

The viscous drag force yields the following equation of motion [8],

$$F_D = \frac{\rho V^2 A_p C_D}{2} \quad , \qquad \text{(Eq.3)}$$

where

F_D is the drag force (N), ρ is the density (kg/m^3), V is the velocity of particle (m/sec), A_p is the cross sectional area of particles (m^2), C_D is the drag coefficient.

Then finally the CRUD motion is governed by the following equation:

$$m\frac{dV}{dt} = -F_D + F_m \quad , \qquad \text{(Eq.4)}$$

where

m is the mass of particle (kg).

With eqs. (1) ~ (3), eq. (4) becomes

$$\frac{dV}{dt} + \frac{9\mu}{2a^2\rho_p}V = \frac{\mu_0 \chi k H_0^2}{2\rho_p}\sin 2(kx - wt) \quad , \qquad \text{(Eq.5)}$$

where

μ is the viscosity (kg/m$\cdot$sec), a is the radius of particle (m), ρ_p is the density of particle (kg/m^3).

If inertial forces are neglected,(it means velocity of particle is constant) i.e., *dV/dT =0*, the particle velocity can be expressed as follow:

$$V_{CRUD} = \frac{ka^2\mu_0\chi H_0^2 \sin 2(kx - wt)}{9\mu} \qquad \text{(Eq. 6)}$$

For a constant magnetic strength, the velocity of the particle varies with the frequency(related to *k*), which depends on the rotating velocity of magnet assembly, magnetic field strength and drag force of fluid (viscosity). Other parameters are terms which is related to magnetic properties of particle.

The separation factor can be defined as the water flow to the particle velocity ratio.

$$V_{flow} = \frac{Q}{A} \qquad \text{(Eq. 7)}$$

where

Q is the flow rate (m^3/sec), *A* is the flow area (m^2).

Finally, the separation factor (η) can be expressed as

$$\eta \propto \varepsilon = \frac{V_{CRUD}}{V_{flow}} = \frac{Aka^2\mu_0\chi H_0^2 \sin 2(kx - wt)}{9\mu Q} \qquad \text{(Eq. 8)}$$

$$\eta = 1 - Exp(-\varepsilon K) \qquad \text{(Eq. 9)}$$

where

K is the characteristic constant

Experiments

A schematic drawing of the experimental equipment is shown in Fig. 3. Water flows from the inlet tank to the outlet tank through the pump, the separator and the flow meter. The driving motor, which is equipped with a controller to adjust the rotating velocity, rotates the magnet assembly in the separator. Details of each component are described in Table 1. All experimental runs were conducted at room temperature and atmospheric pressure because the experimental system, which is at a preliminary stage, is not of the closed-loop type.

Magnetite (Fe_3O_4), cobalt ferrite ($CoFe_2O_4$) and nickel ferrite ($NiFe_2O_4$) particles were used as crud simulants. Hematite (α-Fe_2O_3) particles with an anti-ferromagnetic property were also used to prepare the suspensions. The magnetite and hematite particles were supplied by Aldrich Chemical Company, and the cobalt ferrite and nickel ferrite were obtained from Kojundo Chemical Laboratory Co. Ltd, Japan. The relevant properties of their particles are given in Table 2. Experimental results were obtained for varying flow rates, the rotating velocities of the magnet assembly and suspension concentrations.

Results and Discussion

Flow rate and rotating velocity of magnet assembly

Experimental results with respect to the flow rate and the rotating velocity are shown in Fig. 4, which show the separation efficiency of each input material depending on the flow rate and the rotating velocity of magnet assembly. The results of a comparison of four input materials under the condition of 50rpm are shown in Fig. 5. All cases except the hematite case show comparatively good separation efficiencies. Differences in the separation efficiency of each material are expected to be caused by differences in magnetic susceptibility (or intensity of magnetization), especially since hematite is an anti-ferromagnetic material with weak magnetic properties. Basically, the separation efficiency tends to decrease as the flow rate increase a known characteristic of magnetic filters or electromagnetic filters. This new type of magnetic filter has a unique parameter: the rotating velocity of the magnet assembly. Figure 4 shows that changes in the rotating velocity of the magnet assemblies slightly improve the efficiency of the magnetic filter under the condition of the constant flow rate. Thus, the rotating characteristic of the magnet assemblies may be an advantage and could provide useful flexibility of this magnetic filter system. However, the experimental results show that a faster rotating velocity for the magnet assemblies does not always increase the separation efficiency.

Particle size

Figure 6 shows the separation efficiency of the magnetic filter for various particle sizes of four input materials under the condition of 0.9gpm and 50 rpm. The bigger the particle size, the better the separation efficiency of the magnetic filter system. Above 5micrometer, the separation efficiency is more than 90%. Thus, studying for the development of a particle size enlarger based on the magnetic properties of crud is necessary to increase the separation efficiency.

Small particles are more abundant in the output stage (outlet water) than in the input stage (inlet water), while large particles are more abundant in separated stage. This result implies that "the larger the particle size, the better the separation efficiency"

Comparison with theoretical results

As shown in equation (8), the flow rate of fluid, magnetic susceptibility, particle size and the rotating velocities of magnet assemblies are important parameters, which affect the efficiency of the magnetic filter. Fig 7~9 are the comparison results between theoretical results (line form) and experimental results (symbol). These graphs express the separation efficiency for the various flow rate and particle size of each input material (CRUD simulants: magnetite, nickel ferrite, cobalt ferrite). Experimental results have a tendency to be similar with theoretical results about the change of flow rate and particle size.

Flow analysis in the fluid channel

To analyze the flow in the fluid channel, a Computational Fluid Dynamic(CFD) program (Fluent code 6.0), which can predict direction and velocity of flow, is used. The flow in the fluid channel (from inlet to outlet) is shown Fig. 10. Main stream is made at the bottom of the fluid channel, and a little circulation flow is formed at the middle part of the fluid channel. The optimization of the velocity of the magnet assemblies have a close relation with the velocity of the main stream, because the drag force by fluid is minimized when the velocity of the main stream and the velocity of the magnet assemblies are same. That means the separation efficiency of the magnetic filter maximizes when the drag forces to particles are minimized.

At the experiments, the flow rate varied as 0.5gpm, 0.9gpm and 1.3gpm. The simulation results of 0.5gpm case are shown Fig. 11, which is linear version of the fluid channel. The left figures show the velocity vector, which length of arrow means velocity, and right figures display the main stream in the fluid channel. In cases of 0.5gpm, 0.9gpm, 1.3gpm, the each velocity of main stream can acquire by computer code simulation and the acquired values are about 9-14cm/s, 30-38cm/s, 48-56cm/s. In order to minimize the drag force to the particles, the rotating velocity of magnet assemblies should be controlled as same velocity with main stream. If the velocities of flow converse as rotating velocities of the magnet assemblies, each value is about 15rpm, 45rpm, 70rpm, which values are to expect as optimum velocities of magnet assemblies at each case. Experimental results (Fig. 4) show that the velocity of magnet assemblies influences slightly on separation efficiency of magnetic filter. Some results (magnetite, nickel ferrite cases) have shown good separation efficiencies around optimum velocity of magnet assemblies, which acquired by computer simulation. However, these results can be expected that velocity of magnet assemblies affects the filter efficiency less than other parameters relatively, and some experimental errors such as sample analysis error, residual impurity in the fluid channel and so on, also influence on the separation efficiency.

Discussion

The magnetic filter proposed in this paper has some merits. For example, it uses permanent magnets instead electro magnets, it has a novel design for easily separating the crud and it performs well.

The efficiency of a magnetic filter tends to improve as the flow rate slows and the particle size increases. For a magnet assembly with a constant rotating velocity, the magnet filter performs better with a slower flow rate. On the other hand, the efficiency rapidly decreases when the flow rate accelerates. The rotating velocity of a magnet assembly has some influence on the separation efficiency. This new type of magnetic filter performs relatively well compared to other conventional magnetic filters. In the case of a conventional magnetic filter or electromagnetic filter, only the flow rate turned out to be a dominant parameter along with the strength of the magnetic field. For the magnetic filter proposed in this study, however, the rotating velocity of magnet assemblies is also the parameter that influences separation efficiency.

The study on the optimization of rotating velocity of the magnet assemblies has been performed using computer code (FLUENT 6.0) simulation. In order to acquire more accurate results and to reduce experimental error, cleaning techniques of the magnetic filter system, especially the fluid channel, are required.

Conclusion

For the removal or separation of CRUD, a new design of magnetic filter is proposed, described, and analyzed with preliminary experimental results. The following conclusions can be drawn from the experiments.

- The magnetic filter using permanent magnets can provide good operational properties and shows some potential and advantage for the CRUD removal.
- The efficiency of magnetic filter tends to increase at lower flow rates, higher magnetic susceptibility and bigger particle size.
- In addition to the flow rates, the rotating velocity of magnet assemblies also could be a parameter to vary the efficiency of magnetic filter and provide the useful flexibility for better operation and performances.

The application of magnetic filter could provide an effective method for the removal and separation of CRUD. The proposed method of removing CRUD also could be applied in general to other industry fields, once the current and various future experiments are proved to be successful and the performances of the magnetic filter are verified by the future improvements.

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Table 1. Description of each component of the system

		Material	Size & capacity	Comment
Magnet	Inner assembly	Nd	25×30×20, ~ 6000G	60 EA (rare earth)
	Outer assembly	Nd	56×30×20, ~ 4500G	60 EA (rare earth)
Frame		Al	1040×1530×600	
Flow meter			~ 2.5 gpm	1 EA(rotameter)
Valve		SUS 316		4 EA(ball type) control of flow rate
Motor			~ 120 rpm	
Reservoir		SUS 304	60 liter	
Pump			15 liter/min	1 EA
Pipe		SUS 304		
Fluid channel		SUS 316		1 EA
Vessel		Al		1 EA

Table 2. Summary of CRUD simulants

	Magnetic property	Type (mean size)	Intensity of magnetization (emu/g)	Density (g/cm^3)
Magnetite (Fe_3O_4)	ferrimagnetism	Powder (5~6 μm)	92	5.16
Nickel ferrite ($NiFe_2O_4$)	ferrimagnetism	Powder (3~4 μm)	50	5.38
Cobalt ferrite ($CoFe_2O_4$)	ferrimagnetism	Powder (2~3 μm)	80	5.29
Hematite (Fe_2O_3)	anti-ferromagnetism	Powder (~1 μm)	low	5.24

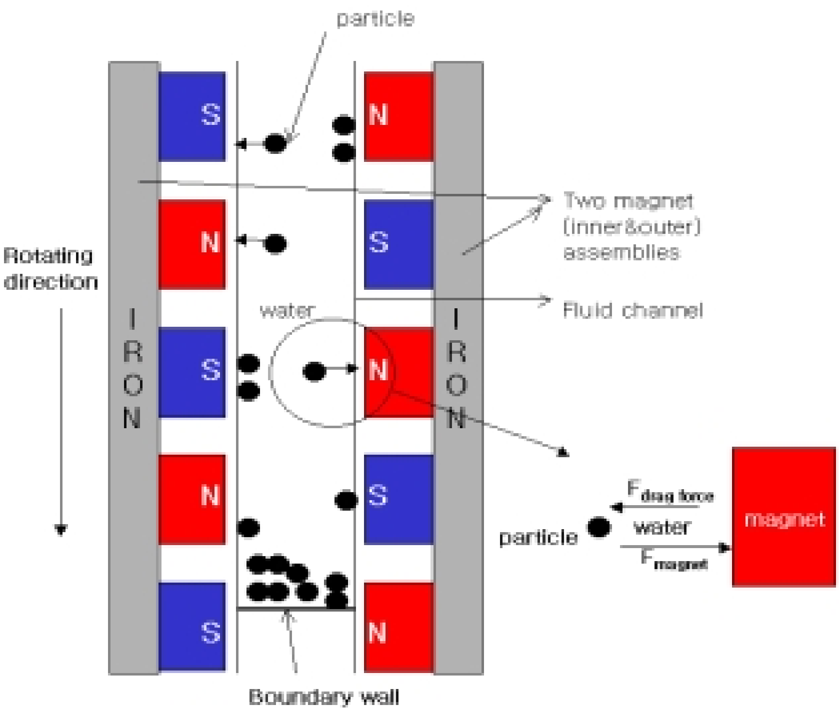


Fig. 1 Modeling of the magnetic separation of this filter

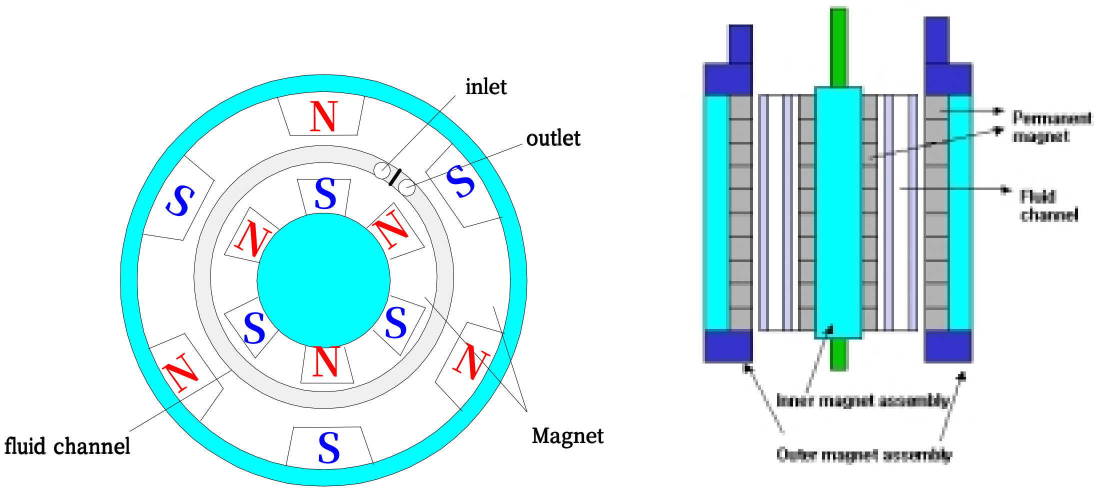


Fig. 2 Cross sectional view of separator (top & side)

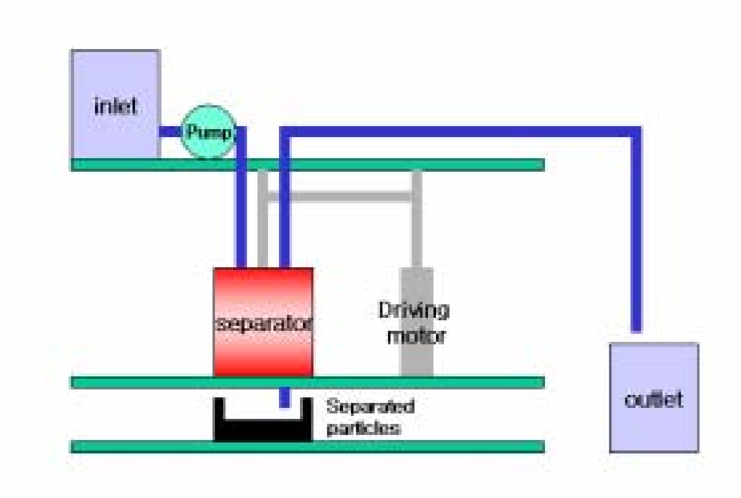
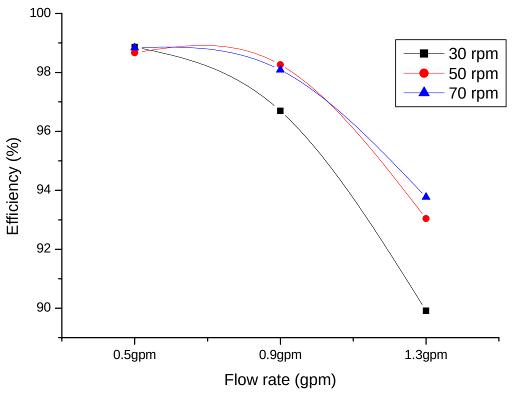
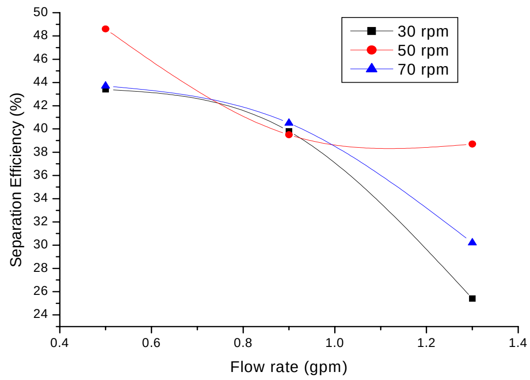


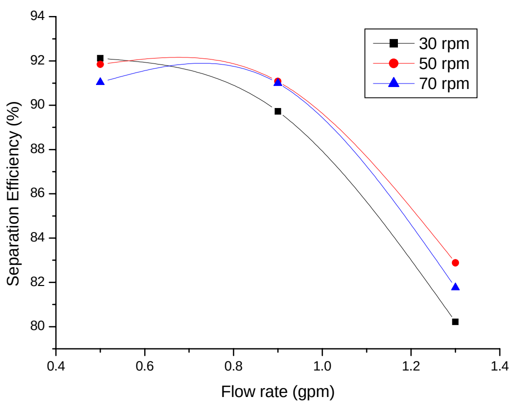
Fig. 3 Schematic drawing of magnetic filtering system



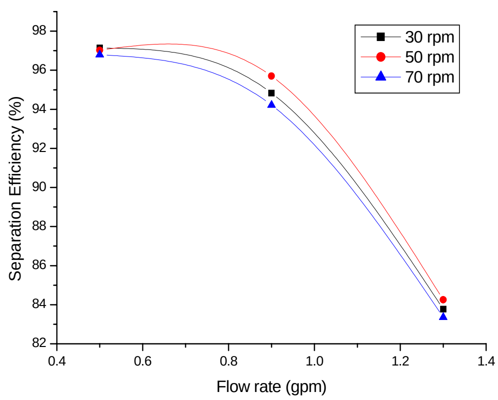
Magnetite



Hematite



Nickel-ferrite



Cobalt-ferrite

Fig. 4 Experiment results

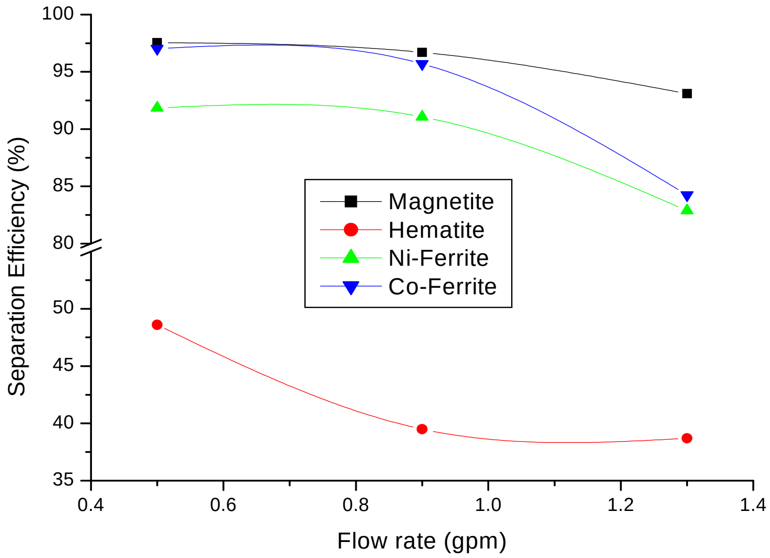


Fig. 5 Separation efficiency at same condition (50rpm)

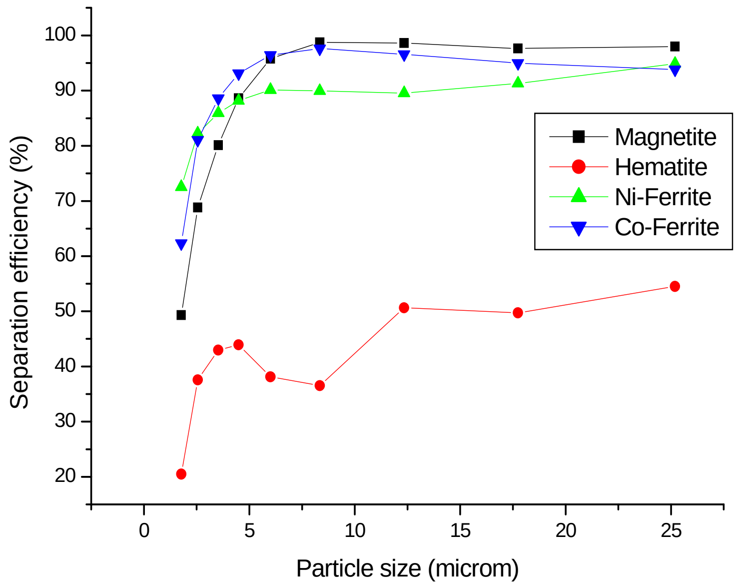


Fig. 6 Separation efficiency as particle size (four input material, 50rpm, 0.9gpm)

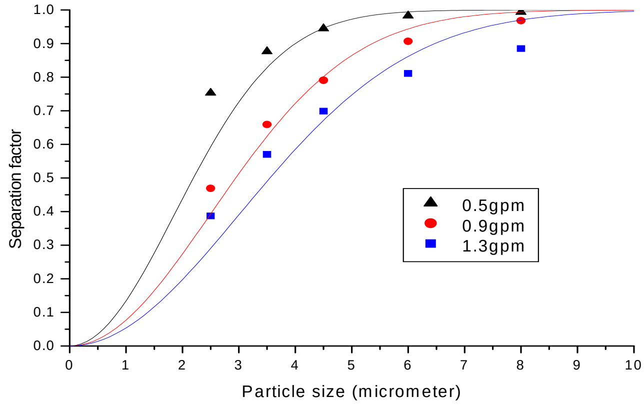


Fig.7 Theoretical results vs experimental results (magnetite, 3000Gauss)

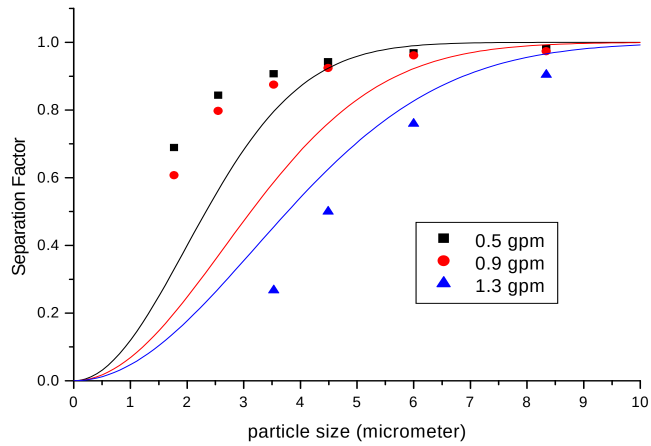


Fig.8 Theoretical results vs experimental results (Co-ferrite, 3000Gauss)

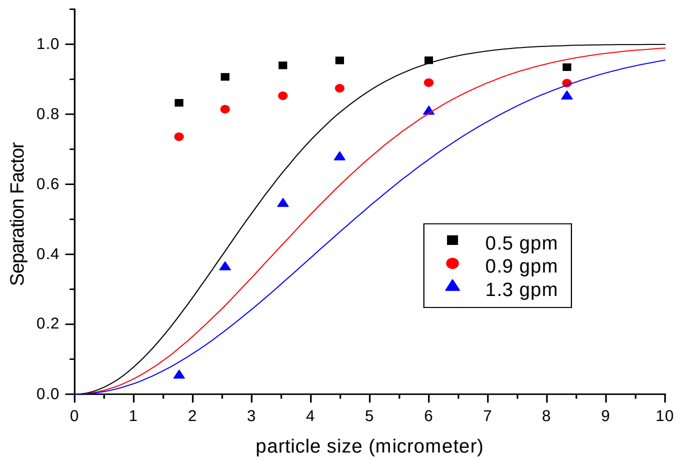


Fig.9 Theoretical results vs experimental results (Ni-ferrite, 3000Gauss)

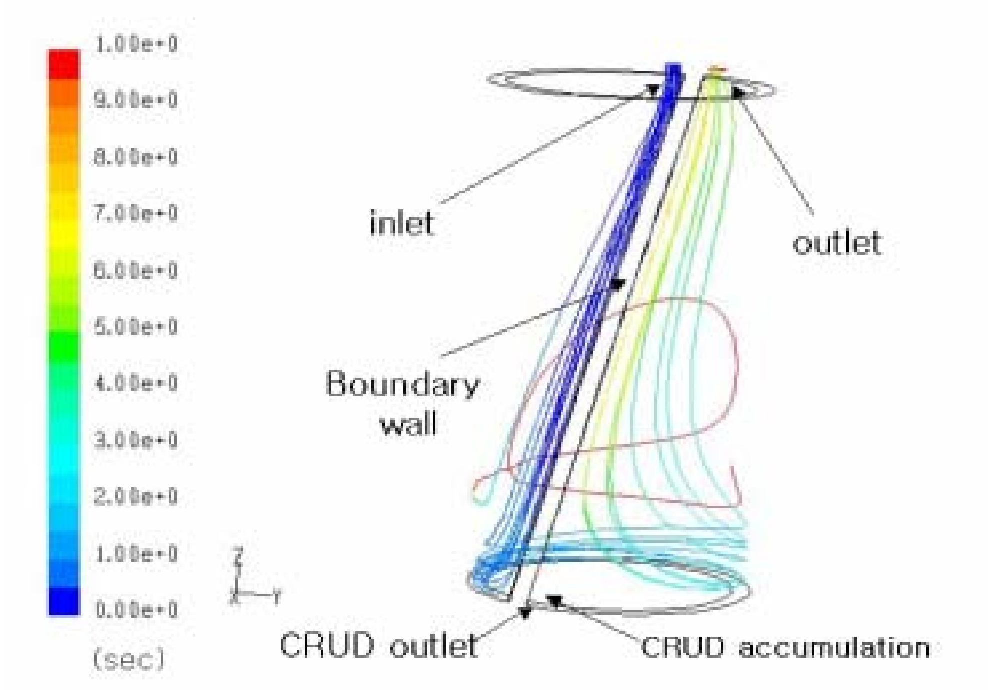


Fig. 10 Flow in the fluid channel (1gal/min)

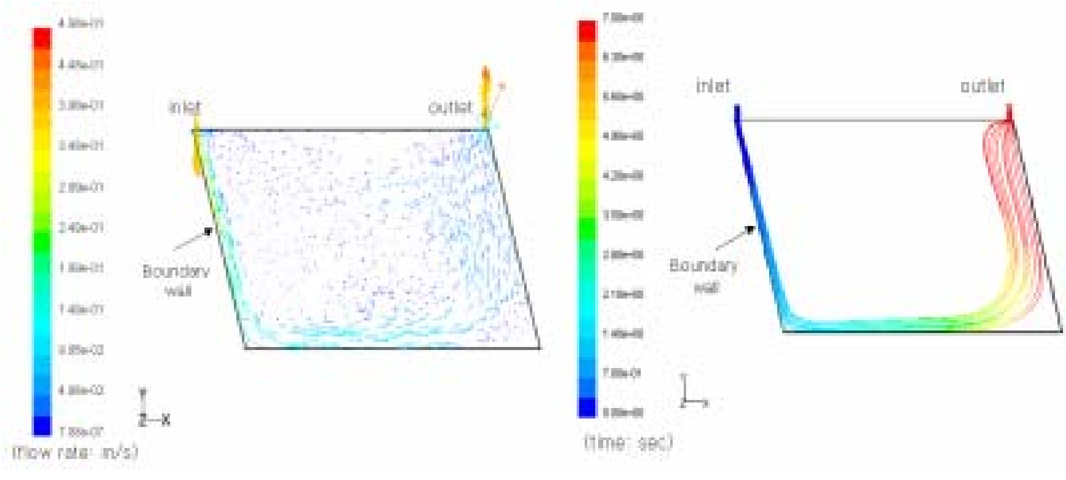


Fig. 11 Flow in the fluid channel (0.5gpm)