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Theoretical Test of Moving Alternative Magnetic Filter to Remove CRUD

Sung-il Kim, Min Chul Song, and Kun Jai Lee

Department of Nuclear Engineering
Korea Advanced Institute of Science and Technology
373-1, Kusong-dong, Yusong-gu, Taejon, 305-701, Korea

Abstract

Some oxides such as the Fe_3O_4,γ-Fe_2O_3, or nickel ferrite found in the nuclear power plant are known to show strong ferrimagnetism. The most important corrosion products for the high temperature filtration of PWR coolants are magnetite and ferrite series materials containing nickel and cobalt. The objective of this study is to develop the concept of moving alternative magnetic filter for the CRUD removal. Separating efficiency depends on the magnetic properties and size of CRUD, flow rates, intensity of magnetic field and temperatures. This study shows the expected magnetic filter performance how to remove the CRUD and hence the moving alternative magnetic filter can be recommended as the effective method for the reduction of radiation build-up.

1.Introduction

It is very important to reduce the build-up of CRUD or to separate the CRUD from the reactor coolant system because major source of ORE (Occupational Radiation Exposure) is coming from the CRUD in the nuclear power plant. The ICRP 60 for the radiation protection for the public requires more strict reduction of the ORE. Some oxides such as the Fe_3O_4,γ-Fe_2O_3, or nickel ferrite found in the nuclear power plant are known to show strong ferrimagnetism[2]. The most important corrosion products for the high temperature filtration of PWR coolants are magnetite and ferrite series materials containing nickel and cobalt. These substances have net magnetic moments per unit volume at the low temperature[1]. Generally the pure paramagnetic substance tends to obey the Curie Law. In order to apply to the ferromagnetic and ferrimagnetic substance, a modified theory is required such as the Curie-Weiss Law. Ferromagnetic substances including the ferrites show the property of magnetic saturation, which is very important property to the design and operation of magnetic filters[1]. The objective of this study is to develop a moving alternative magnetic filter for CRUD removal.

2. A new type of magnetic filter

This is a new type of magnet filter and can be used for high temperature and high pressure. The separator, which has been tried to develop, consists of a cylindrical and annular vessel and permanent magnet assembly. Rotation of permanent magnet assembly surrounding the vessel produces moving alternative magnetic field in the vessel. CRUD such as magnetite in the magnetic field is magnetized. Thus magnetized CRUD may be transferred to the shifting direction of moving alternative magnetic field. CRUD divided from the coolant is deposited in sludge at the vessel wall. And then, CRUD can be easily separated from the coolant by moving alternative magnetic force. Therefore it is very important to analysis of magnetic properties of corrosion products and magnetic separation theory and to evaluate of the advanced CRUD separator. The effectiveness of a magnetic filter in separating particles from a fluid stream depends on the relative magnitudes of the magnetic attractive force. In general, the competing forces are those due to hydrodynamic drag, to the gravitational field and to the inertial effects on the particle. The particle moves to the forward direction of the magnet as shown in Figure 1.

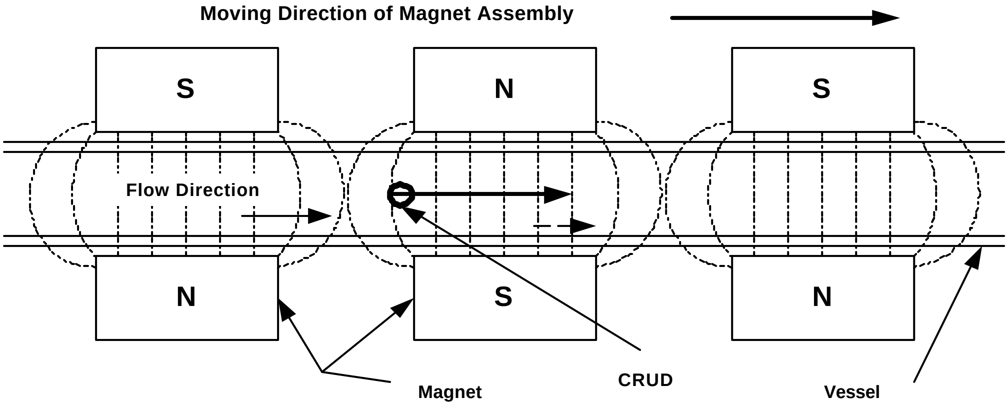

Figure 1. Magnetic separation process

3. Theory of magnetic separation

3.1 Motion equation of the CRUD

Analysis for the movement of CRUD (magnetic particle) under moving alternative magnetic field as follows. First, we see moving of the particle radius “a” under the magnetic field. The particle receives various types of forces[4,8].

- Magnetic force

$$F_m = V_0 cH \frac{dH}{dx} \tag{1}$$

Strength of the moving alternative magnetic field H is given by the following equation.

$$H = H_0 \sin(kx - wt) \tag{2}$$

- Viscous drag force

$$F_D = \frac{rV^2 A_p C_D}{2} \tag{3}$$

Motion equation of the CRUD is,

$$m\frac{dV}{dt} = -F_D + F_m \tag{4}$$

From equations (1)~(3), equation (4) become equation (5).

$$\frac{dV}{dt} + AV = B\sin 2(kx - wt) \tag{5}$$

where

$$A = \frac{9m}{2a^2 r_p}, B = \frac{ckH_0^2}{2 r_p}$$

V_0 : *volume* $[m^3]$
H : *magnetic* intensity $[A/m]$
w: *angular frequency* $[\sec^{-1}]$
r_p : *density* $[kg/m^3]$
A_p : *area* $[m^2]$
a : *radius* [m]

c : *suceptibility* $[T \cdot m/A]$
k : *frequency of magnetic field* $[m^{-1}]$
t : *time* [sec]
V : *velocity* $[m/\sec]$
C_D : *drag coefficient*
m:viscosity [kg/m·sec]

3.2 Separation factor

Separation factor is derived by the following assumptions.

- The CRUD arrived at the vessel wall by attractive force of the magnet is defined as divided CRUD
- Traveling speed of the CRUD is constant speed known as terminal velocity
- Gravitational acceleration is negligible small compared with attractive force of the magnet

The simple model of derived separation factor is shown in Figure 2.

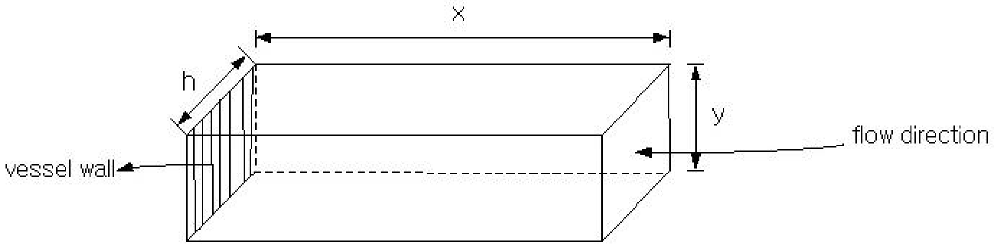

Figure 2. Model of separation factor

Time t_1 required to bring the CRUD to the vessel wall is given by the following equation.

$$t_1 = \frac{x}{V} = \frac{9xm}{2a^2 \boldsymbol{c} H (dH/dx)} \tag{6}$$

Time t_2 required to pass through the channel of the vessel having arc length x is given by the following expression.

$$t_2 = \frac{hyx}{Q} \tag{7}$$

Q: *flow rate* [m^3/sec]
x: axial distance from inlet to vessel wall [m]
y: height of vessel [m]
h: width of vessel [m]

Separation factor($\boldsymbol{h}$) is expressed by the following equation.

$$\mathit{Separation\ Factor}(\boldsymbol{h}) \propto \frac{t_2}{t_1} = \frac{2hya^2 \boldsymbol{c} H^2}{9xmQ} \tag{8}$$

$$\boldsymbol{h} = K \frac{hya^2 \boldsymbol{c} H^2}{xmQ} = K \frac{hya^2 (c\ /T\ ) H^2}{xAe^{B/T} Q} \tag{9}$$

Approximately, separation factor is shown as temperature dependent function.

$$h \approx 1 - \exp[-K \frac{a^2 (1/T) H^2}{e^{b/T} Q}] \tag{10}$$

K: experimental constant

T : $temperature[K]$

Therefore separating efficiency depends on the magnetic properties and size of CRUD, flow rates, intensity of magnetic field and temperatures.

4. Results and Discussion

Equation (5) is numerically solved by successive approximation using parameter A/B. Calculation result is shown on Figure 3. The velocity of the particle depends on frequency of the magnetic field and slows down abruptly at some point. The frequency depends on moving speed of the magnet assembly. In low frequency region, the particle moves together with magnet by attractive force of the magnet, but in too high frequency region, cannot move together due to viscous drag. However the velocity of particle in case of high frequency is faster than that of low frequency as shown in Figure 4.

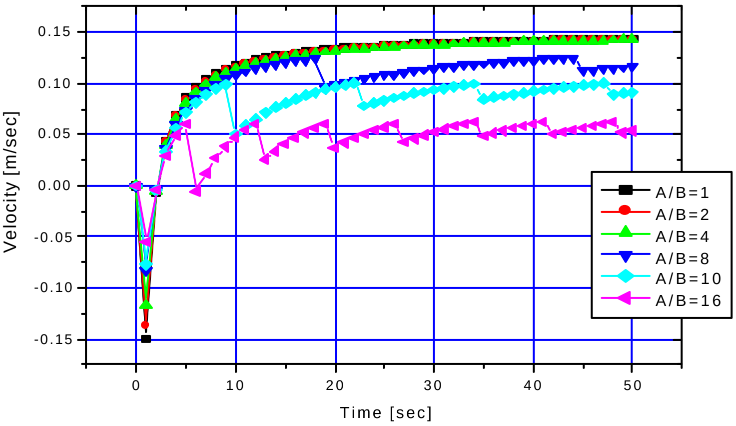

Figure 3. Numerical solution of CRUD motion

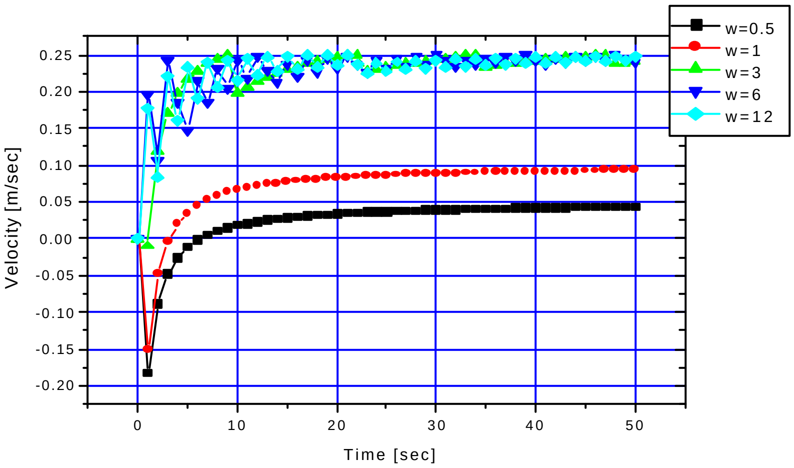

Figure 4. Trends of CRUD velocity on the frequency

As separating efficiency depends on magnetic properties of CRUD and CRUD size, various CRUDs are used in this test. Magnetic properties of CRUD used in this test shown on Table 1.

Table 1. Properties of CRUD[5]

CRUD	Aver.Diameter (m)	Magnetization (H/m)
α–Fe2O3 (hematite)	4.21E-06	0.458E-06
g–Fe2O3 (maghemite)	3.44E-06	9.07E-06
CoFe2O4 (Co-ferrite)	6.95E-06	2.6E-06
NiFe2O4 (Ni-ferrite)	4.88E-06	6.0E-06

Separation factor depends on the magnetic properties and size of CRUD, flow rates, intensity of magnetic field and temperatures as shown Figure 5, 6 and 7. The CRUD removal ability of moving alternative magnetic filter is high in case of large size of CRUD, high magnetization and low temperature. And the separation factor of α–Fe2O3(hematite) is very low because the magnetization of hematite is too low.

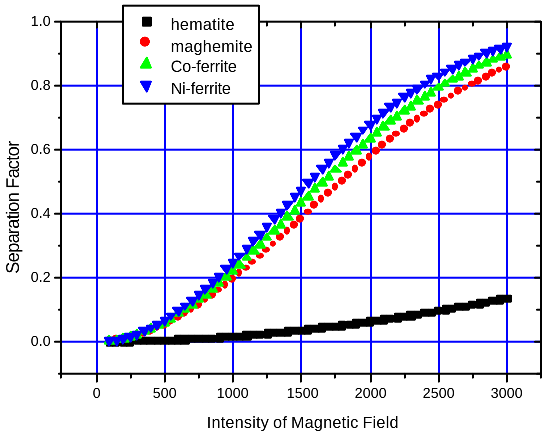

Figure 5. Separation factor with various CRUDs

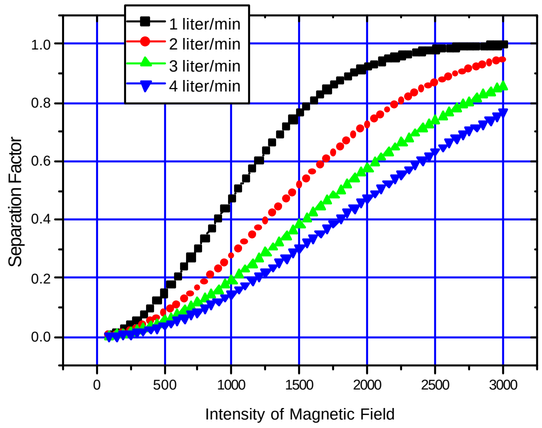

Figure 6. Separation factor on the change of flow rate

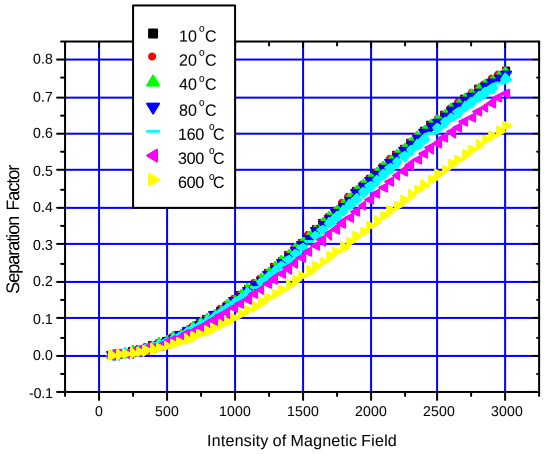

Figure 7. Separation factor on the temperature sensitivity

5. Recommendation

This study shows the expected magnetic filter performance how to remove the CRUD and hence the moving alternative magnetic filter can be recommended as the effective method for the reduction of radiation build-up. Further improvement of the separation factor and validation with experimental test are recommended as future works.

Acknowledgement

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