J. of Korean Oil Chemists' Soc.,
Vol. 31, No. 1. March, 2014. 59~65
ISSN 1225-9098 (Print)
ISSN 2288-1069 (Online)
http://dx.doi.org/10.12925/jkocs.2014.31.1.59

Application of magnetic field to iron contained dust capture

Shan Huang · Hae-Woo Park · Young-Min Jo[1]† · Young-Koo Park[2] · Youn-Che Kim[3]

[1]*Department of Environmental Science Engineering, Kyunghee University*
[2]*Department of Environmental Engineering, Kangwon National University*
[3]*Department of Material and Metallurgical Engineering, Kangwon National University*

(Received February 5, 2014 ; Revised February 25, 2014 ; Accepted February 27, 2014)

Abstract : Indoor air quality including metro subway is of recent interests in large cities. Inflow air to the inside of the train and circulating air flow through MVAC of stations contain large amount of iron based fine particles. This paper evaluated the collection of such a dust by magnetic filters as comparing to conventional particle capturing mechanisms such as inertia, direct impaction and diffusion. It was found that filtration velocity, magnetic field intensity, and fiber size were the most important parameters for magnetic filtration. Application of magnetic force obviously enhances the collection efficiency particularly in fine modes smaller than 10 mm. However, its effect was found greater in 2.5 mm than submicron particles.

Keywords : magnetic filtration, single fiber efficiency, submicron particle, magnetic field intensity

1. Introduction

Fibrous filtration is the most common method for aerosol control due to the advantages of providing high collection efficiencies at low-pressure drop for capturing sub-micrometer particles. It is used in a wide range of applications in indoor air and industrial gas stream for the air pollution control. A fibrous filter consists of a mat of fine fibers arranged in such a way that most are perpendicular to the direction of air flow. And the packing density is on the order of 0.1 or less, representing a relatively porous open packing of fibers that offer small aerodynamic resistance to air flow. A typical operating face velocity of a fibrous filter is in the 0.1 to 3 m/s range [1]. The most common materials of fibers in fibrous filters are cellulose (wood), glass, ceramic, stainless steel and plastic.

In general, various physical mechanisms contribute to a high efficiency fibrous filter's effectiveness in capturing particles. The most predominant mechanisms are interception, inertial impaction and diffusion. In addition, filter efficiency varies with particle size, forless than 0.1 μm in diameter particles, the primary filtration mechanism is diffusion, for above approximately 0.5 μm particles, interception along with inertial impaction are predominant, for particles between approximately 0.1 and 0.5 μm the filter is less efficient in spite of diffusion and interception regime as the particles are too large for a great diffusion effect and too small

---

†Corresponding author
(E-mail: ymjo@khu.ac.kr)

for a large interception effect. Conventionally, electrical effects can improve collection efficiencies by Coulomb force and polarization force.

An additional magnetic mechanism can be incorporated to the conventional gas filtration in order to better retain these paramagnetic/ferromagnetic particles from their emission to the atmosphere. Magnetic technology in gas filtration was first presented by Lucchesi etc[2] by using a magnetically stabilized bed of cobalt for the hot gases filtration with high efficiency. Magnetic filtration is a powerful method for the removal of paramagnetic and ferromagnetic particles [3 – 4]. It offers high filtration rates, low pressure drop across the filter, applicability to small particles (< 1 μm)that would plug most conventional filters, and the capability to release the captured material without disassembling the filter (by turning off the external magnetic field) [5].

There are two types of magnetic filtration systems, one consists of nonmagnetic canisters filled with ferromagnetic filter-matrix elements immersed in an applied magnetic field sufficient to saturate these elements magnetically [6], the other contains a simple magnetic grate.

This paper gives a theoretical study of the capture efficiency of a magnetic filter, the capture mechanisms in the presence of magnetic forces and discussed the dependency of filter performance on filtration velocity and external magnetic field intensity in magnetic filters.

2. Theoretical background

Magnetic force is long range and is the dominant factor in particle capture. The magnetic force acting on a paramagnetic particle in the vicinity of a ferromagnetic collector can be 100 times larger than gravity. The capture cross section of a bare collector in a magnetic field can be 100 times larger than that due to inertial impaction alone [7].

2.1. Trajectory prediction

Consider a small particle near a ferromagnetic cylinder which is in a magnetic field. The path of the particle is dependent on the gravitational, inertial, drag, and magnetic forces acting on it.

The following assumptions were used to calculate of individual particle trajectory:

1) According to the previous study of Zarutskaya and Shapiro[8], particles are spherical in shape, and their rotational effects are negligible. Particles' magnetic susceptibility is assumed to be constant, and their magnetic moments are assumed to be oriented in the direction of the magnetic field.

2) Under a low Reynolds number flow system, the particle trajectory can be calculated by the force balance equation, including gravitational ($\vec{Fg}$), magnetic ($\vec{Fm}$), drag ($\vec{Fd}$), and random ($\vec{Fbr}$) forces.

3) No particle re-entrainment occurs, and deposited particles do not significantly alter the flow and magnetic fields in the unit cell.

The trajectory of a submicron particle moving in a gas with velocity $\vec{v}$ under the action of gravitational, magnetic, drag, and random forces is determined by the force balance equations based on the Newton's second law.

$$m_p \frac{d\vec{v}}{dt} = \vec{Fd} + \vec{Fg} + \vec{Fm} + \vec{Fbr} \qquad (1)$$

Here, m_p is the particle mass; t the time variable.

Particle drag force $\vec{Fd}$ is expressed as

$$\vec{Fd} = f(\vec{u} - \vec{v}) \qquad (2)$$

Where $\vec{u}$ the flow velocity vector; and f the particle friction coefficient given by the stokes law as $f = 3\pi\mu d_p / C_c$ byFriedlander [9], where C_c is the Cunningham slip correction factor, expressed as

$$\mathrm{C_c} = 1 + \frac{2\lambda}{d_p}(1.142 + 0.558 \times \exp(-\frac{0.999 d_p}{2\lambda})) \tag{3}$$

Where λ is the mean free path.

$$\lambda = \frac{\mathrm{K}_B T}{\sqrt{2}\pi {d_p}^2 \rho_{\mathrm{g}}} \tag{4}$$

Where KB is Boltzmann's constant, ρ gas density, dp particle diameter, T temperature.

Because of the small size of particles, the magnetic field in the particle is assumed to be approximately uniform. The following expression was then used to evaluate the magnetic force $\vec{Fm}$ on a magnetic particle:

$$\vec{Fm} = \mu_0 \nabla(\vec{M} \cdot \vec{H}) \tag{5}$$

Where μ_0 is the magnetic permeability of free space, $\vec{H}$ the magnetic field strength, and $\vec{M}$ the particle magnetic moment, whose scale is related to the magnetization of particle by

$$M = \frac{\chi}{1 + \chi/3} H V_p \tag{6}$$

Where χ is the particle magnetic susceptibility, and V_p the particle volume [10].

In Brownian motion, a particle at time t and position p will make a random displacement r from its previous point with regard to time and position. The resulting distribution of r is expected to be (1) Gaussian (normal with a mean of zero and a standard deviation of one), (2) to be independent, and (3) have a root mean square displacement of $\sqrt{2Dt}$ in its x, y, and z coordinates. The random displacement r in one coordinate can be calculated as

$$r = \frac{\sqrt{2Dt}}{\sqrt{2\pi}} e^{-\frac{\zeta^2}{2}} \tag{7}$$

Where ζ is a random number.

The trajectory for a given particle was determined by solving equation (1) using the Runge-Kutta method of the 4th order.

2.2. Efficiency prediction

Direct interception takes place on account of the finite size of the particles, primarily effect particle size larger than 0.1 μm. The single fiber efficiency due to interception η_{I}, is defined

$$\eta_{\mathrm{I}} = \frac{1-\alpha}{K} \cdot \frac{R^2}{1+R} \tag{8}$$

K is called the Kuwabara hydrodynamic factor, and

$$\mathrm{K} = -\frac{1}{2} In\alpha - \frac{3}{4} + \alpha - \frac{1}{4}\alpha^2 \tag{9}$$

Here, α is filter solidity, fraction of the total volume of the filter element actually occupied by fibers.

Inertial impaction occurs when a particle is so large (>0.5 μm) that it is unable to quickly adjust to the abrupt size changes in streamline direction near a filter fiber. The particle, due to its inertia, will continue along its original path and hit the filter fiber. This type of filtration mechanism is most predominant when high gas velocities and dense fiber packing of the filter media is present.

Inertial deposition depends mainly on the Stokes number(Nst):

$$\eta_{\mathrm{Im}} = \frac{N_{st} J}{2K^2} \tag{10}$$

Where,

$$Nst = \frac{\rho_p {d_p}^2 v_f}{18 \mu d_f} \tag{11}$$

J is related to R, and is expressed as follows:

$$J = (29.6 - 28\alpha^{0.63})R^2 - 27.5R^{2.8}$$

for R〈0.4 (12)

$$J = 2.0$$

for R〉0.4 (13)

By definition of the single fiber efficiency due to diffusion

$$\eta_D = 2.6\left(\frac{1-\alpha}{K}\right)^{\frac{1}{3}} Pe^{-2/3} \tag{14}$$

Peclet number (Pe) is equal $d_f v_f / D$, and $D = kTC_c / 3\pi\mu d_p$.

Magnetic filter performance η_M, is basically expressed as follows [11] :

$$\eta_M = \phi(1 - e^{-\xi}) \tag{15}$$

Where ϕ is the fraction of ferromagnetic particles present in the fluid to be cleaned, and ξ is the logarithmic efficiency coefficient described as a function of certain filtration parameters as follows[12] :

$$\xi = 3\times10^{-6}\left(\frac{\chi\mu_1^{1.38}(1-\phi)\ H^2 d_p}{\rho_f v_f^{\,2} d_f}\right)^{0.6} L_d \tag{16}$$

Where $L_d = L / d_f$ is the dimensionless length of the filter, x is the effective magnetic susceptibility equal to $\chi_p - \chi_f$ in which χ_p is the magnetic susceptibility of the particles, χ_f is the magnetic susceptibility of the fluid, m is the magnetic permeability of the matrix elements (spheres in this study), H is the external magnetic field intensity, d_f is the size of spheres (fibers), μ_1 is the relative magnetic permeability of filter elements, v_f is the filtration velocity of the fluid, ε is the porosity of the filter matrix, d_p is the size of particles in the liquid to be cleaned, and L is the length of magnetic filter. Magnetic susceptibility of the magnetic particles (d_p 〈5mm), which may be present in industrial fluids subjected to magnetic filtration, can be assumed as χ = 0.05-0.5 [11].

Common practice has been to combine single-fiber collection efficiencies by simply adding them. This procedure is not rigorously justified but works adequately when one mechanism predominates or when all single-fiber efficiencies are low. Combining of diffusion and interception are proved satisfactory by Lee and Liu [12], while more addition of the individual electrically based single-fiber efficiencies seems unlikely to predict results adequately [13].

3. Filter performance

In the large particle regime (〉0.5μm) in which interception and inertial impaction dominate, the classical mechanisms predict that filter efficiency increases with either increasing V_f or d_p. Filter efficiency (E) can be related to single-fiber collection efficiency(η) as follows:

$$E = 1 - \exp\left(\frac{-4\eta\alpha L}{\pi d_f(1-\alpha)}\right) \tag{17}$$

3.1. Effect of magnetic force on magnetic filter performance

Magnetic force is the most important factor, since it directly affects the filtration process and is dependent on the external magnetic field intensity. Filter performance increases as the external magnetic field intensity increases [3, 14-20]

The predictions show magnetic filtration efficiency increases with particle size which make up for the conventional low efficiency area (0.5-1 μm) (Fig. 1). The values of parameters used in the magnetic filtration are given in Table 1.

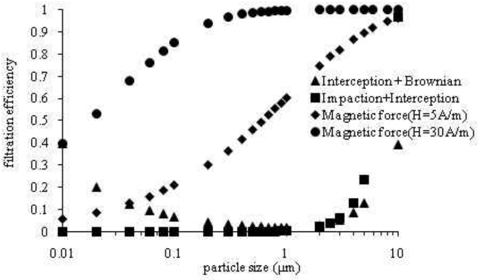

Fig. 1. Filter efficiency predicted by the classical capture mechanisms.

In addition, as shown in equation (16), the magnetic, hydrodynamic and geometric parameters such as H, Vf, df, dp, L that can greatly affect the filter mechanismplay a very important role in filtration. Therefore, these parameters are studied in following parts.

3.2. Effect of magnetic field intensity on filtration efficiency

Many theoretical and experimental studies have shown that the dependence of filter performance on magnetic field intensity (H). Fig. 2 presents the results of filtration for removal of magnetite by applying different external magnetic field intensities. The sizes of the particles are in the range of 0.1-2.5 μm. The effect of external magnetic field intensities on the filter performance is significant, filtration efficiency increases with magnetic field intensity due to the enhanced magnetic force, and the logarithmic efficiency is not linearly dependent on magnetic field intensity.

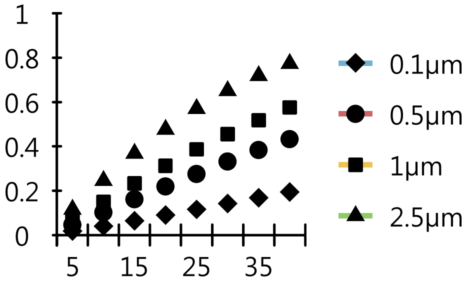

Fig. 2. Effects of magnetic field intensity on filter efficiency.

3.3. Effect of flow velocity and fiber size on magnetic filtration efficiency

Filtration velocity and size of the captured particles are the key parameters affecting the filtration process. Fig. 3 shows the dependence of inverse logarithmic efficiency coefficient on filtration velocity, showing its no-linear relationship for theoretical calculation, conforming to the relationship $1/\xi \propto V_f^2$. High velocity causes high impaction, and the gas will carry the particle penetrate the filter. Meanwhile, less retention time caused by high velocity also decrease the filtration efficiency.

Table 1. Values and dimensions of the parameters used in the magnetic filtration prediction

Parameters	Values	Units
Ferromagnetic particles fraction of all particles (Φ)	1	
Magnetic susceptibility (χ)	0.5	
Fiber diameter (d_f)	0.00004	m
Fiber Length (L)	0.042	m
Magnetic field intensity (H)	5/30	A/m
Fluid velocity (V_f)	0.05	m/s

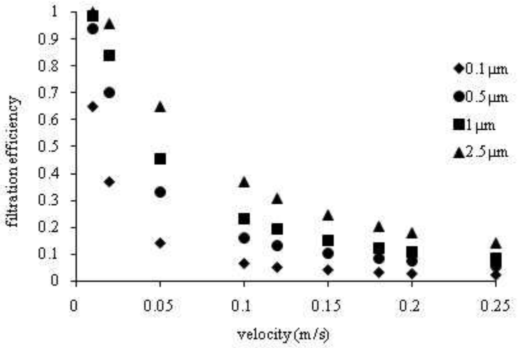

Fig. 3. Effects of flow velocity on filter efficiency.

It is obvious that in Fig. 4 at any given particle size the filtration efficiency falls with the increase of the fiber size. The smaller fiber size, the more contact area, the smaller the pore size, the more efficiency. And the efficiency coefficient on the fiber size has been proportional with df-1.6 according to the equation 16.

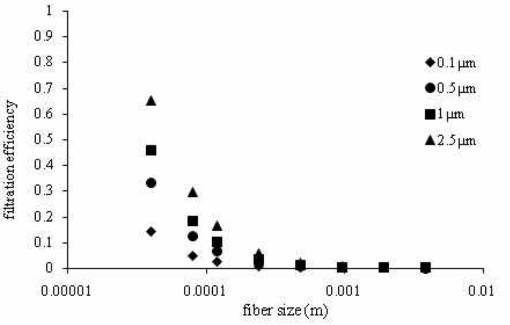

Fig. 4. Effects of magnetic fiber size on filter efficiency.

4. Conclusions

Magnetic attraction between ferromagnetic medium is one of the filtration mechanisms whichinclude diffusion, direct interception and impaction. The efficiency of magnetic filtration is mainly determined by magnetic field intensity, filtration velocity, and fiber size. Magnetic particle fraction is also a key factor for magnetic filtration. Experimental work should be carried out to prove the calculation results.

NOMENCLATURE

α filter solidity

χ magnetic susceptibility

ξ logarithmic filtering coefficient

μ dynamic viscosity ($Pa \cdot s$)

μ_1 relative magnetic permeability

v_f filtration velocity (m/s)

η efficient coefficient

ϕ ferromagnetic fractions of all particles

ρ_f fluid density (kg/m3)

d_p particle diameter (m)

d_f fiber diameter (m)

λ mean free path (m)

K_B Boltzmann's constant

Cc Cunningham slip correction factor

Nst Stokes number

H magnetic field intensity (A/m)

L fiber length (m)

References

1. R. P. Donovan, “Fabric filtration for combustion sources”, p. 2, Marcel Dekker, Inc. New York and Basel(1985).
2. P. J. Lucchesi, W. H.Hatch, F. X. Mayer, and R. E. Rosensweig, Magnetically stabilized beds—new gas-solids contacting technology. In proceedings of the 10th world petroleum congress, 4, 419(1979).
3. R. Gerber, and R. R. Birss, “High Gradient Magnetic Separation”, p. 329,

John Wiley, New York(1983).
4. J. Svoboda, "Magnetic Methods for the Treatment of Minerals", p. 354, Elsevier. New York(1987).
5. B. L. Hirschbein, D. W. Brown, and Whitesides G. M., Magnetic Separations in Chemistry and Biochemistry, CHEMTECH, 12, 172(1982).
6. T. Brewis, Metal extraction by bacterial oxidation, Miner. Mag., 175(4), 197(1995).
7. D. L. Dummings, D. A. Himmelblau, J. A. Oberteuffer, and G. J. Powers, Capture of small paramagnetic particles by magnetic forces from low speed fluid flows, J. of AlChE, 22(3), 569(1976).
8. T. Zarutskaya, and M. Shapiro, Capture of Nanoparticles by Magnetic Filters, J. Aerosol Sci., 31(8), 907(2000).
9. S. K.Friedlander, "Smoke, dust, and haze", p. 31, Oxford university press, New York(2000).
10. L. Li, P. S. Greenberg, W. Kenneth, Street Jr. and D. R. Chen, Study of a Magnetic Filter System for the Characterization of Particle Magnetic Property, Aerosol Science and Technology, 45(3), 327(2011).
11. M. Sarikaya, T. Abbasov and M. Erdemolu, Some Aspects of Magnetic Filtration Theory for Removal of Fine Particles from Aqueous Suspensions, Journal of Dispersion Science and Technology, 27, 193(2006).
12. K. W. Lee, and B. Y. H. Liu, Theoretical study of aerosol filtration by fibrous filters. Aerosol science and technology, 1, 147(1982).
13. F. Loeffler, "Novel concepts, methods and advanced technology in particle-gas separation", p. 206, T. Ariman, Indiana (1978).
14. J. H. P. Watson, Magnetic filtration, J. Appl. Phys., 44, 4209(1973).
15. F. E. Luborsky, and B. J. Drummond, High gradient magnetic separation: Theory versus experiment. IEEE Trans. Magn., 11, 1696(1975).
16. M. R. Parker, The physics of magnetic separation. Contemp. Phys., 18, 279(1977).
17. J. A. Obertteuffer, Magnetic separation: A review of principles, devices and applications. IEEE Trans. Magn., 10, 223(1974).
18. J. Svoboda, The effect of magnetic field strength on the efficiency of magnetic separation, Miner. Eng., 7, 747(1994).
19. J. Svoboda, A realistic description of the process of high gradient magnetic separation. Miner. Eng., 14, 1493(2001).
20. M. Franz and M. Franzreb, Determination of the capture radii of magnetic bearing hydroxide flocs in magnetic filtration, IEEE Trans. Magn., 34, 3902(1998).