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Influence of pulsing-air injection distance on pressure drop in a coke dust bagfilter

Jeong-Min Suh*, Young-Il Lim,†, and John Zhu*****

*Department of Regional Environmental System Engineering, Pusan National University,
50 Cheonghak-ri, Samryangjin-eup, Miryang, Gyeongnam 627-706, Korea
**Department of Chemical Engineering, Hankyong National University, Anseong-si, Gyonggi-do 456-749 Korea
***Division of Chemical Engineering, School of Engineering, University of Queensland, Brisbane 4072 QLD, Australia
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Abstract−The effect of the pulsing-air injection distance between the nozzle and venturi on total pressure drop was investigated in a pilot-scale pulse-jet bagfilter for coke dust of a steel mill factory. Theoretical and empirical models were used to predict the pressure drop. The empirical model contains two parameters--dust cake resistance and exponent of areal mass density--to be estimated by experiment. The optimum injection distance for minimizing the total pressure drop was evaluated by 64 experimental data at a fixed filtration velocity and pulse pressure in the practical ranges of dust concentration and pulse interval time. The dust cake resistance shows a minimum value at the optimum injection distance. The empirical model is in good agreement with the experimental data, showing a correlation coefficient of 0.952.

Key words: Pulse-jet Bagfilter, Coke Dust, Pressure Drop, Modeling, Nozzle Injection Distance

INTRODUCTION

The pulse-jet fabric bag filter is one of the most common items for removing particles from process gases [1-3]. Bagfilters or baghouses have been traditionally used to remove fines not recovered by cyclones [4]. Fabric filters are built for the separation of particles from gases with flow rates of a few cubic meters per hour, up to several million cubic meters per hour [5]. Dust concentrations in the raw gas may vary between below 1 g/m^3 up to several 100 g/m^3. Clean gas concentrations below 5 mg/m^3 can be achieved even for submicron particles. The dust-collecting performance of bagfilters depends on the geometry of the baghouse, the fluid flow distribution in the inlet gas, the characteristics of filter media, the gas composition, the temperature and pressure, and the particle properties [5]. Particles are transported with the gas to the filter felt where the gas flows through the porous filter medium. During the operation, a cake of dust builds up on the outside of the filter fabric. The growth of this cake increases the pressure drop of the filter and makes periodic cleaning necessary.

A pulse-jet regeneration system enables high separation forces due to the pressure wave moving along the filter bag. The operation involves injecting high-pressure backpulse air into the filter bags for a very short time [6]. A short burst of compressed air is discharged from a nozzle at a uniform time interval [7-9], or when the pressure drop across a fabric bag is greater than a set value [10-15]. The pulsing of compressed air is usually directed through a venturi into the filter bag to increase the pulse pressure within the bag [16]. The pulse-jet system is operated on-line or off-line, with gas flow or without gas flow, respectively [3]. Characteristics of the nozzle-venturi system vary with the pulse pressure, nozzle diameter, venturi geometry, and the injection distance between the nozzle and venturi [16].

The baghouse design often depends on the experience of suppliers and users, because the determination of filtration velocity (or baghouse size) has little relevance with physical models in industrial practice [5]. The main operating parameters in the pulse-jet bagfilter are the pressure drop and the filtration velocity. Pressure drop is important because higher pressure drops imply that more energy is required to pull gas through the system [17]. The filtration velocity, or gas volume flowrate divided by total filtering area, determines the unit size and thus capital cost. Higher filtration velocity means less fabric, therefore less capital cost. However, higher filtration velocity leads to higher pressure drop, forcing energy costs up.

The pressure drop of a bagfilter is influenced by many factors such as the diameter of the injection nozzle and its distance from the bag, pulse pressure, pulse duration, pulse interval time, filtration velocity, inlet dust concentration, and dust particle properties [5-8,16-18]. Effects of the design and operating conditions on the pressure drop have been investigated for various dusts such as limestone powder [7,15,19], fly ash [2,3,7,16,20-22], granite powder [7], alumina powder [6,23], and milk powder [4]. Hot-gas filtration was recently reported for bicarbonate power [13]. For the prediction of the pressure drop as a function of the operating conditions, models have been developed statically [7,8] and dynamically [13,24] during the operating time.

Limited studies have been reported on the coke dust filtration. In this study, a pilot-scale pulse-jet bagfilter was constructed to investigate the pressure drop under different operating conditions such as filtration velocity, pulse pressure, dust concentration, pulse interval time and injection distance, using coke dust collected in a steel mill industry. The experiment was performed in a continuous pulse-jet cleaning mode with uniform pulse interval time, which is actu-

†To whom correspondence should be addressed.
E-mail: limyi@hknu.ac.kr

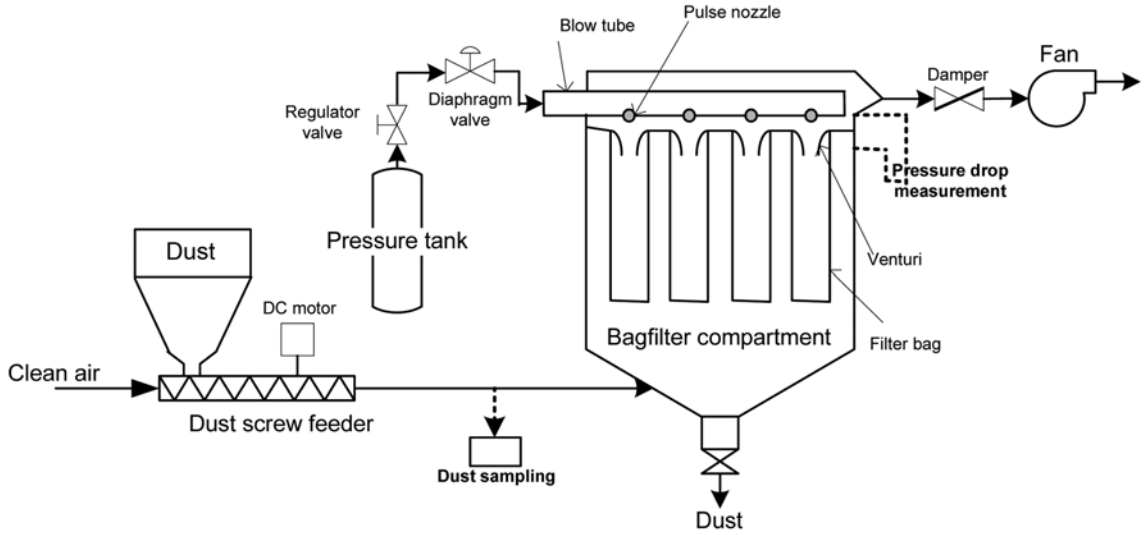

Fig. 1. Schematic diagram of experimental apparatus.

ally being applied to coke dust bagfilters in the steel mill industry to reduce clogging caused by irremovable coke dusts penetrated inside porous filter medium. This study aims to identify an optimum injection distance between the nozzle and venturi under various operating conditions at a given nozzle diameter. Theoretical and empirical models are used to predict the pressure drop.

EXPERIMENTAL METHODS

Experiments were conducted in a pilot-scale pulse-jet bagfilter composed of a screw dust feeder, four blow tubes with diaphragm valves, a pressure tank, a baghouse compartment of 16 filter bags, a damper and an exit fan, as shown in Fig. 1 [25,26]. The pilot-scale experimental apparatus was tested for investigating the performance of filtration of a coke dust on various operating conditions: filtration velocity, pulse pressure, dust concentration, pulse interval time and injection distance.

The dust collected in a coke factory of the steel mill industry is supplied through the screw feeder, where the entry dust quantity is regulated by using a direct current (DC) motor. The concentration of the dust dispersed by air varies in the range of 0.5-3 g/m^3. Four blow tubes located at the top of the bagfilters are installed with four pulse nozzles per each blow tube oriented to the center of each filter cloth. The compressed air from the air tank is supplied at the pulse pressure of 5 kg$_f$/cm^2 (490 kPa). The compressed air is injected for 0.1 s through the pulse nozzle, which is manipulated by a diaphragm valve for each blow tube. The dust cake on the filter fabric is removed by the jet-pulse, where only one row of four blow tubes (*i.e.*, 4 over 16 filter bags) is jet-pulsed at a time with the pulse interval

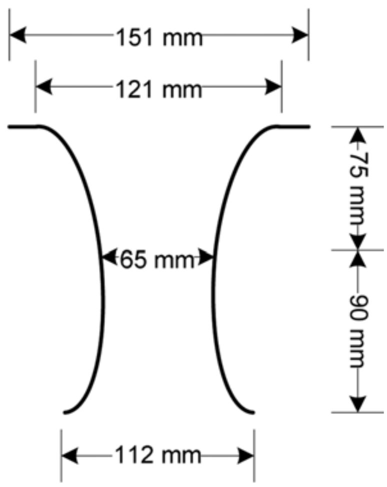

Fig. 2. Venturi geometry used in this study.

Table 1. Design specifications and operating conditions

Design specifications			
Bagfilter diameter (D_{bag}, m)	0.14	Number of bags	16
Bagfilter length (L_{bag}, m)	0.85	Pulse nozzle diameter (m)	0.01
Total filter area (A_{total}, m^2)	5.98	Venturi throat diameter (D_v, m)	0.065
Operating conditions			
Filtration velocity (v_f, m/min)	1.5	Injection distance (d, m)	0.05, 0.11, 0.16, and 0.22
Pulse pressure (P_{pulse}, kPa)	490	Pulse duration (s)	0.1
Inlet dust concentration (c_{in}, g/m^3)	0.5, 1.0, 2.0, and 3.0	Operating time (t, min)	210
Pulse interval (Δt, s)	30, 50, 70, and 90		

Table 2. Characteristics of polyester felt without surface treatment

Specification	Value
Area weight (kg/m^2)	0.564
Felt thickness (mm)	2.34
Breaking strength (kg_f)	169.5
Air permeability ($m^3/m^2/s$)	0.166

Table 3. Characteristics and ultimate analysis of coke dust

Characteristics						Value
VMD (d_V, mm)						58.9
MMD (d_M, mm)						39.7
True density of particle (r_p, kg/m^3)						1,780
Ultimate analysis of coke dust (%)						
C	SiO_2	Al_2O_3	CaO	T-Fe	Others	Total
78.60	6.56	2.74	1.45	0.95	9.70	100

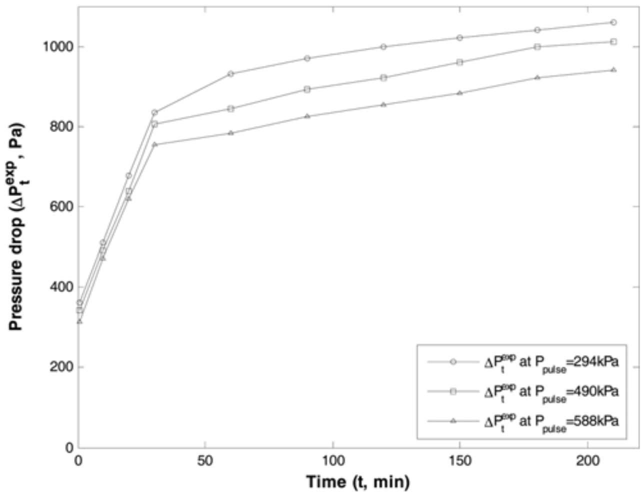

Fig. 3. Total pressure drop versus operating time at v_f=1.5 m/min, c_{in}=3 g/m^3, Δt=90 s and d=0.11 m.

time (Δt) of 30, 50, 70 or 90 s. In this study, the pulse nozzle has a diameter of 10 mm. A conventional type of venturi [10,12] is used, as shown in Fig. 2. The injection distance between the nozzle and venturi varies from 0.05 m to 0.22 m.

The filter cloth is a polyester filter felt without surface coating being used in baghouses of the steel mill industry. There are 16 filter cloths with 0.85 m length and 0.14 m diameter in the rectangular bagfilter compartment. Therefore, the total filtration area is about 6 m^2, as shown in Table 1. Table 2 presents physical properties of the filter felt. The filtration felt used in the steel mill industry is planned to operate for one year. Table 3 reports characteristics and an ultimate analysis of the coke dust, which contains C, SiO_2, Al_2O_3, CaO and T-Fe over than 90% in weight. The volume median diameter (VMD) and mass median diameter (MMD) of the coke dust are 58.9 and 39.7 μm, respectively.

The dust was sampled by a stack sampler (Model XC-572, Apex Instruments, Inc., USA) after the dust screw feeder (see Fig. 1). The sampled dust was heated and dried for 12 hours at 110 ^{o}C in a conventional oven. The dried dust was cooled to the room temperature and its weight was measured to obtain the inlet dust concentration. The pressure drop was measured by a manometer (Dwyer, USA) between the inside and outside of the filter bag in the upper part of the bagfilter compartment, as shown in Fig. 1.

The total pressure drop fell instantaneously at the air-pulsing moment and then stabilized within one second. The pressure drop was recorded after stabilization at a given measurement time. Fig. 3 depicts the typical behavior of the total pressure drop at the measurement times for 210 min. The total pressure drop is divided into two stages. In the first stage, the pressure drop increases rapidly. After a certain threshold time (about 30-50 min), the pressure drop of the second stage tends to linearly increase with a lower slope than the first stage. The specific dust cake resistance was determined sufficiently at an initial operation in pilot-scale testing [9]. Therefore, each experiment was carried out for 210 min at a given set of the five operating conditions, as shown in Table 1. The initial pressure drop before entering the dust was preliminarily measured at the given filtration velocity. Sixty-four (64) experiments for four inlet dust concentrations (c_{in}), four pulse interval times (Δt) and four injection distances (d) were performed at a fixed filtration velocity (v_f=1.5 m/min) and pulse pressure (P_{pulse}=490 kPa) to find an appropriate injection distance between the venturi and pulse nozzle. The total pressure drop (ΔP_t^{exp}) across the filter, dust and venturi was measured at the end of experiment (t=210 min).

MODELING APPROACHES

Theoretical and empirical models are presented to predict the bagfilter pressure drop as a function of operating variables. The theoretical model (TM) presented elsewhere [7] is that the total pressure drop (ΔP_t^{TM}) consists of fabric, dust and venturi pressure drops:

$$\Delta P_t^{TM}=\Delta P_f+\Delta P_d+\Delta P_v \quad (1)$$

where ΔP_f, ΔP_d, and ΔP_v are the clean fabric, dust, and venturi pressure drops, respectively. Since the first and third terms on the right side of Eq. (1) correspond to the initial pressure drop ($\Delta P_{initial}$) with clean air before the dust enters, Eq. (1) is rewritten:

$$\Delta P_t^{TM}=\Delta P_{initial}+\Delta P_d \quad (2)$$

The initial pressure drop ($\Delta P_{initial}$) with clean air includes all kinds of pressure drops caused by hydrodynamics between the upper and lower parts of the bagfilter compartment where the pressure drop is measured [13] and it depends on the filtration velocity.

The pressure drop (ΔP_d) due to the dust cake on the fabric is ideally expressed as a function of filtration velocity (v_f) and areal dust density (w_o) [7-10,17,21,22,27,28]:

$$\Delta P_d=K_{TM}v_f w_o \quad (3)$$

where K_{TM} is the model parameter to be estimated by experiment. The areal density (w_o; kg/m^2) of the dust cake is obtained from:

$$w_o=c_{in}v_f(4\Delta t) \quad (4)$$

where c_{in} is the inlet dust concentration, and Δt denotes the pulse interval time. The entire pulse interval time is multiplied by the factor of four, as only one row of the four blow tubes is jet-pulsed at a time.

Assuming that the coke dust is an incompressible particle, the empirical model (EM) is expressed as [8]:

$$\Delta P_t^{EM} = \Delta P_{initial} + K_{EM}\frac{w_o^a v_f^b}{P_{pulse}^c} \tag{5}$$

where K_{EM} is the dust cake resistance and the three exponent parameters (a, b, and c) are used for the areal density (w_o), filtration velocity (v_f), and pulse pressure (P_{pulse}), respectively. When the filtration velocity and pulse pressure remain constant, the empirical model is reduced as follows:

$$\Delta P_t^{EM} = \Delta P_{initial} + K_{EM}\frac{v_f w_o^a}{P_{pulse}} \tag{6}$$

where the areal density (w_o) has the units of g/m^2 to keep the value greater than unity. The empirical model, in which the areal mass density (w_o) is nonlinearly dependent on the pressure drop (ΔP_t), contains two model parameters (K_{EM} and a), while w_o is linearly dependent ΔP_t in the theoretical model with one model parameter (K_{TM}).

RESULTS AND DISCUSSION

At each injection distance between the nozzle and venturi, the parameters of the two models mentioned above are estimated from the experimental data. The initial pressure drop measured at v_f=1.5 m/min was 186 Pa. The sum square error between the experimental data (ΔP_t^{exp}) and predicted values (ΔP_t^{model}) is minimized to estimate those model parameters. For example, the following minimization problem is applied at each injection distance (d) for the empirical model:

$$\underset{K_{EM},a}{\mathrm{Min}}\ \mathrm{error} = \sum_{i=1}^{16}(\Delta P_{t,i}^{exp} - \Delta P_{t,i}^{EM})^2 \tag{7}$$

The results of the parameter estimation are reported in Table 4. The dust cake resistances (K_{TM}) of the theoretical model show higher values than those obtained from needlefelt filters operating with the filtration velocity of 1.5 to 2.7 m/min for the mass mean diameter

Table 4. Model parameters estimated from experimental data

Theoretical model (TM)			
	K_{TM} (1/s)		R
d_1=0.05 m	1.904×10^6		0.880
d_2=0.11 m	1.397×10^6		
d_3=0.16 m	1.585×10^6		
d_4=0.22 m	1.647×10^6		
Empirical model (EM)			
	K_{EM}	a	R
d_1=0.05 m	5.609×10^9	0.351	0.952
d_2=0.11 m	1.672×10^9	0.683	
d_3=0.16 m	3.048×10^9	0.511	
d_4=0.22 m	3.639×10^9	0.459	

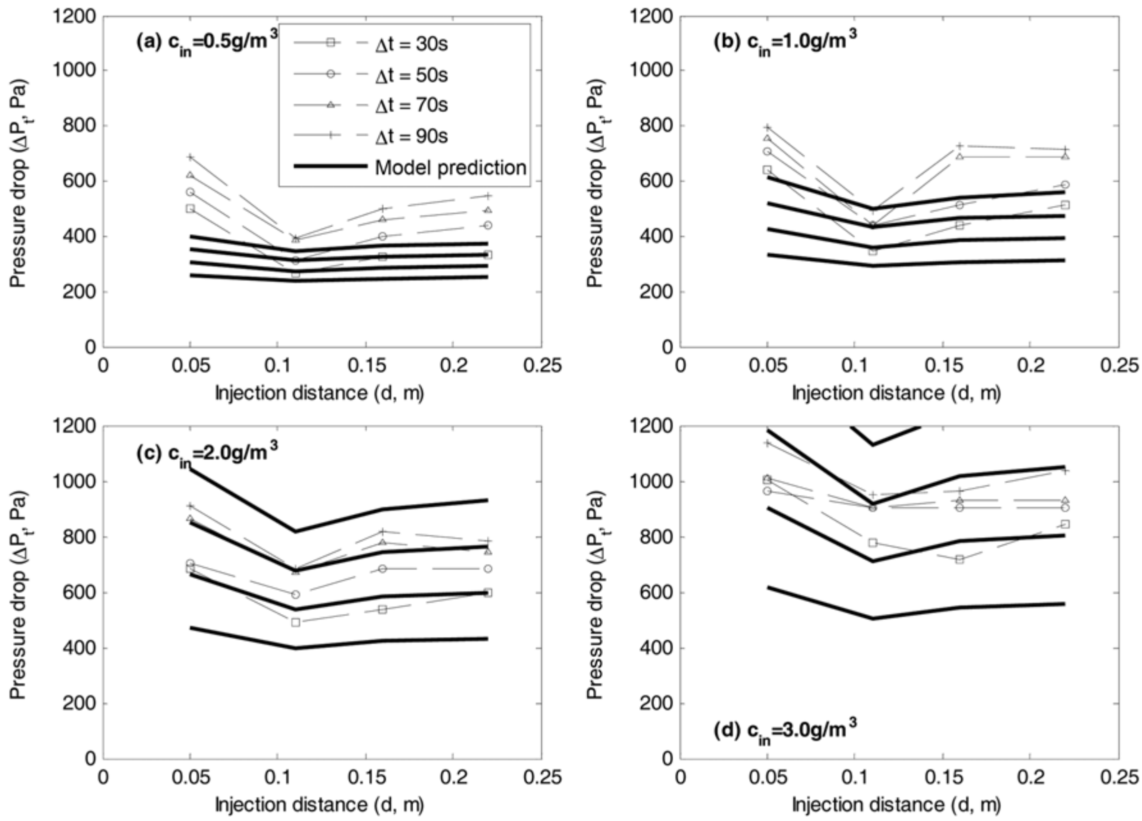

Fig. 4. Comparison of experimental pressure drop (ΔP_t^{exp}) with theoretical model (ΔP_t^{TM}) versus injection distance at v_f=1.5 m/min and P_{pulse}=490 kPa for four inlet dust concentrations (c_{in}).

ranging from 0.5-50 mm [9]. K_{TM} has a minimum at d=0.11 m.

For the empirical model, the exponent (a) of the areal density by Leith and Ellenbecker [8] is consistent with the range found in this study. Since the theoretical model has only one model parameter, the correlation coefficient (R) is lower than that of the empirical model with the two parameters. It implies that the total pressure drop has a nonlinear relationship with the areal density (w_o) rather than linear one.

In Fig. 4, the pressure drops versus the injection distance obtained from the theoretical model (ΔP_t^{TM}) are compared to experimental data for the four pulse intervals (Δt) and four inlet dust concentrations (c_{in}). Higher inlet dust concentration and pulse interval lead to higher pressure drop caused by dust deposit on the bagfilter. The experimental data show a minimum pressure drop at d=0.11 m for all cases except one at c_{in}=3 g/m^3 and Δt=30 s (see Fig. 4). The minimum pressure drop moves slightly to the large injection distance at c_{in}=3 g/m^3 when the pulse interval time is 30 s, as shown in Fig. 4(d).

The theoretical model shows a similar tendency to the experiment, but does not predict precisely the pressure drop. Fig. 5 depicts the correlation plot between the experimental pressure drop and theoretical model one. Many of the predicted values are underestimated or overestimated.

For the empirical model, Fig. 6 and Fig. 7 show the pressure drop versus the injection distance and the correlation plot, respectively. The empirical model with the two parameters predicts better the pressure drop varying with c_{in}, Δt, and d, where the correlation coefficient (R) is 0.952. The empirical model captures well the behavior showing a minimum pressure drop at d=0.11 m. However, considerable discrepancies between the experiment and model are observed, especially, at c_{in}=3.0 g/m^3 (see Fig. 6(d)). That may result

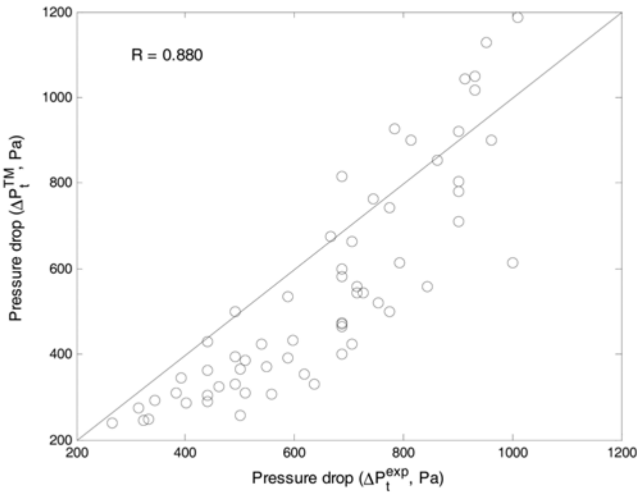

Fig. 5. Correlation plot between experimental pressure drop (ΔP_t^{exp}) and theoretical model (ΔP_t^{TM}).

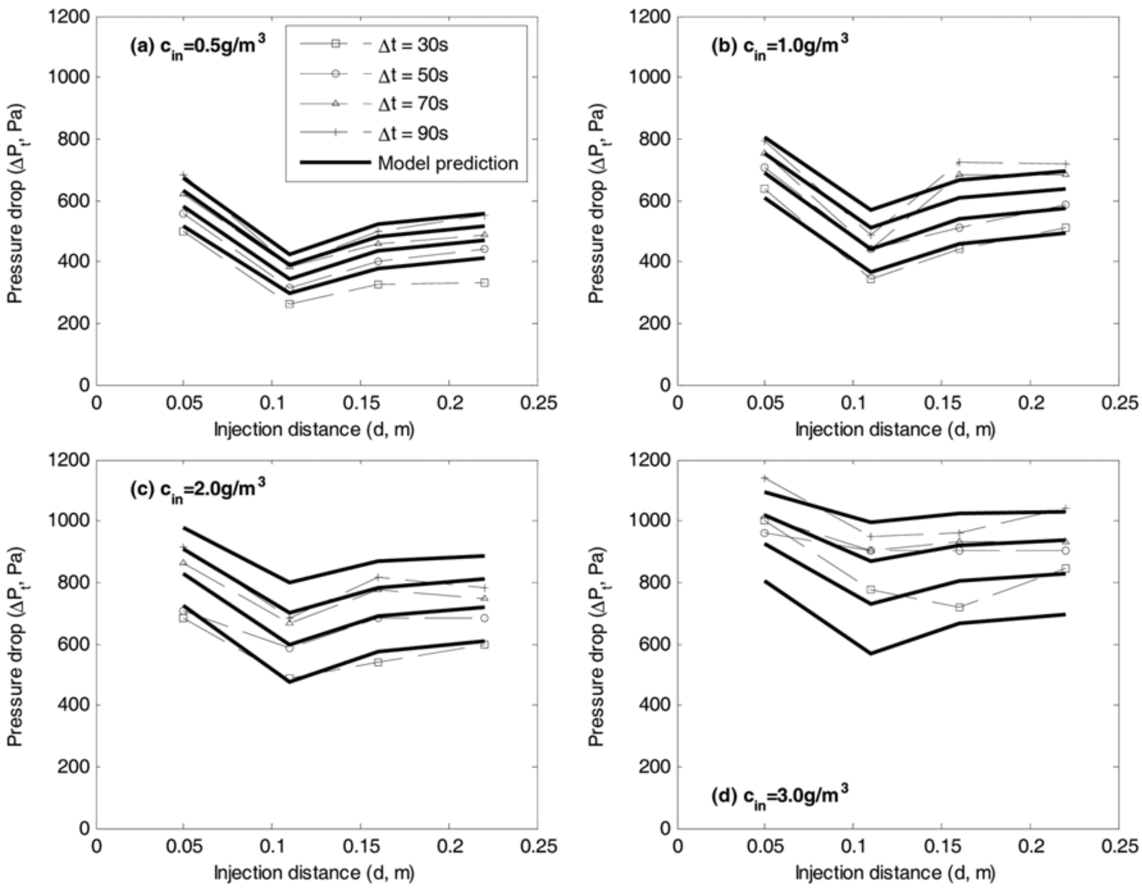

Fig. 6. Comparison of experimental pressure drop (ΔP_t^{exp}) with empirical model (ΔP_t^{TM}) versus injection distance at and four inlet dust concentrations (c_{in}).

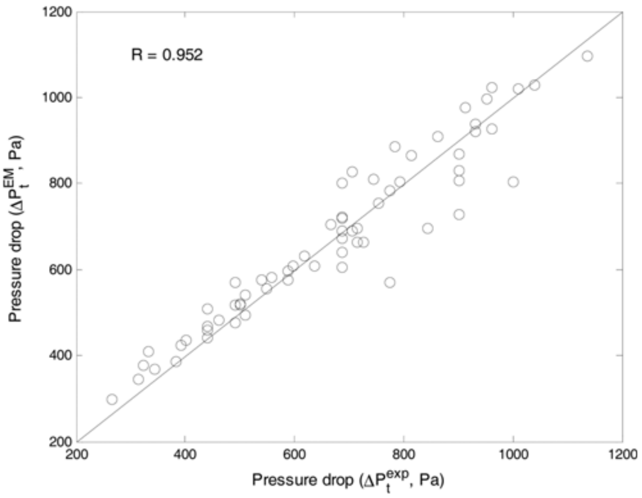

Fig. 7. Correlation plot between experimental pressure drop (ΔP_t^{exp}) and empirical model (ΔP_t^{TM}).

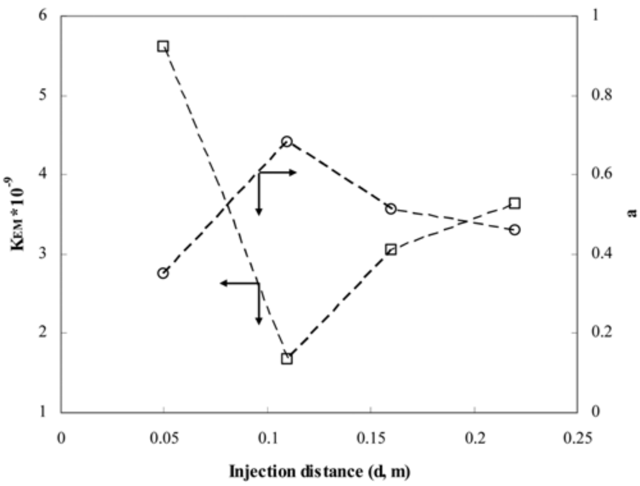

Fig. 8. Unimodal behavior of empirical model parameters (K_d and a) as a function of injection distance (d).

from the dust cake compaction [27,29,30] and unremoval at the high dust concentration, which is not considered by the empirical model. A model taking into account the dust cake compaction and unremoval is thus required to predict more precisely the pressure drop at the high dust concentration as the future work.

This study reveals that an optimum injection distance between the nozzle and venturi exists, when the nozzle diameter and the dimensions of filter bag (length and diameter) and venturi are given. Lu and Tsai [31] have also demonstrated that there is an optimum

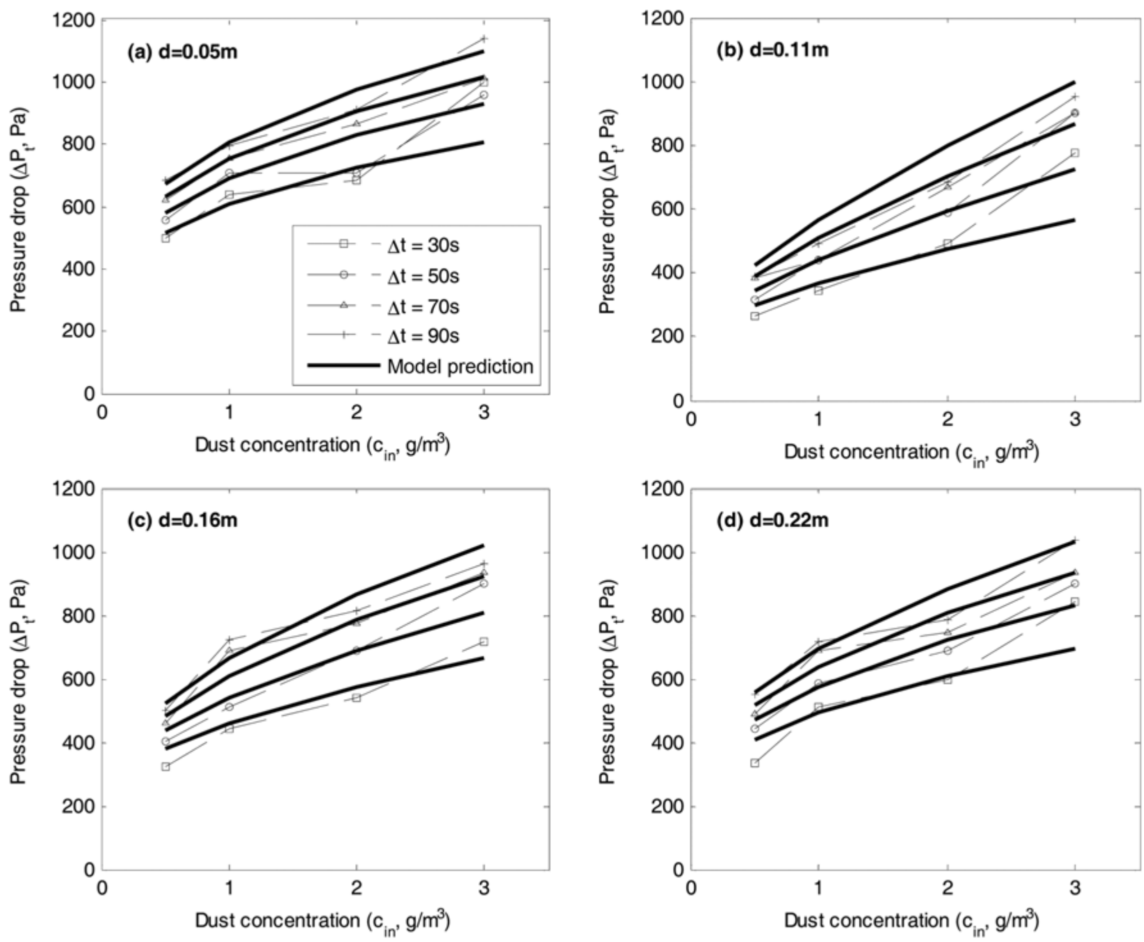

Fig. 9. Comparison of experimental pressure drop (ΔP_t^{exp}) with empirical model (ΔP_t^{TM}) versus inlet dust concentration at v_f=1.5 m/min and P_{pulse}=490 kPa.

distance depending on nozzle and bag diameter. The unimodal behavior on the injection distance can be explained by means of the two parameters of empirical model. In Fig. 8, the two parameters (K_{EM} and a) are plotted with respect to the injection distance (d). The dust cake resistance (K_{EM}) has a minimum value at d=0.11 m. By the pulse-jet air pressure maximized at this distance [31], the dust accumulated on the filter surface is effectively detached and K_{EM} is minimized. The exponent of the areal density (a), which shows also a unimodal profile, rises up by maximum at d=0.11 m. Since the dust is effectively removed at this optimum injection distance, the pressure drops change sensitively with the areal dust density (w_o). In Fig. 9, the pressure drop is reproduced at each injection distance with respect to the dust concentration. The pressure drops of d=0.11 m (see Fig. 9(b)) are lower than those of the three others in the low dust concentrations (0.5, 1.0, and 2.0 g/m^3). However, the pressure drops of d=0.11 m rise to $800 \leq \Delta P_t \leq 1000$Pa in the high dust concentration (c_{in}=3.0 g/m^3), which is almost the same level as those of d=0.16 m and d=0.22 m. As a result, its slopes of pressure drop to the dust concentration are higher than those at the other three injection distances.

CONCLUSIONS

The pressure drop through a bagfilter is one of the most important factors on the operating cost of bagfilter houses. In this study, a pilot-scale pulse-jet bagfilter with about 6 m^2 filtration area was tested for investigating the effects of the injection distance between the nozzle and venturi on the total pressure drop, using coke dust collected from a steel mill factory.

The empirical model was used to predict the pressure drop according to the operating variables: filtration velocity, inlet dust concentration, pulse pressure, pulse interval time, and injection distance. The empirical model contains the initial pressure drop and dust cake pressure drop. The initial pressure drop, which is the total pressure drop before the dust enters, was measured experimentally. The two parameters--dust cake resistance and exponent of dust areal density--of the empirical model were estimated from the experimental data.

The optimum injection distance (d) minimizing the total pressure drop was identified in the experimental data at the fixed filtration velocity and pulse pressure. The dust cake resistance shows a minimum value at d=0.11 m, and the total pressure drop is minimized. This is because the dust cake is removed effectively at this injection distance, maximizing the pulsing pressure inside the filter bag.

The empirical model shows good prediction performance on the bagfilter pressure drop. However, a model taking into account dust compaction and unremoval is required for the improvement of prediction performance in broad operating conditions.

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