

MODEL CALIBRATION FOR PRESSURE DROP IN A PULSE-JET CLEANED FABRIC FILTER

JOHN L. KOEHLER and DAVID LEITH

Physical Sciences and Engineering, Harvard School of Public Health, 665 Huntington Avenue, Boston, MA 02115, U.S.A.

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Abstract—A model based on Darcy's law allows prediction of pressure drop in a pulse-jet cleaned fabric filter. The model considers the effects of filtration velocity, dust areal density added during one filtration cycle, and pulse pressure. Data used to calibrate the model were collected in experiments with three fabric surface treatments and three dusts conducted at three filtration velocities, for a total of 27 different experimental conditions. The fabric used was polyester felt with untreated, singed, or PTFE-laminated surface. The dusts used were granite, limestone and fly ash. Filtration velocities were 50, 75 and 100 mm s⁻¹. Dust areal density added during one filtration cycle was constant, as was pulse pressure. Under these conditions, fabric surface treatment alone largely determined the values for two of the three constants in the model; the third constant depends on pressure drop characteristics of the venturi at the top of each filter bag.

NOMENCLATURE

c_i	dust inlet concentration, kg m ⁻³
K_1	fabric resistance, Pa s m ⁻¹
K_2	specific resistance of dust deposit, s ⁻¹
K_2'	apparent specific resistance of dust deposit, s ⁻¹
K_3	constant, see Equation (3)
K_4	constant, see Equation (3)
K_v	venturi nozzle resistance, Pa m ⁻² s ²
P	pulse pressure, kPa
P_s	maximum static pressure developed inside bag as result of cleaning pulse, Pa
t	time between pulses to each bag, s
v	superficial filtration velocity, m s ⁻¹
w	areal density of dust deposit, kg m ⁻²
w_0	dust areal density added during one filtration cycle, kg m ⁻²
Δp_d	pressure drop due to deposit, Pa
Δp_f	pressure drop across clean fabric, Pa
Δp_v	pressure drop across venturi, Pa
Δp_t	total pressure drop, $\Delta p + \Delta p_d + \Delta p_v$, Pa.

INTRODUCTION

Fabric filters collect small particles very efficiently. Their use has increased recently, as emission regulations have required more control of particulate pollutants. Because pressure drop across a fabric filter can greatly affect system operating cost, accurate methods for predicting pressure drop are important. This paper concerns calibration of a model that can be used to predict pressure drop across a pulse-jet cleaned fabric filter.

Pressure drop across a conditioned fabric can be represented as the sum of pressure drops across the clean fabric, Δp_f , and pressure drop due to the presence of dust on and in the fabric, Δp_d . Because flow through the fabric is laminar, pressure drop across the clean fabric is:

$$\Delta p_f = K_1 v \quad (1)$$

where K_1 is usually called fabric resistance and v is superficial filtration velocity. A value for K_1 can be determined from fabric permeability, defined as the velocity of the gas, v , passing through clean fabric at an applied pressure drop of one-half inch of water ($\Delta p_f = 125$ Pa).

Ideally, pressure drop due to dust on the fabric is

$$\Delta p_d = K_2 v w, \quad (2)$$

where K_2 is the specific resistance of the dust deposit and w is the areal density of the dust deposit. Carman (1937), Williams *et al.* (1940), Stephan *et al.* (1960), Pich (1969) and Rudnick (1978) studied gas flow through porous media. This work can be used to predict K_2 from the properties of the dust, the gas, and the porosity of the dust deposit, with the assumption that the dust deposit is unaffected by the supporting fabric. In practice, however, the specific resistance of the dust deposit can depend on properties of the fabric that supports the dust. The importance of the fabric effect should increase if the dust deposit is thin relative to the fabric surface convolutions, but, according to Dennis *et al.* (1978), becomes negligible if the dust deposit is sufficiently thick.

For felts of the kind used in pulse-jet filters, the fabric surface convolutions may be large relative to the dust deposit thickness, so that the specific resistance of the dust deposit on these felts cannot be calculated from the properties of the dust, gas and deposit porosity alone. In place of specific resistance, K_2 , the apparent specific resistance, K_2' , must be used to include the effect of the fabric on dust deposit structure. Although specific resistance, K_2 , can be calculated from theory, apparent specific resistance, K_2' , cannot; it must be determined empirically. A rougher, more convoluted fabric surface should develop a dust deposit that is more porous near the dust-fabric

interface; therefore, apparent specific resistance, K'_2 , should be less than specific resistance, K_2 .

A practical model for pressure drop must also consider the effect of incomplete fabric cleaning. Experimental work by Dennis *et al.* (1975, 1978) demonstrated that virtually all dust is removed from only some portions of woven fabrics cleaned by shaking or reverse air, and that other portions are hardly cleaned at all. Dennis and Wilder (1975) showed that more than half the dust is normally removed from woven bags cleaned off-line by shaking. However, for felt bags pulse-jet cleaned while on line, Ellenbecker (1979), Ellenbecker and Leith (1979) and Leith *et al.* (1977) showed that only a few per cent of the dust on the bags is removed and transferred to the dust hopper per cleaning cycle; almost all of the dust remains on the bags.

Leith and Ellenbecker (1980) reviewed these matters and derived an expression for pressure drop across the fabric and dust deposit in a pulse-jet cleaned fabric filter

$$\Delta p_f + \Delta p_d = \frac{P_s - K_4/K_3 + K_1 v}{2} \quad (3)$$

$$- \frac{\sqrt{(P_s - K_4/K_3 - K_1 v)^2 - 4w_0 v K_2/K_3}}{2},$$

where P_s is the maximum static pressure developed in a bag as a result of a cleaning pulse, w_0 is the dust areal density added during one filtration cycle, K_3 is a constant expressing effectiveness with which the cleaning pulse removes dust and K_4 is a constant expressing the effect of reverse fabric motion.

In a pulse-jet cleaned filter, gas leaves through a venturi at the top of each bag. The venturi induces gas from the cleaned-gas plenum to flow into the bags with the pulse air. The induced gas flow helps to isolate the cleaning bag from those that continue to filter, and to clean the pulsed bag more efficiently by flushing collected dust from the fabric. Although the venturis primarily affect cleaning, they affect operation during filtration as well. Cleaned gas flows from the interior of each bag through the venturi at its top to reach the gas outlet plenum. Pressure drop from gas flow through the venturi during normal filtration, Δp_v , must be added to the pressure drop across fabric and dust, Δp_f and Δp_d , to give total pressure drop, Δp_t

$$\Delta p_t = \Delta p_f + \Delta p_d + \Delta p_v \quad (4)$$

Because air flow through a venturi is turbulent, Δp_v is proportional to the square of the velocity of the gas passing through it; this velocity is proportional to filtration velocity through the bag so that

$$\Delta p_v = K_v v^2 \quad (5)$$

where K_v varies with venturi design, but is constant for a venturi of given design.

Leith and Ellenbecker (1980) suggested that K_4/K_3 in (3) is less than 2% of P_s from which it is subtracted to

calculate steady-state pressure drop. If so, K_4/K_3 is negligible. Substituting (3) and (5) into (4), neglecting K_4/K_3 , gives

$$\Delta p_t = \frac{P_s + K_1 v - \sqrt{(P_s - K_1 v)^2 - 4w_0 v K_2/K_3}}{2} + K_v v^2 \quad (6)$$

for total pressure drop across a pulse-jet cleaned fabric filter.

The purpose of the present paper is to evaluate the constants in (6) over a range of experimental conditions.

EXPERIMENTS

Experiments were conducted using three fabric surface treatments and three dusts at three filtration velocities for a total of 27 different conditions. Replicates were run at each condition, so that 54 experiments were conducted in all. All experiments were conducted using a three bag, pilot-scale filter described by Ellenbecker and Leith (1980). This filter was identical to an industrial unit except for its limited number of bags.

The fabric tested was 543 g m⁻² polyester felt with different surface treatments. One felt had untreated surface; this surface was comparatively rough and convoluted. The second felt had singed surface. Most fibers protruding from the surface of this fabric were removed in the singeing process; this fabric surface was considerably smoother than that for untreated felt. The third felt had a lamination of microporous polytetrafluoroethylene (PTFE) applied to its surface to make that surface extremely smooth. At the beginning of each experiment, three bags of the appropriate kind were installed in the filter. Pressure drop in the first 27 experiments was measured after 20 h of conditioning new bags with dust. Pressure drop in the second 27 experiments was measured after 20 additional hours of conditioning using the same bags.

The dusts used were fly ash, granite and limestone. Size distributions for these dusts, determined by sieve analysis, are given in Fig. 1. Dusts were fed to the inlet gas using an NBS dust feeder (Hinds, 1982), after sieving through a 600 μ m screen to remove debris. Fly ash was kept at 150°C so it would

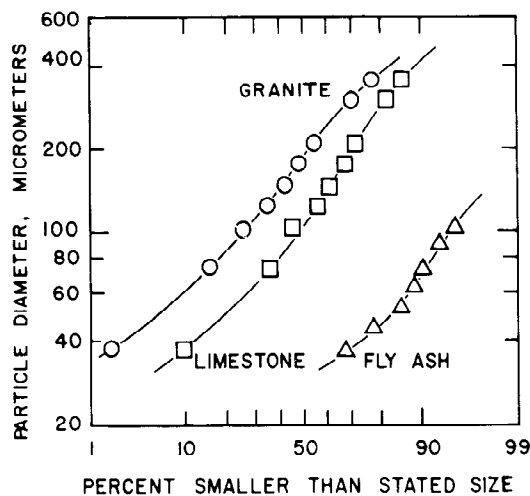


Fig. 1. Cumulative size distributions by mass for test dusts, determined by sieve analysis.

flow through the dust feeder: the other dusts were fed at room temperature. Examination of dust samples using the scanning electron microscope revealed that many fly ash particles were smooth, round cenospheres. Granite and limestone particles had amorphous shape, but were isometric.

The superficial filtration velocities used were 50, 75 and 100 mm s⁻¹, corresponding to air flow rates of 473, 709 and 946 m³ h⁻¹. Laboratory air was used as the gas in these tests.

For all tests, the time between cleaning pulses to each bag was one minute and pulse pressure was 690 kPa (6.9 bar). A relationship between pulse pressure, *P*, and static pressure developed inside the bag, *P_s*, for a 6.4 mm (1/4") jet discharging into a standard pulse-jet venturi was determined by Leith and Ellenbecker (1980)

$$P_s(\text{Pa}) = 164P(\text{kPa})^{0.6} \quad (7)$$

From (7), the induced static pressure, *P_s*, was 8280 Pa in all 54 experiments. For a pulse pressure of 620 kPa, Bakke (1974) reports that *P_s* is about 10% lower than that given in (7).

If the filter collects all incoming particles, dust areal density added between cleaning, *w₀*, is

$$w_0 = c_i vt, \quad (8)$$

where *c_i* is inlet dust concentration and *t* is the time between pulses to each bag. In these experiments, *w₀* was held constant at about 3.8 × 10⁻³ kg m⁻².

Pressure drop across the venturis, Δ*p_v*, was measured by operating the filter without bags at flow rates equivalent to filtration velocities from 50 to 125 mm s⁻¹. These data were analyzed using (5) to determine *K_v*.

Experiments were also conducted to determine *K₁*, the resistance of a clean fabric. Fabric samples 254 mm square were placed in a frame through which air passed at velocities from 50 to 150 mm s⁻¹. Pressure drop across the fabric was measured at each velocity; these data were used with (1) to determine *K₁* for each fabric surface treatment.

RESULTS AND DISCUSSION

The pressure drop vs velocity squared results from the empty filter experiments were analyzed by linear regression. The slope from this regression is an estimate of *K_v*, and was 57,500 Pa m⁻² s². The pressure drop vs velocity results obtained from the clean fabric experiments were also analyzed by linear regression; the slopes of these regression lines are estimates of *K₁* for each fabric surface treatment and are given in Table 1. Data for total pressure drop, Δ*p_t*, are plotted as geometric symbols against filtration velocity in Figs 2-4 for the untreated, singed and PTFE-laminated fabrics, respectively.

Equation (7) can be solved for constant *K₂/K₃*

$$K_2/K_3 = \frac{(P_s - K_1 v)^2 - [P_s + K_1 v - 2(\Delta p_t - K_v v^2)]^2}{4w_0 v} \quad (9)$$

Table 1. *K₁* and *K₂/K₃* from regression analysis

Surface treatment	Clean fabric resistance, <i>K₁</i> Pa s m ⁻¹	<i>K₂/K₃</i> Pa s ⁻¹
Untreated felt	712	0.674 × 10 ¹⁰
Singed felt	613	0.444 × 10 ¹⁰
PTFE Laminated felt	1530	1.880 × 10 ¹⁰

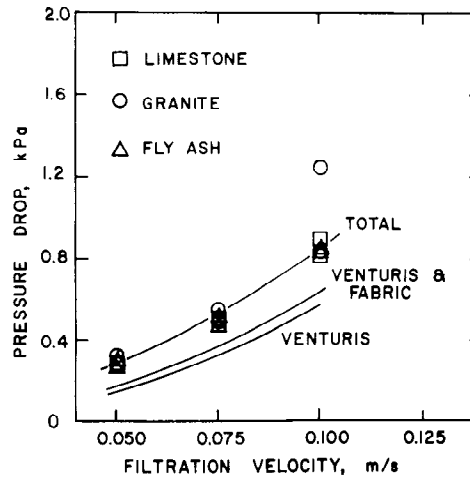


Fig. 2. Pressure drop vs filtration velocity for felt with untreated surface. Symbols represent measured values, lines represent calculated values; see text.

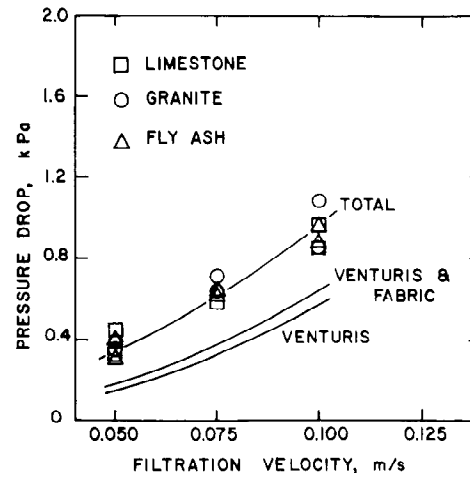


Fig. 3. Pressure drop vs filtration velocity for felt with singed surface. Symbols represent measured values, lines represent calculated values; see text.

With data for all terms on the right side of (9), values of *K₂/K₃* were calculated for all 54 experiments. An analysis of variance found significant variations in *K₂/K₃* between fabric surface treatments and between filtration velocities, but *not* between dust types. The analysis also found significant variations between velocities within each fabric surface treatment. Of the three significant sources of variation, one source, fabric surface treatment, explained 82% of the observed variance in *K₂/K₃*. To develop a less complicated model for total pressure drop, *K₂/K₃* values were averaged only for each fabric surface treatment. Table 1 gives these *K₂/K₃* values.

Both *K₁* and *K₂/K₃* depend essentially on fabric surface treatment alone for the data analyzed here. The *K₁* and *K₂/K₃* values from Table 1 can be used in (6) to calculate total pressure drop. Calculated total

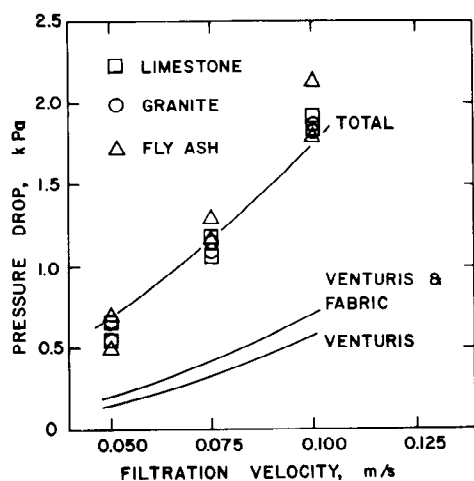


Fig. 4. Pressure drop vs filtration velocity for felt with PTFE-laminated surface. Symbols represent measured values, lines represent calculated values; see text.

pressure drops are plotted as solid curves against filtration velocity in Figs 2-4. Figure 5 is a plot of calculated pressure drop against measured pressure drop for all experiments. The correlation between calculated and measured Δp_t was good ($r = 0.98$).

Equations (5) and (1) can be used simultaneously to characterize pressure drop due to the venturis, Δp_v , and the clean fabric, Δp_f . Pressure drop due to the dust deposit, Δp_d , can be found by subtracting the pressure drops of the venturis and clean fabric from the total pressure drop determined from (6). Also shown on Figs 2-4 are plots of pressure drop against filtration velocity calculated from these equations. In each figure the lowest curve represents pressure drop due to the venturis (Δp_v) and the middle curve represents pressure drop across the venturis and clean fabric ($\Delta p_v + \Delta p_f$). The highest curve represents total pressure

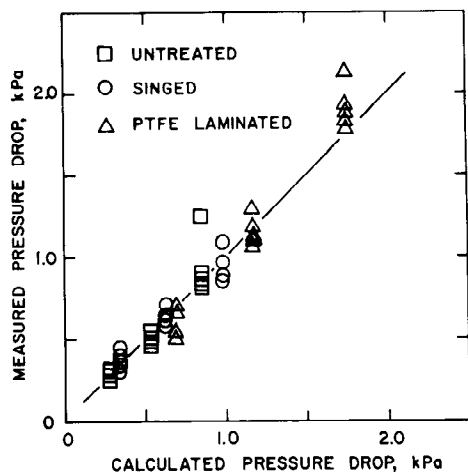


Fig. 5. Calculated pressure drop vs measured pressure drop.

drop, Δp_t , which occurs after the fabrics are conditioned with dust.

Pressure drop across the venturis was, of course, the same regardless of the fabric used. Figures 2-4 show that pressure drops across the clean fabrics were, in all cases, a relatively small fraction of total pressure drop. Total pressure drop became higher as the fabric surface became smoother. Pressure drop was higher for the felt with singed surface than for the felt with untreated surface, and highest for the felt with PTFE laminated surface.

Differences in total pressure drop for the fabrics tested were largely due to differences in the pressure drop across the dust deposit. For example, at a filtration velocity of 75 mm s^{-1} , the pressure drop across venturis and clean fabric was about 400 Pa for all three fabrics as shown in Figs 2-4. Pressure drop due to the dust deposit, however, increased from about 200 Pa for the untreated felt to 300 Pa for the felt with singed surface, and to 800 Pa for the felt with PTFE laminated surface. Clearly, fabric surface treatment affected the pressure drop characteristics of the dust deposit.

Equation (2) shows that at any velocity, pressure drop due to the dust deposit depends on the (apparent) specific resistance of the deposit and on deposit areal density, w . As discussed by Leith and Ellenbecker (1982), the areal density of the deposit in these experiments was always greatest for the felt with untreated surface, somewhat less for the felt with singed surface, and much less for the felt with PTFE-laminated surface. This order is the reverse of that necessary to explain pressure drop trends on the basis of areal density, w . Apparent specific resistance of the dust deposit, K'_2 , evidently had an effect on pressure drop even greater than dust deposit and density. Apparent specific resistance, therefore, must have been affected by the fabric surface treatment in the present experiments.

The felt with untreated surface presents a rough, convoluted surface to incoming dust. The dust deposit that develops on and in this fabric is not continuous, but is open, rough and convoluted like the fabric. Even though a comparatively large amount of dust may remain with this fabric after pulse-jet cleaning, the comparatively open structure of the dust deposit permits gas to flow through readily and causes low pressure drop. A true, continuous dust cake will not form until the dust deposit is very thick, probably much thicker than is found on these fabrics in practice. Over time, the open structure of this fabric will permit considerable amounts of dust to pass through the surface into the felt interstices. If enough dust lodges in the interstices, pressure drop will increase substantially above that reported here, the fabric will likely 'blind', and require replacement.

The felt with PTFE-laminated surface presents a uniform, smooth, microporous surface to incoming dust. The deposit that develops on this surface is continuous, much like a true dust cake. This dust

deposit has internal structural integrity (it behaves as a continuous deposit) because it contacts the fabric only at the fabric surface. This deposit is removed as large agglomerates relatively easily by pulse-jet cleaning, yet the residual dust is so tightly structured that relatively high pressure drop is necessary for gas to pass through it. As long as the smooth surface remains intact, little dust should penetrate through to reach the fabric interstices, and the fabric will probably not 'blind'.

The felt with singed surface presents a surface to incoming dust that is smoother than untreated felt, but not as smooth as PTFE-laminated felt. The characteristics of this felt are between those of the rough, untreated felt and the smooth, PTFE-laminated felt.

These data suggest that, in the experiments conducted here, dust type did not greatly affect pressure drop. This surprising finding should not hold if the dust deposit on each fabric develops sufficiently to become a true, continuous dust cake. For a true cake, pressure drop should depend largely on the properties of the dust, such as its size distribution and shape, and somewhat on the conditions under which it collects, such as filtration velocity, but not at all upon the underlying media that supports it. Because fabric surface treatment did affect the characteristics of the dust deposit and its contribution to pressure drop, and because dust type did not, true dust cakes apparently did not develop on the surface of these fabrics.

CONCLUSIONS

A model for total pressure drop across a pulse-jet cleaned fabric filter has been presented. According to the model, pressure drop depends on filtration velocity, v , pulse pressure, P , the amount of dust added to the bag between cleanings, w_0 , two constants, K_1 and K_2/K_3 , which depend on the type of fabric surface treatment used, and the resistance of the venturi through which cleaned air leaves each bag, K_v . The model was calibrated with data taken on a three bag filter using each of three fabric surface treatments and dusts, operated at each of three filtration velocities. The data used to calibrate the model define the operating conditions over which it works effectively:

- (1) Filtration velocities from 50 to 100 mm s⁻¹;
- (2) Granite, limestone and fly ash dusts;
- (3) Polyester felts with untreated, singed and PTFE-laminated surfaces;
- (4) Constant w_0 of 3.8×10^{-3} kg m⁻²;
- (5) Time between pulse to each bag of 60 s and
- (6) Pulse pressure of 690 kPa, which corresponds to P_s of 8280 Pa, according to (7).

The model provides a practical method for estimat-

ing the effect of process changes on total pressure drop. Outside the above operating conditions the performance of the model is less certain and should be used with caution. Further work is required to better understand governing factors at other conditions.

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