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EXPERIMENTAL STUDY OF FILTER CAKE FORMATION ON DIFFERENT FILTER MEDIA

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Removal of particulate matter from gases generated in the process industry is important for product recovery as well as emission control. Dynamics of filtration plant depend on operating conditions. The models, that predict filter plant behaviour, involve empirical resistance parameters which are usually derived from limited experimental data and are characteristics of the filter media and filter cake (dust deposited on filter medium). Filter cake characteristics are affected by the nature of filter media, process parameters and mode of filter regeneration. Removal of dust particles from air is studied in a pilot scale jet pulsed bag filter facility resembling closely to the industrial filters. Limestone dust and ambient air are used in this study with two widely different filter media. All important parameters like pressure drop, gas flow rate, dust settling, are recorded continuously at 1s interval. The data is processed for estimation of the resistance parameters. The pressure drop rise on test filter media is compared. Results reveal that the surface of filter media has an influence on pressure drop rise (concave pressure drop rise). Similar effect is produced by partially jet pulsed filter surface. Filter behaviour is also simulated using estimated parameters and a simplified model and compared with the experimental results. Distribution of cake area load is therefore an important aspect of jet pulse cleaned bag filter modeling. Mean specific cake resistance remains nearly constant on thoroughly jet pulse cleaned membrane coated filter bags. However, the trend can not be confirmed without independent cake height and density measurements. Thus the results reveal the importance of independent measurements of cake resistance.

Keywords: Filter cake, Pressure drop, Cake resistance, Cake formation

1. Introduction

Removal of particulate matter from gases generated in the process industry is important for product recovery as well as emission control. Dynamics of the filtration plant depend on the operating conditions. The models, that predict filter plant behaviour, involve empirical resistance parameters which are usually derived from limited experimental data and are characteristics of the filter media and filter cake (dust deposited on filter medium). Pressure drop is function of flow resistance, which depends upon cake porosity or/and specific resistance, cake area load (cake mass per unit area), and filtration velocity in addition to filter medium. Generally the cake area load and filtration velocity are taken average which, in reality, may be highly non-uniform resulting in non-uniform local flow distribution on the filter surface. The cake, therefore, may have locally different properties. Patchy cleaning has been reported on rigid as well as flexible filter media
[1, 2].

Needle felts are the most common filter media these days, which are physically and/or chemically treated to improve dust capturing and cake detachment on one hand and resistance to chemical attack on the other hand. Some characteristics of the most commonly used needle felts are summarized in [3]. Nevertheless, to less or greater extent, some dust always penetrates the surface of the filter medium and forms an intermediate zone, which may be called particle-fiber (PF) layer. This layer is responsible for clogging of filter media but also helps in dust separation. The surface layer is characterized by

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porosity and pore size distributions [4].

Operational characteristics of filter bags are greatly influenced by the surface properties and the cloth structure of the filter medium [5]. The mass and distribution of the surface layer is critical to the evolution of pressure drop. Operation at higher velocity is disadvantageous due to higher cake resistance [6] caused by compact cake formation.

Removal of dust particles from air is studied in a pilot scale jet pulsed bag filter facility [7] resembling closely to industrial filters. Limestone dust and ambient air are used in this study with two widely different filter media. Filter behaviour is also simulated using estimated parameters and a simplified model and compared with the experimental results.

2. Experimental and Procedures

2.1. *Bag filter set-up*

Experimental set up (Fig. 1) presented elsewhere [7] consists of a two screw single component feeder (1), dispersion nozzle (3), vibrating chute (2), bag filter (4), load cell and dust collector (5), bags (6) and discharge fan (8). Cake detachment is accomplished on line with jet pulses. Jet pulses are issued for a certain number of bags in a cyclic order either at pre-set upper pressure drop or time interval. The gas flow is measured using an orifice plate. A frequency converter is provided to regulate gas flow at the set value. Change in pressure drop due to temporarily increased gas flow after jet pulse is corrected according to Equation 1.

$$\Delta p_{\text{true}} = \frac{\Delta p_{\text{actual}}}{\text{Flow}_{\text{actual}}} \tag{1}$$

Because the transient dust feed and dust collected in the filter are known, the dust fraction settling in the filter and the dust concentration relevant for filtration can be calculated.

2.2. *Materials*

Commercial grade non precipitated Limestone (ρ_s = 2700kg/m^3) with weight mean diameter ($d_{50,3}$) of 5µm and bulk density (ρ_b) of 1200 kg/m^3 is used as dust. Two types of needle felt are tested. One is made of two polymers, Polyimide (PI) and Polyphenylensulfide (PPS) fiber on PI scrim. The second is made of PTFE laminated Polyester needle felt. The former is heat treated on dust side while the later is membrane coated on dust side. Table 1. Lists some of the characteristics of tested needle felts.

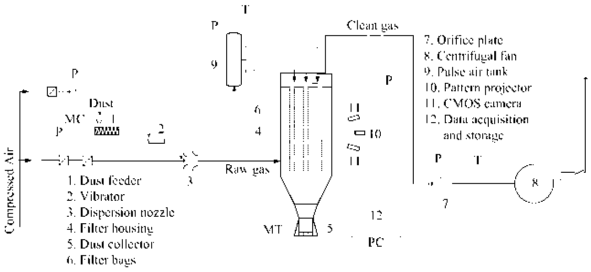

Figure 1. Bag filter set-up.

Table 1. Some of the mechanical properties of the tested needle felt [Source: Company provided data sheets].

Fiber content	Polyphenylene-sulfide+ Polyimide	PTFE laminated Polyester	Unit
Air permeability at 200Pa	79.5		5 l/dm^2 – min
Weight	575	407	g/m^2
Felt Construction	Supported needle felt	Supported needle felt	
Service Temperature		135	°C
Max. Surge Temperature		149	°C
Thickness		1.4	mm

2.3. *Procedures*

2.3.1. *Filter media surface*

Surface roughness of filter media is measured with a microscope using procedures presented elsewhere [8]. A series of images of the surface are taken while the lens traverses from the highest to the lowest position. A 3D surface is constructed by the built-in software. Constructed 3D surface is then analyzed for surface characteristics of filter media. In this work 2D images are presented for comparison (Fig. 2).

2.3.2. *Cake formation test procedure*

New filter bags are subjected to dust filtration for significant time (filter conditioning) prior to study of cake formation. The procedures are elaborated for PI+PPS needle felt elsewhere [8]. Fig. 3 displays the transient data plot of Δp, dust feed rate, gas flow (V), and dust collected (m) versus time(t) for one filtration cycle at u = 20.7mm/s with conditioned membrane coated bags alongwith in-situ intermittent cake height measurement, which is not discussed here. Gas fan is switched on and all bags are thoroughly cleaned using jet pulses for the 1st test. Residual pressure drop is recorded (300s-500s) and height measurements at 'b', 'c', …,'j' are performed after stopping the dust feed temporarily. At the end of the cycle, dust is switched off and the bags are subjected to repeated jet pulses again.

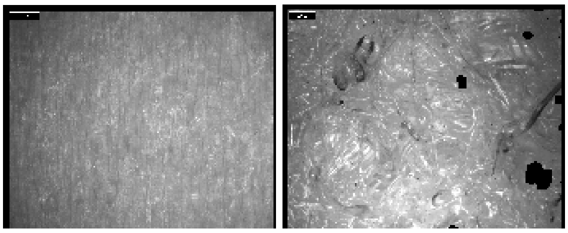

Figure. 2. Microscopic view of the surface of PI+PPS (Left) and membrane coated (Right) needle felts.

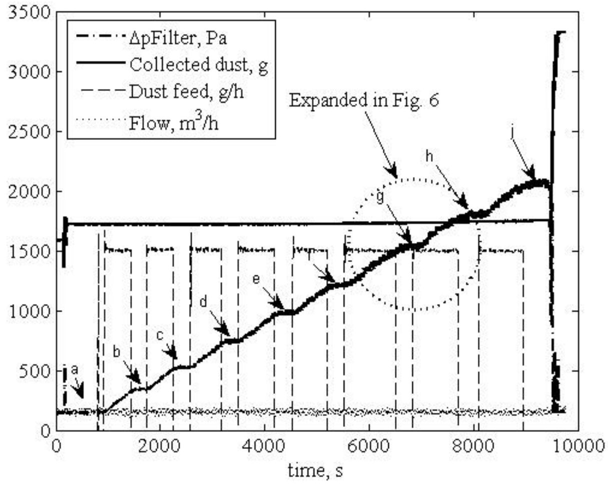

Figure 3. Transient data plot during cake formation on thoroughly jet pulsed membrane bags at u = 20.7mm/s.

Filtration is started in another test, Fig. 4, on thoroughly cleaned bags and continued while one third of filtration area (one row) is cleaned with a single jet pulse at ΔP_{max} (1200Pa). Once all bags have been subjected to jet pulses during the test, cake heights are measured intermittently during the next filtration cycle. All bags are cleaned to a steady residual pressure drop finally.

2.4. *Simulation model*

Resistance parameters are estimated from the experimental data for a simplified model [3] given in equation 2. Pressure drop is then simulated for both needle felts operated under similar conditions.

$$\Delta p = km.\mu.u + kc.\mu.u \qquad (2)$$

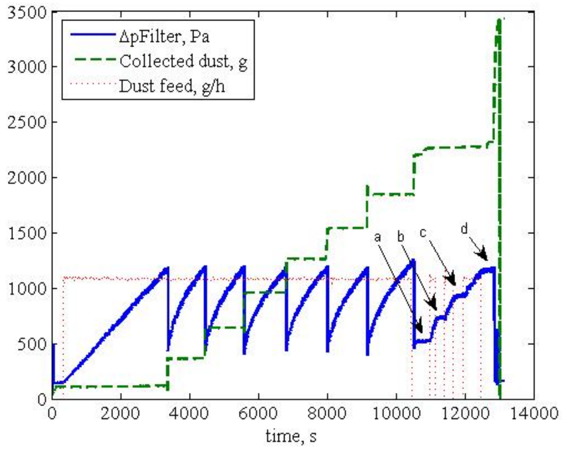

Figure 4. Transient data plot during steady state cake formation on partially jet pulsed membrane bags at u = 20.7mm/s.

3. Results and Discussion

3.1. *Surface roughness of needle felts*

The microscopic images (Fig. 2) reveal that the surface of membrane bags is smooth as compared to that of PI+PPS needle felt as expected. The internal structure of the heat-treated media is also visible, which is randomly oriented. Burned fibers are also visible in heat-treated needle felt. Thus the surface treatment modifies the surface texture significantly.

3.2. *Transient pressure drop*

Pressure drop rise during cake formation over 500 seconds for PI+PPS needle felt (on-set of dust feed) and membrane coated needle felts are shown in Fig. 5. It can be noticed that ΔP exhibits two distinct trends in case of PI+PPS needle felt after the lag time (20 − 30 s) where the dust concentration, relevant for filtration, reaches a steady state value (point 'A'). The steeper part of the curve is relatively short (150s) as compared to the overall cycle time. A gradual transition from steep to moderate and linear rise is evident.

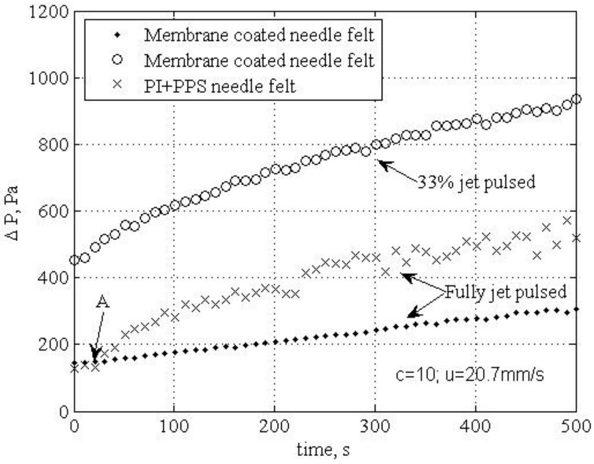

Figure 5. Transient pressure drop across the filter.

Pressure drop across the filter is normally a sum of two contributions [3], one of the filter medium, and the other of the deposited cake. In case of online jet pulse cleaning, the cake is disintegrated and detached, which falls down by gravity and is collected in a dust collector located underneath. Since the duration of jet pulses is relatively very small, concentration of dust in the gas temporarily increases. Rate of cake formation is proportional to dust concentration at constant velocity (dw/dt = cu), therefore, it can be higher after regeneration. Increased dust concentration decays quickly reaching the normal dust concentration level in a short time. Accordingly rapid increase in pressure drop after regeneration decays quickly as well reaching a uniform value. This transitional state should not last more than lag time (ratio of the hold volume to the gas volume flow i.e. 20s).

Permeability distribution of filter medium may also lead to initial steep pressure drop rise. Assuming a porous structure of needle felt matrix, pore blocking may take place during filtration near the surface until a particle-fiber layer is formed prior to a true surface filtration, which leads to steeper pressure drop rise as observed in this case. This typical behavior is reported for surface treated filter media in [4]. At low mechanical stability cake compaction is also considered as one of the reasons for non-linear i.e. convex ΔP increase, which results in shorter cleaning intervals [9]. A steep increase of ΔP shortly after regeneration i.e. concave ΔP, is often related to particle re-entrainment and/or patchy cleaning [10]. Patchy cleaning results in a locally higher filtration velocity leading to rapid formation of the cake in regenerated areas [11] producing similar effect as observed in the present case. Concave rise of pressure drop also takes place when only a fraction of total filter area is cleaned at the end of filtration cycle which is pointed out and simulated by [12]. Concave rise is observed when 33% area of Membrane coated bags is cleaned by jet pulses at the upper pressure drop limit (Fig. 5).

In present case of PI+PPS needle felt, the bag cleaning is done off line; therefore, reattachment or increased dust concentration is excluded. Since all bags are cleaned, therefore, none of the fractional cleaning, reattachment, or increased dust concentration, is obviously responsible for the observed steep ΔP rise at the onset of dust.

Contrarily in the case of membrane coated needle felt, except initial few seconds where dust concentration reaches its steady value, pressure drop is linear. Concave rise is not observed at the onset of dust feeding in case of thoroughly cleaned bags. Residual pressure drop remains around 150Pa at u = 20.7mm/s of conditioned membrane bags. The pressure drop curve shows jumps after 1000Pa in Fig. 3 which may result from increased dust concentration, increased local velocity or cake compaction.

High dust concentration can be excluded because dust feed and gas flow is well regulated to assume constant dust concentration. Increased velocity is not appropriate reason since the bags are thoroughly cleaned prior to dust feeding. It can be argued that the cake formed on thoroughly cleaned filter medium possesses relatively low mechanical strength on account of its formation at uniform gas velocity. As the cake thickness increases, pressure drop across the cake increases and hence the compressive stress, which causes compaction of the cake starting at nearly 1000Pa and above. Schmidt also reported cake compaction in [13].

A part of data of Fig. 3 is enlarged in Fig. 6. Transient dust feed is also displayed to show on and off instances of dust feed. A jump at 'a' follows a linear rise with a permanent offset shown by arrow (1). Then ΔP keeps on rise for approximately 80s after the dust feed is stopped at 'b'. However a jump is observed at 'c' slowly decaying afterwards.

The ΔP rises along arrow (2) as the dust feed is turned on at ‘d’. Afterwards it tends to follow the direction indicated by arrow (3). Another jump is observed at ’e’ followed by another one at ’f’ although ΔP reached a steady value. The rise is linear afterwards. The jumps at ’a’, ’c’, ’e’, and ’f’ are probably due to mechanical failure of the cake and represent a sudden process. However rise before and after ’e’ indicates a slow compaction process, which lasts for approximately 200s.

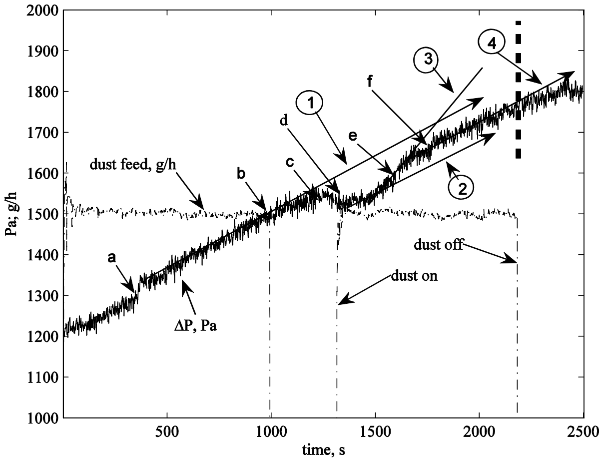

Figure 6. Local cake compaction at higher ΔP at u = 20.7mm/s.

The rise after ’b’ is perhaps due to deposition of residual dust in the line. Although time to displace the hold volume is nearly 20s, the rise continuing for 80s indicates some activity and readjustment in the filter cake surface. The jump at ‘c’ without an obvious reason further supports this argument. Nearly 40-50Pa offset in pressure drop is observed without any other obvious reasons.

Although pressure drop across thoroughly jet pulse cleaned bags is slightly higher than that for the new bags at respective cake load, the pressure drop evolves linearly from the start of filtration (Fig. 7). At higher cake load the signal becomes noisier reflecting some activity at/in the cake causing pressure drop fluctuations. The pressure drop is concave if fraction of total area is subjected to jet pulses. It is evident that concave pressure drop rise does not result solely from incomplete cleaning (patchy cleaning) but may also be due to cleaning of a fraction of total filter area. Either or the both can cause non uniform distribution of cake area load and hence the gas flow which may lead to concave pressure drop rise. Thus concavity of ΔP curve for membrane coated bags is, in principle, because of cleaning a fraction of total filter area.

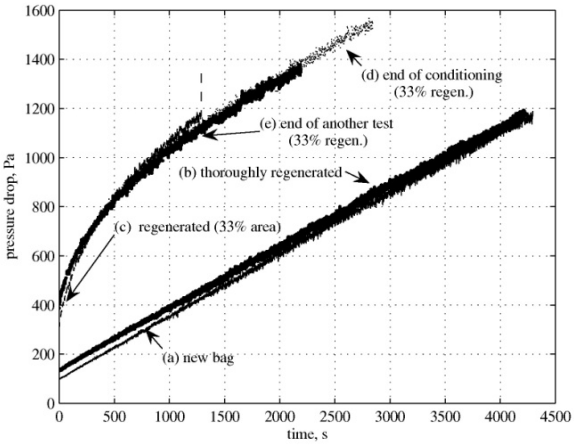

Figure. 7. Pressure drop rise during cake formation of limestone dust on (a) the new membrane bags, (b) thoroughly regenerated bag, (c) after first regeneration (33% area jet pulsed), (d) end of conditioning period (33% area jet pulsed), (e) end of another filtration test at u = 20.7mm/s.

Actual pressure drop as well as simulated pressure drop for two filter media evolving from thoroughly cleaned filter bags by jet pulses is presented in Fig. 8 versus cake area load using resistance parameters estimated from experimental data. Pressure drop of membrane coated filter media is simulated fairly accurately while that of PI+PPS filter medium is under estimated. The concavity of pressure drop curve is not captured properly by a linear model assuming uniform distribution of cake load. Concave pressure drop rise is typical of industrial filters where only a fraction of total filter area is subjected to jet pulses at the end of a filtration cycle. Thus the models that account for the distribution of cake area load on filter surface are more appropriate to simulate industrial bag filter operation. Therefore, the measurement or prediction of distribution of cake in terms of its mass, height and density, or porosity is important.

3.3. Specific cake resistance

Specific resistance of filter cake (kc) is calculated according to Darcy’s law and represents the mean value over the interval Δt (arbitrarily selected). The kc is plotted versus cake area load (w) in Fig. 9 (filled circles). The values are higher at the beginning of filtration cycles (steep ΔP rise), and lower for rest of the cycle where ΔP rise is linear. Cake area load at the upper pressure drop limit decreases from 300g/m^2 at the end of the first cycle to 230g/m^2 at the end of fourth cycle. However, specific resistance is constant at higher cake loads within range of measurement error despite cake area load varies from cycle to cycle.

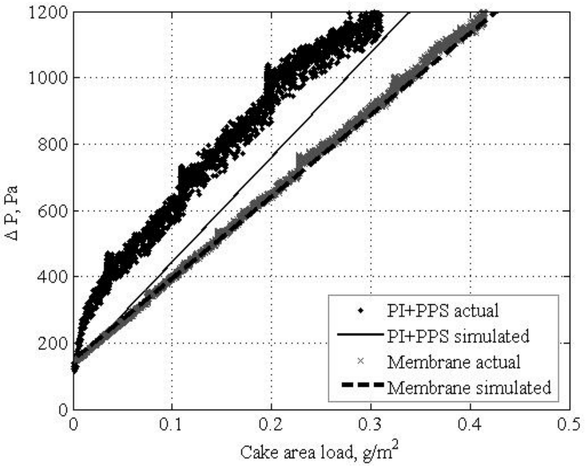

Figure 8. Comparison of actual pressure drop with the simulated pressure drop for two filter media.

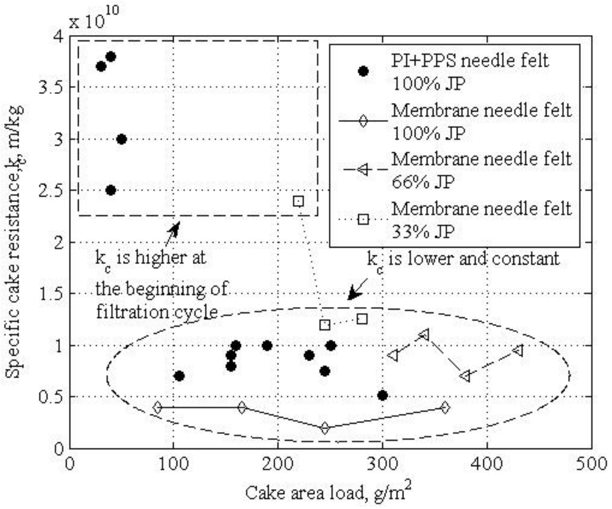

Figure 9: Specific cake resistance of limestone dust cake on PI+PPS and Membrane coated needle felts at u = 20.7mm/s.

Specific resistance of filter cake formed on membrane coated filter media is also plotted for three cases (a) 100% filtration area is jet pulsed at ΔPmax, (b) 66% area is jet pulsed at ΔP_{max}, and (c) 33% filtration area is jet pulsed at ΔP_{max}. The kc is the lowest and constant for the cake formed on 100% jet pulsed needle felt. It is higher for the cake formed in case (b), and the highest in case (c). Because the cake resistance is computed based on mean gradient of ΔP between dust feed on and off points, the effect of local compaction is, perhaps, not reflected by the computed specific cake resistance. The kc is higher just after regeneration and lower afterwards on 33% jet pulse area. This behavior is similar to that observed with cake formed on PI+PPS needle felt. The computed results suggest that the characteristics of the cake formed on regenerated filter media are different than the characteristics of the cake formed later on. However, an unequivocal statement cannot be given because independent measurements of specific cake resistance are not available at this moment.

4. Conclusions

Cake formation on two filter media, PI+PPS needle felt on PI scrim and membrane coated polyester needle felt, is investigated using limestone dust and air at ambient conditions. The Δp rise at the start of filtration is steeper for PI+PPS needle felt which becomes moderate and linear later on. On membrane coated bags the Δp rise is convex for few seconds at the start of dust feed, dilution effect, and linear later on. When a fraction of area is regenerated, the pressure drop evolves steeply, immediately, after regeneration and turns to moderate and linear on membrane coated needle felt. The membrane bags, which possess a smooth surface, do not show such a steep rise when all bags are jet pulsed at the upper pressure drop limit. Thus uneven distribution of filter cake on filter bag surface also gives rise to concave rise of ΔP curve. Similar effect due to patchy cleaning is reported by others [1, 2].

Concave pressure drop rise on PI+PPS needle felt indicates the distribution of residual cake height or porosity on regenerated surface. Formation of denser layers of cake is expected followed by coarser layers as soon as the specific resistance of new and old cake is equilibrated. A uniform cake formation and linear ΔP rise there on is observed. Thus uneven distribution of combined resistance to flow can be considered responsible for the concave pressure drop rise on jet pulse cleaned bag filters. Linear model for pressure drop simulation based on uniform distribution of cake area load on partially jet pulsed bag filters are not appropriate (see Fig. 7 and 8). Distribution of cake area load is therefore an important aspect of jet pulse cleaned bag filter modeling.

Mean specific cake resistance, calculated from the average gradient of pressure drop curve, mean velocity, corrected dust concentration, and viscosity, remains nearly constant on thoroughly jet pulse cleaned membrane coated filter bags. It declines quickly to a steady value for the cake formed on PI+PPS needle felt filter bags from onset of dust feeding to the end of filtration cycle. Similar behavior is observed for membrane coated needle felt when only a fraction of filter area is subjected to jet pulses. The change of mean specific cake resistance indicates the prevalence of different cake characteristics. However, the trend can not be confirmed without independent cake height and density measurements. Thus the results reveal the importance of independent measurements of cake resistance.

Acknowledgements

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