Korean J. Chem. Eng., **24**(5), 717-722 (2007)

A lab-scale study on the humidity conditioning of flue gas for improving fabric filter performance

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(*Received 7 June 2006 • accepted 14 February 2007*)

Abstract−A centrifugal separator was constructed to examine the effect of flue gas humidity on the adhesional force between fabric and collected dust. A lab-scale fabric filter sampling system (FFSS) was also manufactured by using a piece of flat fabric as a sample of bag material. In addition, an automatic control system for gas humidity was devised and installed in the FFSS, and, then, the following effects were studied: (i) the influence of gas humidity on the adhesional force between fabric and dust particles; (ii) the influence of gas humidity on the performance of fabric filter in terms of pressure drop, ΔP, dust removal efficiency, η, and specific cake resistance, K_2'; (iii) the variations in the composite-performance indices with gas humidity; and (iv) the influence of gas humidity on cleaning of dust-cake in terms of effective residual pressure drop. The main objectives were to determine the minimum and maximum values for the gas humidity range and to find the appropriate conditions for dust cleaning in terms of the critical value of effective residual pressure drop.

Key words: Adhesional Force, Humidity Conditioning, Fabric Filter Performance, Effective Residual Pressure Drop, Specific Cake Resistance

INTRODUCTION

Both electrostatic precipitators (ESPs) and fabric filters have been used as primary dust-collectors; however, the ESP is less efficient when collecting dust with high electrical resistivity, needs a large amount of land for installation, has high initial costs, and is less efficient when the flow rate of the dust-laden gas varies. On the other hand, fabric filters have some advantages including high collection efficiency over a broad range of particle sizes, but also have some shortcomings such as (i) cost of operation; (ii) lower efficiency than ESP when collecting fine dust; and (iii) inappropriateness when used for treatment of highly humid gas. Thus, many investigators, including Dennis and Klemm [1], Ellenbecker and Leith [2] and Park et al. [3], have conducted fundamental studies on bag-cleaning and dust collection in order to reduce operating costs and to enhance collection efficiency for fine dust so that the fabric filters can be used more widely. Although some studies have used water steam to reduce dust resistivity in ESP and to regenerate catalysts in photoreactors, there do not appear to be any reports on the appropriate range of gas humidity. Various designs and operation parameters such as scale and gauge pressure of the reverse-air storage tank, dimensions of blow-tube nozzles, emission characteristics of the diaphragm valves, venturi shape, pulse duration of the compressed air supply, and dust characteristics have been known to affect the performance of fabric [4-8]. In order to lengthen filtration duration, the removal of dust-cake should be excellent; thus, the effective residual pressure drop as an index of the quality of the dust-cake removal should be small. The relationship between effective residual pressure drop and gas humidity varies with the initial pressure of the air-storage tank and the diameter of blow-tube nozzles. Filtration duration increases as the effective residual pressure decreases and the initial pressure of air-storage tank increases to some extent. On the other hand, if the effective residual pressure drop is large, the filtration duration shortens, and as a result, the frequency of removing the dust-cake and replacing the bag-modules increases and the associated costs also increase.

Thus, the recommended values of initial tank pressure and effective residual pressure drop should be examined in relation to gas humidity so that the operating costs of the fabric filters can be reduced, and the removal efficiency of fine dust can be improved by forming a thicker dust layer with larger porosity.

In this study, a centrifuge and a fabric filter sampling system (FFSS) equipped with a fabric sample of flat geometry were manufactured. An automatic humidity controller was devised and installed in the FFSS, and then the following experiments and analyses were conducted: (i) to study the variations in adhesional force between dust particles and fabric with gas humidity; (ii) to investigate the influence of gas humidity on pressure drop, dust removal efficiency, and specific cake permeation resistance as fly-ash laden gas passed through a variety of polyester sample as bag-module material; (iii) to examine the variations in various composite-performance indices with flue-gas humidity; (iv) to investigate the influence of gas humidity on fabric cleaning; (v) to determine the critical value of initial tank pressure; and (vi) to investigate the influence of blow-tube nozzle size on fabric cleaning. The most significant objectives of this study were to establish a recommended range of gas humidity to be conditioned and to determine appropriate operating conditions in a pulse-jet cleaning system.

MATERIALS AND METHODS

1. Centrifuge

In order to measure the adhesional force between fabric and col-

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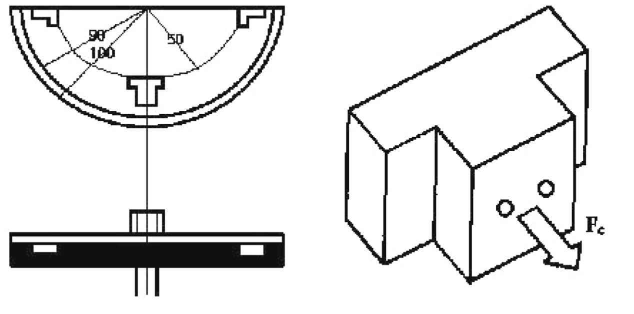


(a) (b)

Fig. 1. Detail of rotor (a) and its test surface (b) in a centrifuge.

lected dust particles, a centrifuge with a rotor (Fig. 1) was manufactured. A teflon plate of 10 cm in diameter and 3 cm thick was hollowed out so that four pieces of a T-shaped test surface could be fitted into it. Cells of 1.3 cm in diameter and 2 mm thickness were placed above this test surface. Pieces of polyester nonwoven fabric (0.7 cm in diameter, 6.12×10^{-4} g/cm^3 weight, 1.35 mm thick, and 20 cm^3 (air)/cm^2 (fabric area)·sec of permeation) were attached to the cells. A motor with an upper limit of 8,000 rpm was used to operate the centrifuge to which an electrical voltage regulator was connected. A tachometer was employed to determine rotation speed, and separation experiments for the dust deposited onto fabrics were conducted for rotation speeds of 500, 1,000, 1,500, 2,000, 3,000 and 4,000 rpm.

2. FFSS and Automatic Humidity Control System

A lab-scale FFSS, which could be cleaned in pulse-jet fashion, was manufactured as shown in Fig. 2 in order to conduct experiments on the performance of dust filtration and dust-cake cleaning. Three blow-tubes were arrayed 7 cm apart and 10 cm away from a filtering fabric (300×500×1.35 mm) indicated by I in Fig. 2, and eight-hole nozzles were placed 5 cm apart along each tube. In order to supply moisture to the flue gas, a steam generator was installed downstream from a blower. The first chamber was installed to mix air and steam, and the second chamber mixed steam, air and fly-ash. It was installed between the dust feeder and the fabric filter. A screw-type dust feeder was used and the feed rate was controlled by a DC servo motor. To inhibit the reverse flow of dust and compressed air, a check-valve was placed between the second mixing chamber and the inlet of the fabric filter. A automatic humidity-control system consisting of a solenoid valve (WV220-8), a humidity sensor, and a control box, as shown in Fig. 3, was devised and installed between the steam generator and the first mixing chamber. If the sensor in the first mixing chamber detected humidity lower or higher than the value set in the control box, a signal was sent to the solenoid valve at the exit of the steam generator, resulting in the opening or closing of value.

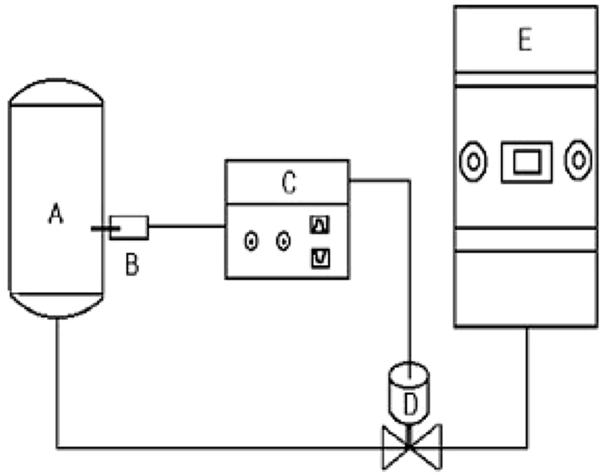


Fig. 3. Schematic diagram of an automatic control system for gas humidity.
A. Primary mixing chamber
B. Humidity sensor
C. Control box
D. Solenoid valve
E. Steam generator

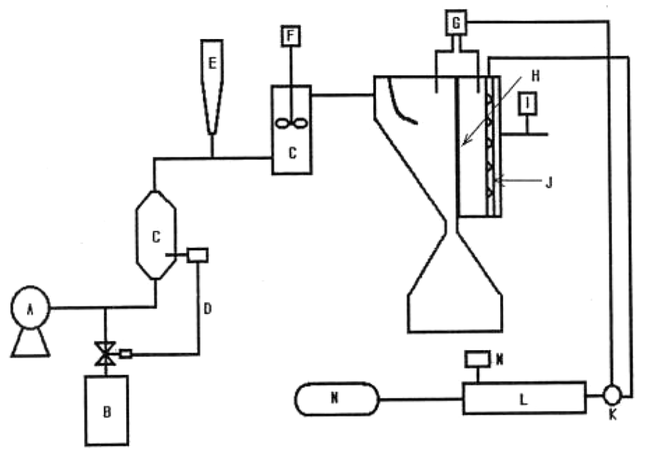


Fig. 2. Experimental apparatus of a pulse-jet fabric filter sampling system.
A. Blower
B. Steam generator
C. Mixing chamber
D. Automatic humidity controller
E. Dust feeder
F. D.C motor
G. D/P transmitter
H. Polyester fabric
I. Flow meter
J. Flow pipe
K. Diaphragm valve
L. Air reservoir tank
M. Air pressure tank sense
N. Air compressor

3. Fabric and Dust Sample

The fabric sample (30×50 cm) was normal polyester that was nonwoven, untreated, inexpensive, and commonly found in industry. For comparison purposes, two other polyester fabrics were used. One had an anti-static finish and the other was water repellant and had an anti-static finish. The design and operating conditions of the

Table 1. Design and operating conditions of the pulse-jet FFSS

Filtration area, A (cm^2)	1,500
Nozzle diameter, d_n (cm)	0.8, 1.0
Blow tube diameter, d_t (cm)	2.0
Filtration velocity, V (cm/s)	2.33
Dust loading, L (g/s)	0.65
Single pulse duration, T_{pd} (s)	0.1
Flue gas humidity, R.H. (%)	45-85
Initial tank pressure, P_{tko} (10^3 g_f/cm^2)	1-3

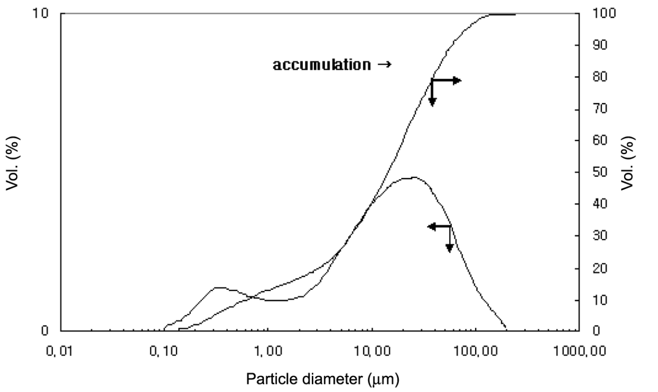


Fig. 4. Size distribution of the fly-ash particles.

pulse-jet FFSS are shown in Table 1.

Fly ash as the dust sample was supplied at constant rate (0.65 g/sec) by using a screw-type dust feeder positioned between the first and second mixing chamber, and injected into the FFSS by a blower with a static pressure of 85 mm H_2O. The physical characteristics of the fly ash sampled from a power plant were as follows: median diameter, 14.88 μm; cumulative 10 percent diameter, 0.73 μm; cumulative 90 percent diameter, 60.10 μm; and true density, 2.65 g/cm^3. The main components of the fly ash were SiO_2 (56.36% by wt.), Al_2O_3 (31.54%) and Fe_2O_3 (3.40%). The size distribution of dust sample is shown in Fig. 4.

4. Operating Method

The flow rate and pressure drop across the fabric sample were continuously measured. Removal of the dust cake began with an injection of compressed air for 0.1 sec (single pulse duration) through the blow-tube nozzles when the pressure drop reached at a set value (e.g. 5.51 cm H_2O), as a result, the diaphragm valve opened. The dust-cake cleaning process was forced to cease and the filtration process restarted when the effective residual pressure drop dropped down below a set value (e.g., 1.50 cm H_2O). In order to approach the above research objectives, separation experiments were conducted for various combinations consisting of two nozzle sizes, three steps of initial tank pressure ranging from 1 to 3 kg/cm^2, and 5 steps of gas humidity ranging from 45 to 85%. The mass of dust attached to a sample fabric was determined after 20 hrs conditioning of the fabric in a chamber at constant temperature and humidity.

5. Determination of Filter Performance

The filter mass difference between the before and after dust separation was applied to Eq. (1) [9] to determine the adhesional force at various rotation speeds under the assumption that detaching force was equal to the adhesional force.

$$F_{det}=4\pi^2 m\cdot N^2\cdot l \quad (1)$$

where m is the mass of the detached dust particle (g), N is the rotation speed (sec^{-1}), l is the distance between a particle and the rotating axis (cm), and F_{det} is the particle detaching force (dyne).

The filtration performance indices used by Sanchez et al. [10] were defined by using the collected dust weight (W (g)), filtering area (A (cm^2)), filtration duration (Δt (sec)), superficial filtering velocity (V (cm/sec)), and relative fabric cost (C_R) in addition to pressure drop across the fabric (ΔP_f($_K$Pa)) and dust separation efficiency (η (%)) as Eqs. (2)-(4). The greater the value of the indices, the better the performance of the fabric filter.

$$I_p=\eta/\Delta P \quad (2)$$

$$I_F=(W/A\cdot\Delta t)\cdot V/\Delta P \quad (3)$$

$$F=I_F\cdot\eta/C_R \quad (4)$$

where I_P($_K$$Pa^{-1}$) is a quality factor indicating the filter performance, I_F is a dimensionless filtration index, and F is a dimensionless index.

The effective residual pressure drop (extrapolated pressure drop for clean fabric), and the specific cake permeation resistance coefficient were determined by using Eqs. (5) and (6) [11].

$$\Delta P=\Delta P_f+\Delta P_p=K_1\mu V+K_2\mu W_1 V=K_1' V+K_2' W_1 V$$
$$=(P_E)\Delta w+K_2'\cdot c\cdot V^2\Delta t \quad (5)$$

$$K_2'=d(\Delta P/V)dW_1=dS/dW_1 \quad (6)$$

Where W_1=dust-cake aerial density before cleaning [g/cm^2]
c=dust concentration [g/cm^3]
μ=gas viscosity [g/cm·sec]
S=drag [dyne·sec/cm^3]
K_1'=residual fabric resistance [dyne·sec/cm^3]
K_2=specific cake resistance [cm/g]
K_2'=specific cake resistance coefficient [dyne·sec/g·cm, or sec^{-1}]
$(P_E)_{\Delta W}$=effective residual pressure drop [dyne/cm^2]
ΔP_f=pressure drop across fabric [dyne/cm^2]
ΔP_p=pressure drop across particulate layer [dyne/cm^2]

EXPERIMENTAL RESULTS AND DISCUSSION

1. Variations in the Adhesional Force Between the Dust and Fabric with Gas Humidity

The centrifugal forces that were obtained at various rotation speeds and caused 80% (by wt.) of the particles to detach from sample fabric, F_{20}, were assumed to be the adhesional force for their respective gas humidities. Fig. 5 shows that for rotation speeds exceeding 2,000 rpm, the adhesional force between the dust particles and fabric exponentially decreased as gas humidity approached 50%, and logarithmically increased beyond the humidity level. The parabolic pattern of adhesional force vs gas humidity appears to be largely derived from the overall variation pattern of the resistivity and tensile strength of ash with gas humidity [12]. However, this variation pat-

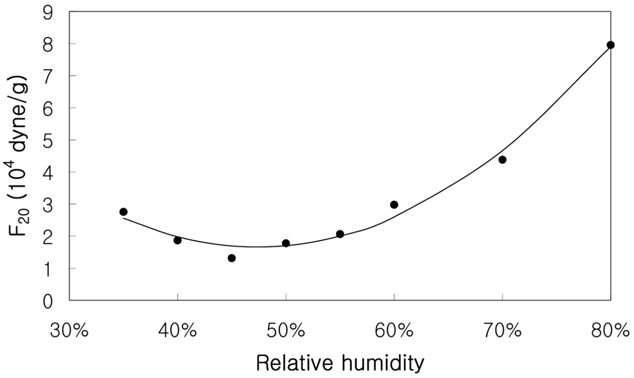
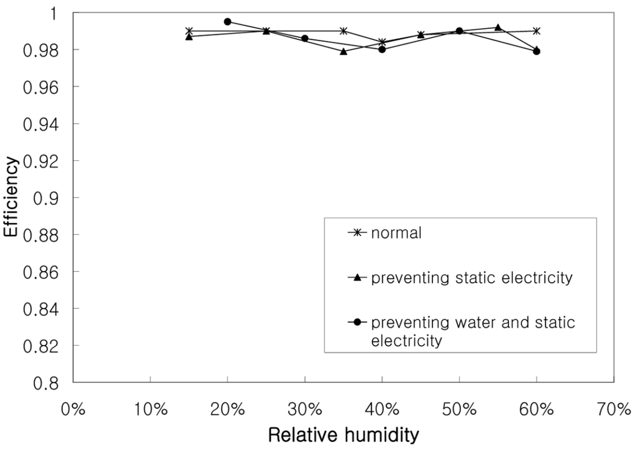
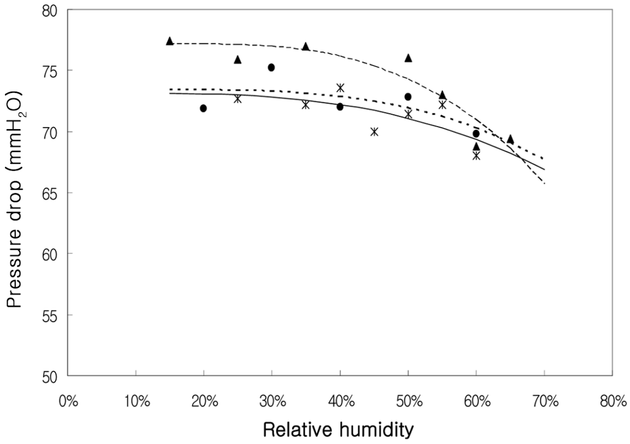


Fig. 5. Variations in the adhesional force of ash particles attached to polyester nonwoven fabric with gas humidity.



(a)



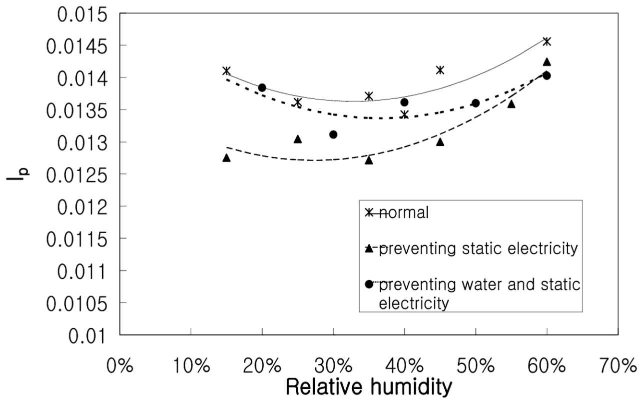
(b)

Fig. 6. Variations in (a) dust removal efficiency, and (b) pressure drop with gas humidity (superficial filtering velocity=6.67 cm/s, filtering area=1,500 cm^2, dust loading=0.183 g/s, (cumulative weight percent for particles less than 5 μm=20%), filtering duration=1,800 s, gas humidity=15-65%).

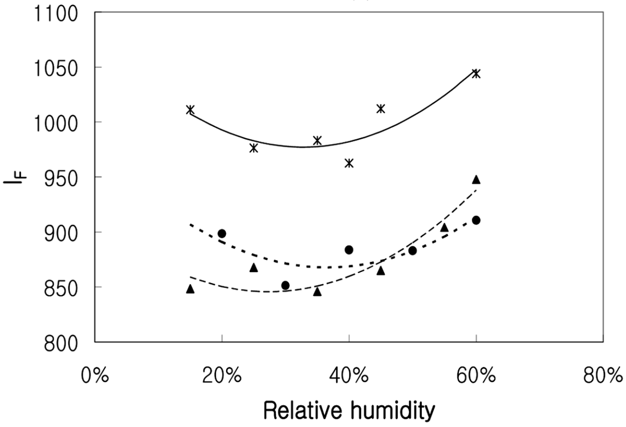
tern of the adhesional force is different from that for silica particles attached to glass plate, which slowly increases from 10% to about 80% humidity and rapidly increases beyond 80%, but decreases as humidity falls below 10% [13].

2. Influence of Gas Humidity on Dust Removal Efficiency and Pressure Drop

The measurements of dust removal efficiency under varying gas humidities are shown in Fig. 6. Though dust can be steadily removed with high efficiency (>99%) over a wide range of gas humidities, any variations in the pattern of dust removal efficiency with gas humidity were not identified because filtration duration was kept constant, that is, alterations to filtration-cleaning were not controlled by a fixed pressure drop across the fabric and dust layer. However, this figure is the basis for understanding Fig. 7(a). The pressure drop, ΔP, decreased as the humidity increased over at least 15% if dust concentration and filtration duration were kept constant. This result appears to be due to the enhanced dust cake porosity caused by liquid-bridging between neighbouring particles whose shapes approached a spherical form through absorption and condensation of water vapor as the gas humidity increased [14]. The slope of the graph, ΔP/Δr·h, for an anti-static polyester fabric became larger than that for the other sample fabrics, when humidity was greater than 50%. This result appears to be due to the larger thickness and fiber density of the anti-static fabric.



(a)



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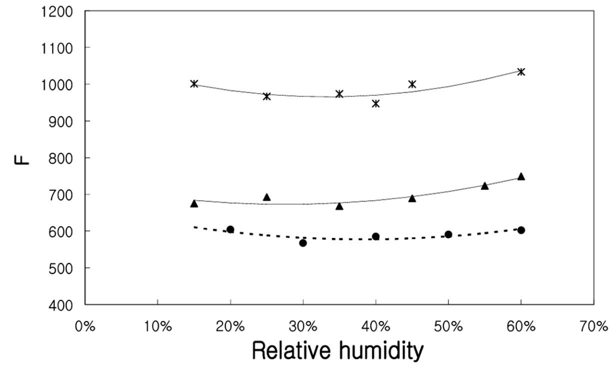

(c)

Fig. 7. Variations in the various combined performance indices with gas humidity: (a) I_P, (b) I_F, (c) F.

3. Variations in Composite Performance Indices with Gas Humidity

The values of the combined performance indices such as I_P, I_F and F are plotted in Fig. 7. The combined performance indices included various factors such as dust removal efficiency (η), pressure drop (ΔP), gas permeation (u), dust deposition rate per unit fabric area (W/A·Δt), and relative fabric cost (C_R). These indices indicate that the overall performance improves if the gas humidity is over about 40%. The value of I_P depended on gas humidity and followed a quadratic function with a minimum value at gas humidity of 30-40%. Considering Fig. 6(b), the increase of I_P beyond 30-40% humidity appears to suggest that fan operation costs decrease with gas humidity for constant removal efficiency. The pattern of I_F variation appears to be similar to that of I_P, and Figs. 7(b) and 7(c) reveal that normal polyester fabric is superior to other fabrics with respect to air permeation and dust deposition rate as well as relative cost.

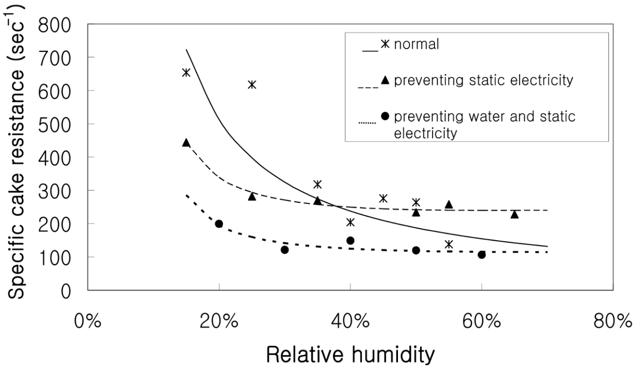

Fig. 8. Variations in the specific cake resistance coefficient with gas humidity for polyester nonwoven fabric.

4. Influence of Gas Humidity on Specific Cake Permeation Resistance

Fig. 8 shows the influence of gas humidity on specific cake resistance coefficient, K_2', for a superficial filtering velocity of 4 m/min. The exponential decrease of K_2' (sec^{-1}) with gas humidity for three of the polyester fabrics differs from Schmidt and Pilz's [15] results for a filter face velocity of 1.67 m/min in that the decreasing pattern is not linear, and the level of gas humidity where K_2' starts to decrease is not about 60%, but at least 15% (the lowest level given in the first investigation in this study). The pattern appears to be similar to a consistent monotonic regression, Y=−0.25 log(X)+1.03 where Y=normalized K_2' and X=gas humidity (%), published by Snyder et al. [12]. Considering that the increase of gas humidity causes high dust cake porosity and K_2' decreases with gas humidity, the efficiency of fine dust removal should improve due to the thicker dust-layer accumulated over the extended filtration duration [16]. It appears to be reasonable to set 50% as the lower limit of

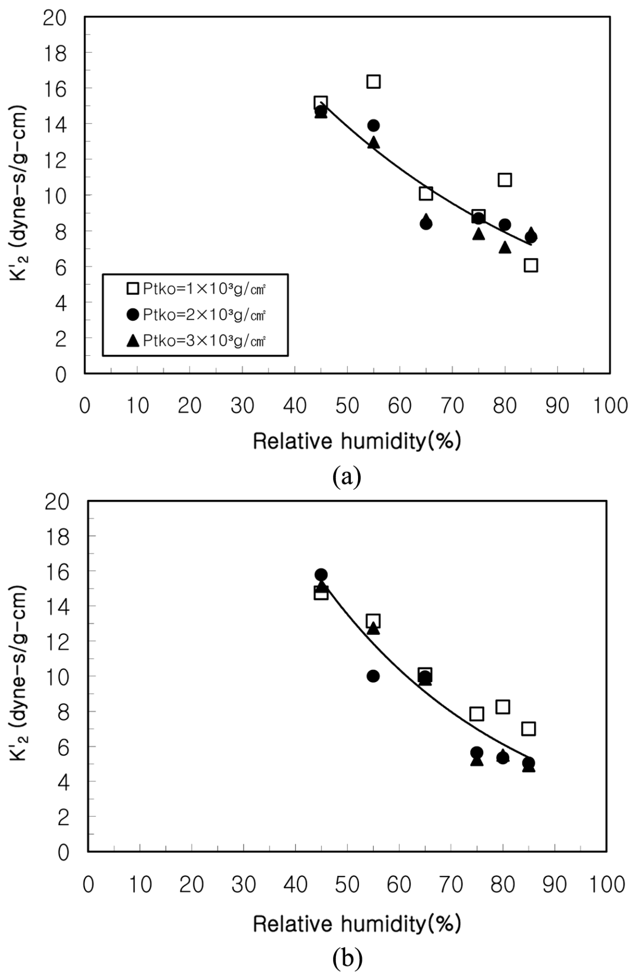

Fig. 9. Variations in the specific cake resistance coefficient with gas humidity for various cleaning conditions: (a) d_n=0.8 cm, (b) d_n=1.0 cm.

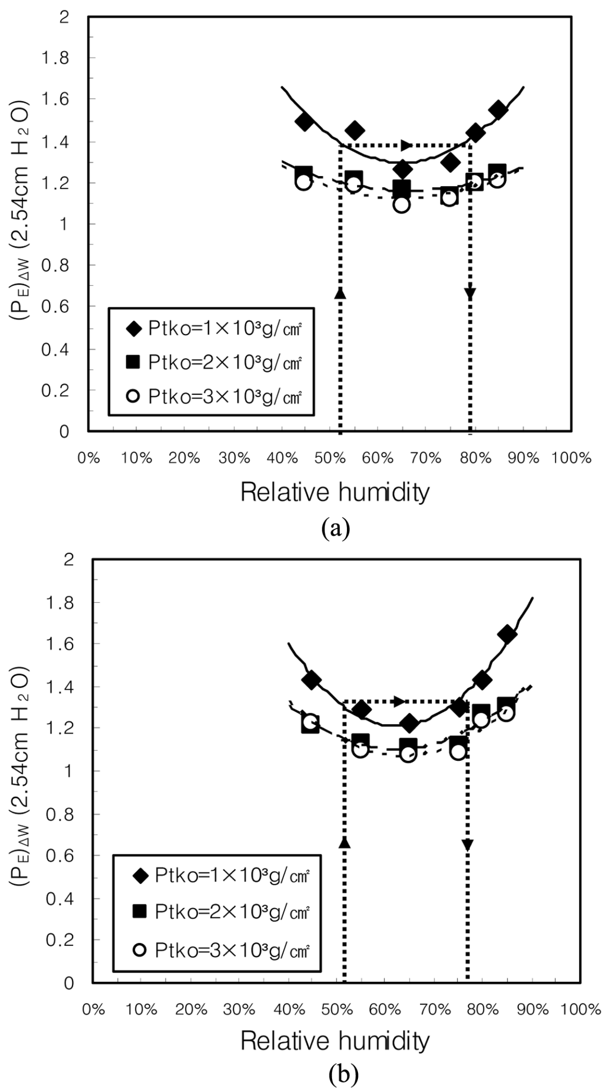

Fig. 10. Variations in the effective residual pressure drop with gas humidity for normal nonwoven polyester fabric: (a) d_n= 0.8 cm, (b) d_n=1 cm.

gas humidity to improve fine dust removal.

Fig. 9 shows that the specific cake resistance coefficient exponentially decreases with gas humidity at least beyond 50% (the lowest level used in the second investigation in this study) regardless of the cleaning conditions such as initial tank pressure (Ptko) and blowtube nozzle diameter (d_n). This phenomenon appears to be due to the fact that as gas humidity increases, moisture-condensed dust particles approach spherical shape and larger clusters are formed by coagulation due to liquid - bridging between neighboring particles; as a result, the porosity of dust layer increases [14,16]. Fig. 9 suggests that the previous report on K_2' vs gas humidity by Schmidt and Pilz [15] is wrong in that the decreasing trend is not linear.

5. Influence of Gas Humidity on Fabric Cleaning Performance

Fig. 10 shows that as the gas humidity increases to about 50%, the effective residual pressure drop, $(P_E)_{\Delta W}$ decreases, but it increases if the gas humidity is beyond about 70%. This appears to be due to the fact that the enhanced adhesional force between moisture-condensed dust particles and the fabric inhibits dust detachment due to capillary condensation during periods of excess humidity (>65%) as reported by Schmidt and Pilz [15]. The reduced level of dust-cake detachment enhances the residual pressure drop after dust cleaning and causes the duration of filtration to shorten; as a result, the fan operation and bag-module replacement costs increase [5]. Thus, it seems reasonable to take the humidity, for which $(P_E)_{\Delta W}$ value is the same as that for humidity 50% (the lower limit), as the upper limit of gas humidity. After taking Figs. 5-10 into consideration, it seems reasonable to set 80% as the upper limit of gas humidity regardless of the initial tank pressure.

CONCLUSION

As strategies for improving the efficiency of fine dust separation in fabric filters and for reducing the fan operation and bag-module replacement costs are developed, the operating conditions for a bag-cleaning system and the optimal range of gas humidity are required to be determined. To this end, experiments using a centrifuge and a lab-scale fabric filter sampling system were conducted, and the following conclusions were drawn.

Adhesional force between fabric and collected dust particles is at its minimum level when gas humidity is about 50% at normal temperatures. The force rapidly increases with gas humidity beyond 50% following a logarithmic function. Under constant conditions of dust concentration and filtration duration, the pressure drop across the fabric and dust layer remains nearly constant for gas humidity up to about 40%, but decreases with gas humidity beyond the level. The decreasing slope of the curve given by Δp vs $\Delta r \cdot h$ for anti-static polyester fabric is larger than that for other fabrics, probably due to the larger values of fabric thickness and fiber density.

The specific cake resistance coefficient, K_2', exponentially decreases with gas humidity, and the decreasing slopes ($\Delta K_2'/\Delta r \cdot h$) for surface-treated polyester fabrics are less than the slope for normal polyester fabric. The gas humidity range recommended for improving the efficiency of dust separation and reducing the operation costs is 50-80%.

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