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An Experimental Study on the Characteristics of Electromagnetic Filter

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전자기 필터의 특성에 관한 실험적 연구

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Abstract

The electromagnetic filter has been recognized as a technological replacement for the conventional filtration systems of the nuclear power plant coolant. But, as of now there are neither clear understandings of the phenomena occurring in the electromagnetic filter nor the general theoretical analyses. These facts make the application of the electromagnetic filter to the real systems a little risky, and therefore it has not been commercialized although it shows excellent performances in such situations as the plant abnormality, where the conventional filters usually fail.

This experimental study of the low power electromagnetic filter aims at the clarification of the general characteristics under varying operational parameters. Since the detailed characteristics may differ from one electromagnetic filter to another, they are considered secondary. The impurities applied are the highly magnetic magnetite (Fe_3O_4) and the diamagnetic cuprous oxide (Cu_2O). The empirical equations are derived from the experimental data by the regressional analyses. They are classified of three types : Efficiencies vs. Time, Efficiencies vs. Load, and Load vs. Time. The characteristics of the electromagnetic filter observed in this experiment agreed well with other related works in many aspects. Especially in this study, some assumptions and discussions including the physical deposition are combined for the explanations of the filter characteristics found in our and other experimental works.

요 약

전자기 필터는 기존의 냉각수 정화계통에 대한 기술적 대체물로 주목받아 왔다. 그러나 현재로

선 전자기 필터의 물리적 현상에 대한 명확한 이해나 이론적 접근이 몹시 부족한 상태이다. 이러한 이유로 전자기 필터의 실제 적용에 어려움이 있으며, 우수한 성능에도 불구하고 광범위하게 상업화되지 못한 상태이다. 저출력 전자기 필터를 사용한 본 실험적 연구에서는 다양한 운전 변수들이 변하는 조건에서 전자기 필터의 특성에 관한 연구를 수행하였다. 단, 전자기 필터의 구체적 수치등은 필터마다 다르므로 부차적인 것으로 간주되었다.

실험에 사용된 불순물은 강자성의 사삼산화철과 반자성인 산화제일구리를 사용하였으며, 측정된 자료에 대해서는 회귀분석을 실시하였다. 그 결과로 효율 대 시간, 효율 대 필터부하, 필터부하 대 시간에 대한 근사 방정식이 얻어졌다. 본 실험에서 얻어진 전자기 필터의 일반적 특성은 지금까지의 연구와 잘 일치하는 것을 보였으며, 특히 본 연구에서는 지금까지의 연구들에서 밝혀진 특성들을 설명하기 위하여 물리침착등의 몇가지 가설이 제시되었다.

1. Introduction

The application of electromagnetic filter was initiated by Ianchelli et al.[1] to extract the iron stained anatase (titanium dioxide) present in kaolin for the benefication of kaolin in 1970. At the same time Heitman and his coworkers used it to remove iron oxide corrosion products from steam condensate at the 320MW power station of Nordwestdeutch AG in Keil, West Germany. Its basic idea is that the magnetic particles with the substantially large magnetic susceptibility, k, defined as the relative magnitude of the induced magnetic field to the applied field, can be removed in the ferromagnetic matrix magnetized by the applied field by magnetic force overcoming the net forces involved under the thermodynamic environments of power systems. Fortunately, the corrosion products of main concerns in the nuclear power systems are strongly magnetic.

Of the conventional methods for the treatment of the corrosion products, the demineralizer in CVCS uses the ion exchange resins. But for the effective operation and protection of the resin, the temperature and pressure must be reduced by heat exchanger, orifice and control valve, which could cause undesirable effects such as the thermal efficiency reduction. In addition, the treatment capacity amounts only to 0.05% of the total primary coolant inventory, thus the effects are not satisfactorily sufficient. Also the all volatile treatment (AVT) can reduce the corrosion products generation by increasing pH of the coolant. But also in this case the prerequisites that the condenser tube material should be austenitic stainless steel or titanium while the copper in the coolant system must be minimum must be met for the effectiveness.

The electromagnetic filter is free of defects in high pressure and high temperature conditions, and it shows an even increased removal efficiency under the abnormal situations such as the unexpected power load change or plant start-up in which the corrosion products are generated much more rapidly and in a large scale. It can be installed without large scale rearrangement of the already existing facilities, and can reduce the corrosion products inventory in the coolant system with only fractional treatment of coolant and therefore with the reduced personnel radiation exposure. The problem is nonmagnetic particles such as the copper and its oxides which are immune to the magnetic forces. Presently, the electromagnetic filters are studied and applied in many countries. As of the end of 1970, about 80 units were being tested or operated[2].

In 1970's, magnetic filtration has gained increasing acceptance as a replacement for conventional methods of removing particulates from the coolant systems[3,4,5]. However, present magnetic filter designs could not fully exploit the advantages that can be realized by application of the best state of the art in magnetic separation because the analytical or quantitative studies have not been so much developed and critical understandings of filtrations parameters and filter designs for the optimal use of magnetic filtration in power plants have not been made yet. The main concerns of this study are how the filter efficiency varies with input concentration, under sudden change of flow rate, under reverse flow conditions. Additionally, the characteristics of the sieve matrix, a kind of expanded metal matrix, are studied.

Finally, noting the fact that the Cu_2O is diamagnetic, the another focus is also given to the mixture of the highly magnetic Fe_3O_4 and the Cu_2O. The above five topics are selected because they can illustrate key characteristics for the simulation of the plant abnormal situations and for the best benefication of the electromagnetic filter. In studying the flow-rate fluctuation effects, it is expected that the filtration process independent of the pressure and temperature, provided that the spatial magnetic field gradient is substantially large, is confirmed. The experimental loop is open circuit, so it is very hard to establish high pressure and thus the experiment is done at the atmospheric pressure and the room temperature. It is known that the pressure drop across the electromagnetic filter is very small and thus can not be used for the criterion of the backflushing[1]. Empirical relationships for the efficiency of the filter are to be derived by the regressional analysis. The measurements are to be done using the atomic absorption spectrophotometer (AAS).

2. Theory

2.1. Physical Description of the Magnetism

All materials react to some extents with the magnetic fields, but the degree of reaction varies enormously from materials to materials. Therefore the materials concerned with the practical magnetic separation are limited to specific species. If the magnetic field is applied in a space filled with some materials, the total magnetic field in the space is the sum of the applied field and the induced field[6,7]. The induced field is due to the mutual reaction between the magnetic moment in the materials and the applied field. Now, let B represent the total measurable magnetic field. Then it can be expressed as follows.

$$B=H+4\pi J \tag{1}$$

Here, H is the vector representing the applied field, and $4\pi J$ can be thought of as the induced field by the existence of the materials in the space. Because the magnetic field is not isotropic generally in a material space, the vectors B, H and J are not parallel to each other[6,8]. Usually, the vector J is called the intensity of the magnetization, equivalent to the magnetic moment per unit volume of a material. Regarding the electromagnetic filter operation, the most important property of a material is the magnetic susceptibility k, expressed as the ratio of the induced field magnitude and the applied field magnitude. It is defined as

$$k=|J|/|H| \tag{2}$$

Also important is the specific magnetic susceptibility τ, equivalent to the magnetic susceptibility divided by the material density ρ. That is,

$$\tau=k/\rho \tag{3}$$

Typically the vectors B, H and J are expressed in Gauss, Oersted, and emu/cc. But the three units are equivalent in reality. Thus, the magnetic susceptibility is nondimensional and the τ becomes the specific volume unit. The induced field J either enforces or suppresses the applied field. Therefore, the Eq. (1) can be written as follows in terms of the measured magnitudes of the components.

$$|B|=|H|+4\pi\,|J| \tag{4}$$

Now dividing the Eq. (4) by $|H|$, we get

$$B|/|H| = 1 + 4\pi k \quad (5)$$

Defining the value $|B|/|H|$ as the magnetic permeability μ, it becomes finally

$$\mu = 1 + 4\pi k \quad (6)$$

If the space is free of a material the term 4π k is zero, leaving the magnetic permeability of unit magnitude. In fact, the magnetic susceptibility k is plus or minus.

The macroscopic magnetism for a material results from the atomic structure and atomic or molecular compositions of that material and it can be classified into three categories based on how the material reacts with the magnetic field[7]. They are the paramagnetism, the ferromagnetism, and the diamagnetism. The characteristics of the paramagnetism is the plus k value basically independent of the applied field. While the diamagnetism represents the small and J-independent minus k. The ferromagnetism has on the other hand very high plus value of k. In the ferromagnetic material, the vector J increases sharply to a point as the applied field vector H increases, and then the increasing rate gets small. The small increasing rate of J with H is called the magnetic saturation which affects the real application of the electromagnetic filter. The three magnetisms described above are represented in a graphical form in the Fig. 1. The most important corrosion products in the high temperature filtration for case of PWR are ferrites series containing nickel and cobalt. Table 1 lists the magnetic moments of important compounds[1,6].

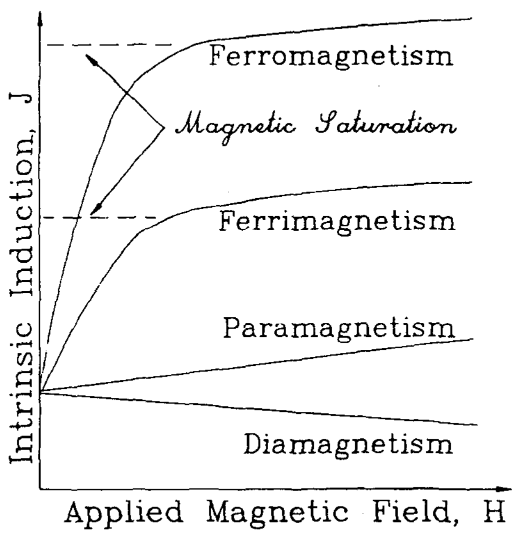

Fig. 1. Three Magnetisms

Table 1. Electromagnetic Moments of Metallic Compounds

Compounds	Values(emu/gm)
Chrome Steel(AISI 52100)(AECL data)	200
Magnetite(Fe_3O_4)	92
CANDU Crud(AECL data)	77
Nickel Ferrite($NiFe_2O_4$)	50
Maghemite(γ-Fe_2O_3)	74
Haematite(α-Fe_2O_3)	0.4
Copper Ferrite($CuFe_2O_4$)	25
Cobalt Ferrite($CoFe_2O_4$)	80
Cupric Oxide(CuO)(calculated)	1.2×10^{-2}
Cuprous Oxide(Cu_2O)(calculated)	-5.6×10^{-4}
Lithium Ferrite($Li_{0.5}Fe_{2.5}O_4$)	65

2.2. Working Equations in the Magnetic Filtration Process

The success of the electromagnetic filter in capturing out the magnetic materials from the fluids depends on the relative magnitude of the magnetic force overcoming the other forces existing and affecting the impurity particles in the filter matrix. The magnetic force on a particle can be simply expressed as the following equation[6,7]

$$F_{mag} = v(J \cdot \nabla H) \quad (7)$$

where v is the volume of the particle. For a particle having homogeneous magnetic moment per unit volume, the above equation can be expanded as

$$F_{mag,x} = kv\left(H_x\frac{\partial H_x}{\partial x} + H_y\frac{\partial H_y}{\partial x} + H_z\frac{\partial H_z}{\partial x}\right) \quad (8)$$

for the x component. This equation indicates that the magnetic gradient is very important. Therefore, for the best performance of the electromagnetic filter the magnetic gradient must be increased as can be possible in addition to the absolute magnitude of the magnetic field strength by a proper filter design. In most cases, the main force competing with the magnetic force is the hydraulic drag force F_{drag} expressed as in the equation

$$F_{drag} = 3\pi\phi D U \quad (9)$$

where ϕ is the fluid viscosity, D is the particle diameter and U is the fluid velocity vector. For the particle to be captured in a magnetic field, the magnetic force must exceed the hydraulic drag force. Thus the key point in the application of the electromagnetic filter is to maintain the magnetic force greater than the drag force. As can be seen easily from the Eq. (8), the magnitude and the sign of the magnetic force depend on the magnetic susceptibility k. If the sign as in the diamagnetic materials is minus, the force is repulsive. All above equations are not applied well to the particles having significant volume or nonhomogeneous properties, but provide reasonable estimations for the practices.

3. Experiment

3.1. Experimental Apparatus

Fig. 2 shows the experimental loop diagram used for this study. The main merits obtainable by forming the loop like this open structure are the easy parameter changeability, maintenance and feasibility increment due to its simplicity. The merits indicated above are from the view point of

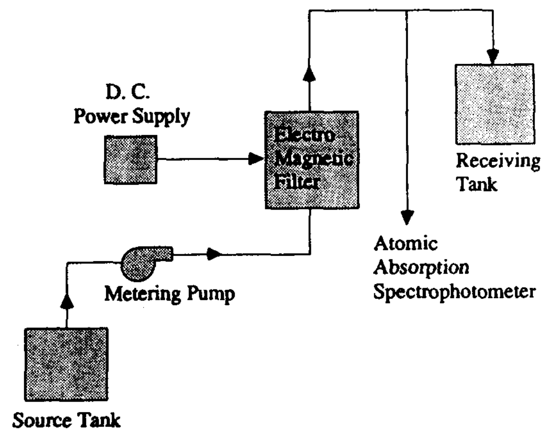

Fig. 2. Experimental Loop

ad hoc experimental purposes in studying the physical characteristics of the electromagnetic filters. The defect of this loop may be such that there are many sources of disturbances affecting the experimental results, which may be thought of as the front and back of a coin. However the object is in the general trend of the filter, not in the numerical details. One point to be emphasized is that the all materials were made from the non-magnetic materials to keep the magnetic chemical species from adhering to them. Fig. 3 shows the sizes and the cross sectional views of upper, middle and the lower supporters of the electromagnetic filter. Fig. 4 represents the electromagnetic filter body assembly composed of the three supporters.

3.2. Experimental Methodology

The five parameters varied in this experiment are the solenoid current or the magnetic field strength, the flow-rate, the corrosion product input concentration, the type and size of the filter matrix elements and the chemical species. The basic philosophy of experiment is to see how the filtration efficiency of the electromagnetic filter vary as the experimental parameters do. As shown in the Table 2, each parameters has its own symbol. The table also shows the parameters and their

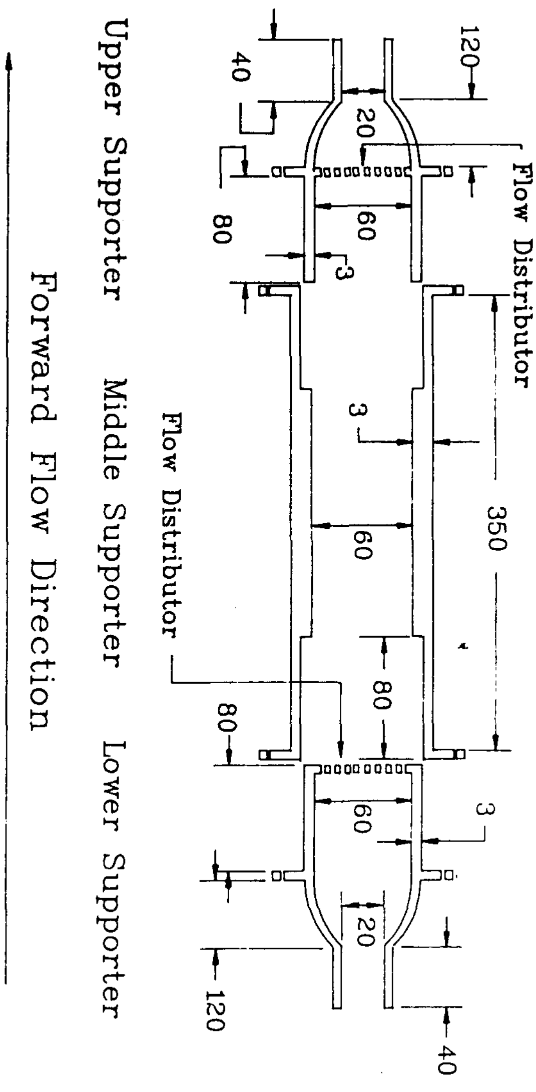

Fig. 3. Three Supporters(dimensions in mm)

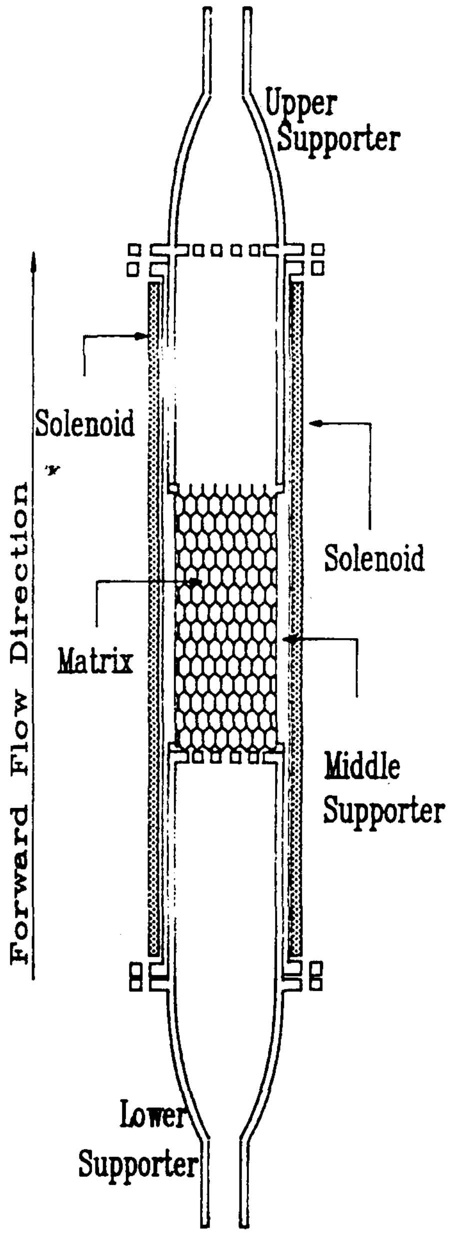

Fig. 4. Assembled Filter Body

ranges. The direct results of experiments, i.e. the relations between filter efficiency and the parameters will produce derived results as noted above in the introductory description.

In this study, The forward flow direction is just the normal one, that is, down–up. But both forward and backward flow directions are used to explore the filter behavior under reverse flow conditions. In the practical operation of a nuclear reactor, the corrosion products become larger in the abnormal or transient states than a normal and stable states. But this experimental study is only concerned with the situations where the flow–rates are increased and decreased with no change in the fluid impurity compositions and properties since this study use only one characteristic che-

Table 2. Experimental Sets

set#	V1*	V2*	V3*	V4*	V5*
1	2	0.67	1250	9.49	Fe_3O_4
2	2	0.67	1250	5.53	Fe_3O_4
3	2	0.67	1250	2	Fe_3O_4
4	2	0.67	1250	0.2	Fe_3O_4
5	2	1.33	1250	5.53	Fe_3O_4
6	2	2.67	1250	5.53	Fe_3O_4
7	2	1.33	1250	2	Fe_3O_4
8	2	2.67	1250	0.2	Fe_3O_4
9	5	0.67	1250	5.53	Fe_3O_4
10	5	0.67	1250	2	Fe_3O_4
11	2	0.67	250	5.53	Fe_3O_4
12	2	0.67	50	5.53	Fe_3O_4
13	2	0.67	250	2	Fe_3O_4
14	2	0.67	50	0.2	Fe_3O_4
15	2	0.67	1250	5.53	Cu_2O
16	2	0.67	1250	0.2	Cu_2O
17	2	0.67	1250	5.53	$Fe_3O_4+Cu_2O$

*These represent the Experimental Variables;
V1(Current of DC power supply in Ampere)
V2(Flowrate in ml/sec)
V3(Concentration in ppm)
V4(Matrix elements sizes: 9.49, 5.53 mm for Ball diameters, 2, 0.2 mm for Steel line Gaps of the Sieves)
V5(Chemical Species)

mical species at one experiment. As a filter component, two sizes of both ball and sieve matrix elements are used. Finally to explore the filter performance under mixed solution condition, the mixture of 50% Fe_3O_4 and 50% cuprous oxide was used, and the results was compared with those for the cuprous oxide alone.

3.3. Data Analysis

The model for this multiple regression analysis is polynomials. The dependent variable is the efficiency and the independent one is the time. The model equation, e.g. for efficiency, is

$$E_m = \sum_{i=0}^{k} a_i T^i \tag{10}$$

The basic philosophy is to minimize the squared sum of the error, SSE. This is so called the least squares method. SSE is expressed as follows.

$$SSE = \sum_{l=1}^{n} (E_l - E_{ml})^2 \tag{11}$$

In this study the statistics package MINITAB was used for the multiple regression of the experimental data with k=6.

As noted previously, the direct results of the experiments are of the forms, efficiency versus time for each set of variables. But it seems that the time can not become a pivot parameter for the evaluation of the electromagnetic filter performance. The real and possible parameter is the filter load which is defined in this context as the mass of the impurities per unit volume of the filtering media. The filter load can be obtained by the numerical integration. F is the flow-rate assumed to be constant with time, C_i and C_o are the input and the output concentration, respectively. S is the filter load and V_{fm} is the volume of filtering media and E is the filter efficiency. Establishing the mass balance,

$$FC_i = \dot{S} V_{fm} + FC_o \tag{12}$$

Since the output concentration C_o can be expressed as $C_o=C_i(1-E)$, the filter load can be obtained by the following equation

$$S = \frac{FC_i}{V_{fm}} \int_{t_{min}}^{t} E(t)\,dt \tag{13}$$

The induced results was derived based on the direct results to see the characteristics of the filter more clearly. Table 3 lists the regression equations for the efficiency vs. loads. These are made by watching the efficiency variation as the experimental variable changes at some time. Also the efficiency variation with the load will be observed. For every experimental set of variables, the load variations with time are also plotted.

Table 3. Regressed Efficiencies in Terms of Loads

set#	a_0	a_1	a_3	a_4	a_5	a_6	R^2(%)
1	1.106×10^{10}	-2.284×10^{7}	6.395×10^{2}	0.000×10^{0}	-4.756×10^{-3}	0.0×10^{0}	97.0
2	1.100×10^{10}	-2.216×10^{7}	6.016×10^{2}	0.000×10^{0}	-4.471×10^{-3}	0.0×10^{0}	96.7
3	1.060×10^{10}	-7.371×10^{6}	5.802×10^{1}	0.000×10^{0}	0.000×10^{-0}	-2.6×10^{-7}	92.6
4	1.045×10^{10}	-5.405×10^{6}	4.346×10^{1}	0.000×10^{0}	0.000×10^{-0}	-2.0×10^{-7}	94.9
5	1.064×10^{10}	-6.583×10^{6}	5.440×10^{1}	-6.973×10^{-2}	0.000×10^{-0}	0.0×10^{0}	98.6
6	1.104×10^{10}	-7.099×10^{6}	1.877×10^{1}	0.000×10^{0}	-1.444×10^{-5}	0.0×10^{0}	96.8
7	1.014×10^{10}	-9.078×10^{5}	2.172×10^{0}	0.000×10^{0}	0.000×10^{-0}	-3.2×10^{-9}	99.3
8	1.028×10^{10}	-1.154×10^{6}	1.119×10^{0}	0.000×10^{0}	0.000×10^{-0}	-2.0×10^{-10}	97.9
9	1.109×10^{10}	-2.006×10^{7}	5.401×10^{2}	0.000×10^{0}	0.000×10^{-0}	0.0×10^{0}	95.7
10	9.887×10^{9}	-1.599×10^{6}	-4.123×10^{1}	9.392×10^{-2}	0.000×10^{-0}	-9.0×10^{-8}	99.4
11	1.045×10^{10}	-4.135×10^{7}	1.814×10^{4}	-2.091×10^{2}	0.000×10^{-0}	0.0×10^{0}	99.8
12	1.113×10^{10}	-7.883×10^{8}	2.056×10^{7}	0.000×10^{0}	-1.733×10^{5}	0.0×10^{0}	97.5
13	1.123×10^{10}	-1.227×10^{8}	9.919×10^{4}	-1.105×10^{3}	0.000×10^{-0}	0.0×10^{0}	96.1
14	1.113×10^{10}	-5.280×10^{8}	9.463×10^{6}	-5.004×10^{5}	0.000×10^{-0}	0.0×10^{0}	96.0
15	3.438×10^{9}	-2.991×10^{8}	2.729×10^{6}	0.000×10^{0}	-6.743×10	0.0×10^{0}	96.8
16	7.295×10^{9}	-2.375×10^{7}	4.345×10^{3}	0.000×10^{0}	-3.162×10^{-1}	0.0×10^{0}	96.9
17	6.596×10^{9}	-1.849×10^{8}	3.161×10^{5}	0.000×10^{0}	-1.577×10^{2}	0.0×10^{0}	97.8

Note that the regressed efficiencies are modelled as

$E_m = a_0 + a_1 S_m^1 + a_3 S_m^3 + a_4 S_m^4 + a_5 S_m^5 + a_6 S_m^6$,

where E_m represents the efficiency multiplied by 10^8

S_m represents the load and m represents the experimental set number.

4. Results and Discussion

4.1. Effects of Input Concentration

The effects of input concentration can be observed from Fig.s 5 and 6. In Fig. 5, the curves #2, #11, #12 represent the performances for ball matrix of diameter 5.53 mm. These three curves show explicitly the fact that the higher the impurity concentration the better the efficiency of the electromagnetic filter. The degree of performance improvement is nearly proportional to the concentration increment. The performance gap, i.e. the difference of performances between the higher and lower concentrations is shown to be very large, a remarkable fact, while the curves #3, #4, #13 and #14 represent the sieve matrix performances. As can be seen from the curves #3 and #4, the filter performances change little as the gap between the steel lines of the sieve matrix element does, though the sieve matrix element with a smaller gap, #4 shows some improvement, which is suspected of as the result of so called the mechanical trapping. The general observation that the higher input concentration improves the filter performance is also seen in this case of sieve matrix. But comparing the curves #3 and #13 carefully, the degree of performance improvement is shown to be much larger than that for the ball matrix, #2 and #11, with the same concentration increment. Note that the performance gap between #4 and #14 is much larger than that between #3 and #13. But this performance gap between #13 and #14 is due to the much larger concentration increment. In summary, the electromagnetic filter performance is improved as the input concentration increases. And the sieve matrix shows better performance than that of the ball matrix.

The observations seen in the Fig. 5 can be represented in a more explicit form in terms of the loads. In Fig. 6, it is shown that in the starting and the ending period of filtration with the ball matrix, the efficiency for the input concentration of 250 ppm is larger than that for 1250 ppm. The sieve matrix with a smaller steel line gap shows better efficiency as time goes on, though the input concentration is smaller. Also note that the sieve matrix generally maintains larger efficiencies with time than the ball matrix, a fact not observed in the Fig. 5.

The above observations from the Fig.s 5 and 6 indicate that as long as the loads are small the efficiency can maintain high value and the magnetic attractions between the matrix and the impurities are very important for the improved filter performance as it must be. But here, we can note that the efficiency generally drop sharply with the load as the input concentration get smaller as can be seen in the Fig. 5. One possible explanation for this is based on the assumption that once the impurities are trapped sufficiently in the matrix and thus the local magnetic field gradient becomes small, the main mechanism of impurity trapping is turned into the physical deposition from the magnetic force, and the probability of the physical deposition is proportional to the number of particles in space, that is, the concentration of impurities. Therefore the higher the concentrations, the higher the probability of depositions in some points of matrix, which explains the general trends shown in Fig. 5.

4.2. Effects of Flow-Rate

In Fig. 7, we observe that the higher the flow-rate the better the performance of the electromagnetic filter, an unreasonable observation at a first glance. Also note that the sieve matrix performs better here, too. In Fig. 8, to some point in time the efficiencies are higher for the lower flow-rates. But after that point the efficiencies are

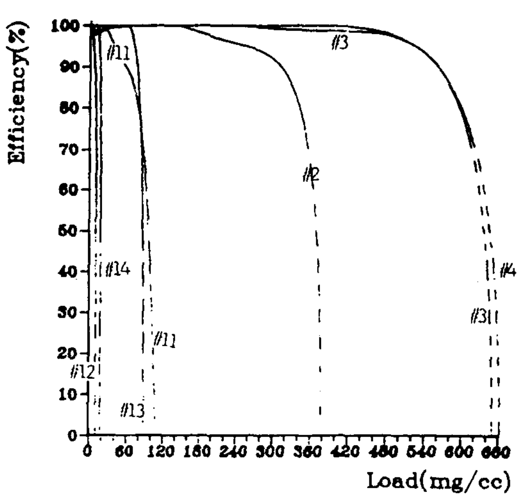

Fig. 5. Efficiencies vs. Load for the Parameter Concentration

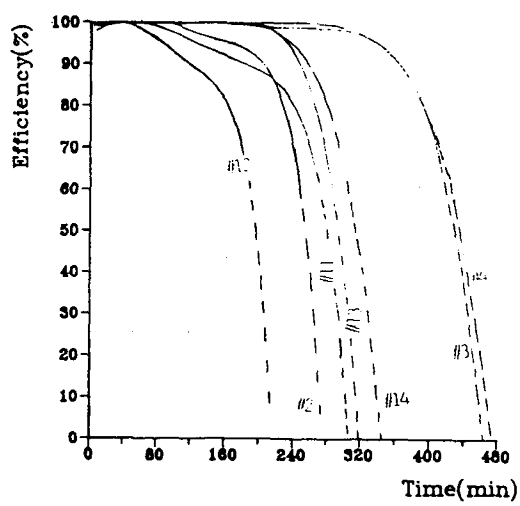

Fig. 6. Efficiencies vs. Time for the Parameter Concentration

lower for the lower flow–rates. Common observations in the two figures are the unusual trends that the higher the flow–rate the better the performances of the electromagnetic filters. This observation is also seen in the other reports[6,9] on the characteristics of the electromagnetic filter.

This phenomenon occurs because the flow–rate does not reach the critical value yet and may be explained as follows. Once the load reaches to some point high enough for the magnetic gradient and thus the magnetic strength to become less effective, the trapping or filtration processes of the impurity particles are performed by some non-magnetic causes. The main mechanism suggested earlier was the physical deposition which is assumed to be proportional to the number density or concentration of the impurity particles. Now also we can expect that the probability of deposition increases when the particles can penetrate more deeply into the lumps of the trapped impurities or into the residual trapping positions hard to approach. An increased flow–rate may provide the appropriate hydraulic inertia for those situations to be possible. Of course, for the very high flow–rate, the results of taking away the trapped impurities may cancel the effects of the penetrations and then depositions because of the very high dragging force on the particles.

4.3. Effect of Matrix Parameter

The figures related to the matrix parameter are Fig.s 9 and 10. Since the magnetic gradient is proportional to the inverse powers of the radius of curvature, the performance for the ball with a smaller diameter might be better than that for the ball with a larger diameter. In discussing the effects of the input concentration, it was also shown that the increase of trapping nuclei density by the narrower steel line gap does not secure the performance improvement.

Although the exact mechanisms affecting the filtration processes must be known for the clear understanding of these phenomena, common observations in this study suggest some idea that for the low power electromagnetic filter there might be some upper limit of filter matrix porosity or quantity of filter matrix elements per unit

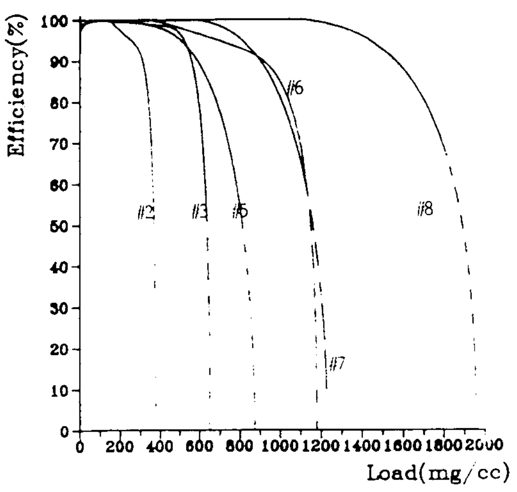

Fig. 7. Efficiencies vs. Load for the Parameter Flow-rate

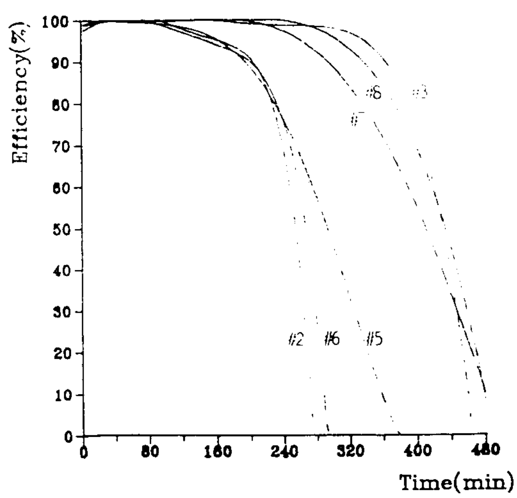

Fig. 8. Efficiencies vs. Time for the Parameter Flow–rate

volume beyond which other forces like the hydraulic dragging force from the increased flow retardation due to the denser filter matrix can overcome the magnetic attraction force. In this point of view, the optimal matrix porosity, that is, a quantity of filter matrix per unit volume with a full embodyment of the magnetic force with a little desorption of the impurities by the forces like the dragging force, is important for the ease of backflushing and economic considerations. Anyway, if it were not for the poor backflushing and weak structural formation, the sieve matrix shows an excellent performance.

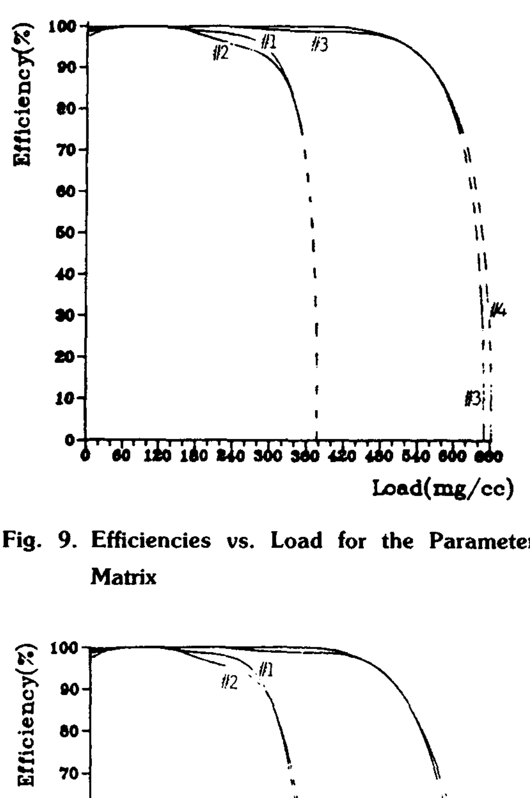

Fig. 9. Efficiencies vs. Load for the Parameter Matrix

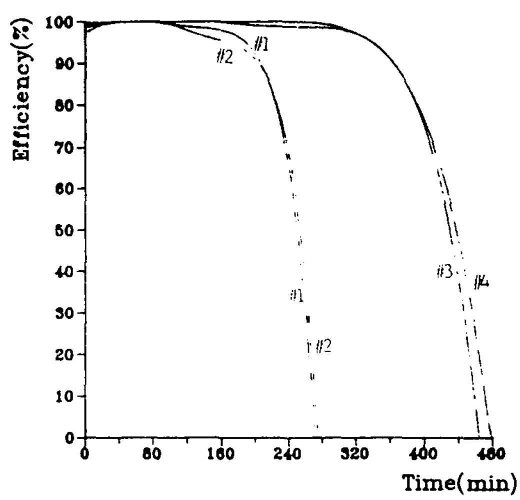

Fig. 10. Efficiencies vs. Time for the Parameter Matrix

4.4. Performances according to the Chemical Species

In this study, two chemical species are used. One is the highly magnetic Fe_3O_4 and the other is diamagnetic Cu_2O. Since the magnetic force provides the main cause for the impurity particles to be filtrated in the electromagnetic filter, it is expected that the magnitude can be filtrated with very high efficiency. In Fig. 11, the curves #2 and #15 represent the performances for the Fe_3O_4 and the Cu_2O, respectively in the ball matrix of diameter 5.53 mm. While the curves #4 and #16 represent those in the sieve matrix of steel line gap 0.2 mm. These exactly show the expectation that the highly magnetic Fe_3O_4 is filtrated with a remarkable performance while the diamagnetic Cu_2O shows very poor filtration. The reason that the sieve matrix shows a better efficiency is of course due to the steeper local magnetic gradient.

From the Fig.s 11 and 12, the cuprous oxide, even though it is diamagnetic, shows some filtrability. Moreover, note the high performance in the sieve matrix, even reaching 100% efficiency at some time. For these observations, it can be thought that some mechanisms other than the magnetic force play a significant role in the filtration processes. In analysing the effects of concentration and flow-rate, it was physical deposition whose effects are materialized when the magnetic forces become weak by the accumulation of the impurity particles in the matrix. Now since the Cu_2O is diamagnetic, it is unreasonable to think that the filtrability of it in this study is the result of the magnetic attractions. A possible explanation is the mechanical trapping. In other words, the Cu_2O particles are captured due to some hydrodynamic origins, or the mechanical or structural formations of the matrix, since the matrix is denser. This point of view can make it plausible that the sieve matrix shows significant performance for the filtration of the nonmagnetic particles.

The peculiar characteristics to the Cu_2O is the sharp increase of the efficiency during some period, and sharp decrease after that. This may be due to the weak retention strength of the mechanical trapping. In other words, the impurities trapped earlier by the mechanical trapping are apt to be desorbed easily even with a little addition of impurities on those positions. The impurities desorbed may adhere to space where the impurities are not still so large. But the period during which the desorption and resettlement of the impurities is so short that there is a sharp increase in the efficiency. However, the catastropic downflow of the impurities after the first desorption rapidly get rids of the space for resettlements, thus making the efficiency decrease sharply.

A final point to be noted is the curve #17 representing the performance in the case of mixture of the Fe_3O_4 and the Cu_2O, with a mixing ratio 1 to 1 in mass. It explicitly shows the improvement relative to the case of Cu_2O only. The reason why the performance is improved when the diamagnetic materials are mixed with the highly magnetic materials suspected to be the com-

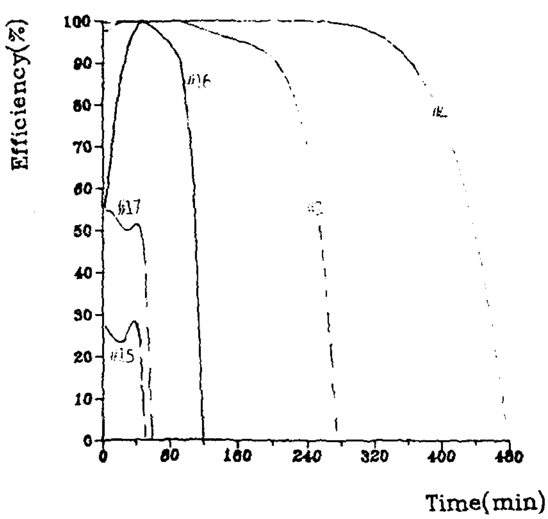

Fig. 12. Efficiencies vs. Time for the Parameter Chemical Species

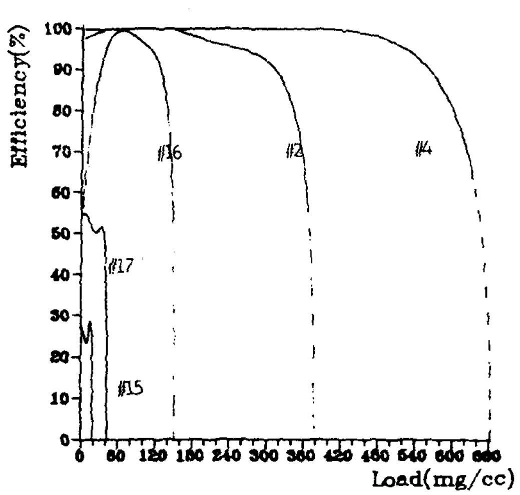

Fig. 11. Efficiencies vs. Load for the Parameter Chemical Species

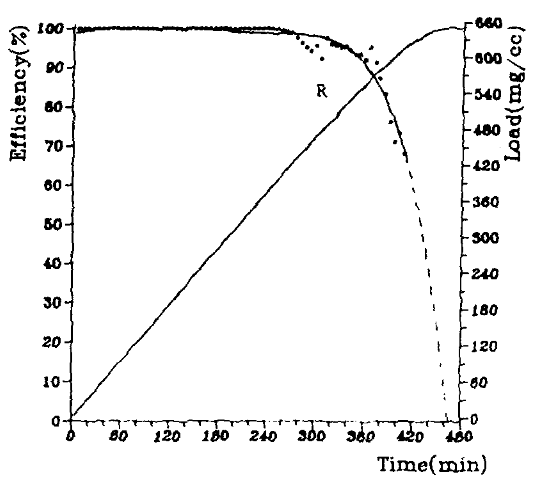

Fig. 13. Measured, Regressed Efficiency and Load for Experiment Set #3

binational behavior of the diamagnetic materials with the magnetic materials by some causes such as the surface adsorption of nonmagnetic materials to the magnetic materials or substitutions for the magnetic materials. For examples, the copper ferrite $CuFe_2O_4$ is ferrimagnetic with a saturation magnetization of $\sigma_s=25$ emu/gm.

4.5. Behaviors under the Reverse Flow

We can find the effect of reverse flow in the Fig. 13, where the label R on the measured efficiency represent the points at which the flow directions are reversed. The purpose of the reverse flow direction is to see how the upper portion of the electromagnetic filter elements behaves which is supposed to be used ineffectively. But as the figure shows, the reversed flow increases the efficiency only instantly. This observation make the reversing action is undesirable considering the troublesome or complicated efforts to reverse the flow direction. Comparing the results of the reverse flow experiments with those of forward flow, it is apparent that the flow direction nearly have no effects on the performances of the electromagnetic filter.

5. Conclusions and Suggestions

From this experimental study, following conclusions are made.

(1) The performance of the electromagnetic filter is improved as the impurity concentration and the flow-rate increase.

(2) There is an upper limit of the trapping nuclei density or filter matrix porosity beyond which the filter performance is no longer improved.

(3) The sieve matrix generally shows better performance than the ball matrix because of higher local magnetic gradient due to smaller radius of curvature.

(4) The nonmagnetic effects such as the physical deposition can explain fairly well the characteristics of the electromagnetic filter after the magnetic force becomes weak because of load increase.

(5) The current increase to the solenoid apparently improves the filter performance as it is expected.

(6) Although the diamagnetic materials show poorer performance than the magnetic materials, the mixed impurities of magnetic and nonmagnetic materials can be filtrated somewhat with an improved performance.

(7) The mechanical trapping plays significant roles in filtrating the impurity particles.

(8) The reverse flow filtration does not affects the filter performance any longer.

(9) The flow-rate fluctuations have no effects on the filtration as long as the magnetic force remains strong.

The final conclusion implies that in order to overcome the highly transient thermohydraulic environments existing in the nuclear power plant for the still effective operation of the electromagnetic filter can be done by the maintenance of the magnetic stability in those environments. In the abnormal situations of the nuclear power plant, it is known that the impurity generation increase, in amount and sizes of the particles, and the flow-rate generally increases. Now as long as the flow-rate is below the critical velocity of the electromagnetic filters, the abnormal situations are none other than the conditions in which the electromagnetic filter show improved performances. This point, examined in this study, is an excellent characteristics peculiar to the electromagnetic filter.

As a further suggestion, the nonmagnetic mechanisms affecting the filtration processes in the filter matrix such as the physical deposition should be studied carefully for the state of the art use of the electromagnetic filter. With respect to this, the optimal matrix porosity or the trapping nuclei density showing maximum performance with the least dragging force should also be studied. The clear understanding of these topics will contribute to the realistic explanations of the concentration effects and the flow-rate effects or the critical velocity. Also it is recommended that for the real applications a set of characteristics peculiar to a given electromagnetic filter, such as the performances with regard to concentration, flow-rate, etc., be specified especiallly because, as noted earlier, the general theory has not been developed yet.

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