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Effect of filtration velocity and dust concentration on cake formation and filter operation in a pilot scale jet pulsed bag filter

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Abstract

Bag filters are used for the removal of fine solid particles from process gases. Thus, understanding the filter cake build up and its properties is a subject of interest. The filter cakes properties may depend on many factors like, for example, filtration velocity and dust concentration. The effect of dust concentration and filtration velocity on filtration time, specific cake resistance and mean cake density is investigated in a pilot scale jet pulsed bag filter. An in situ optical system is used to measure cake thickness distributions on the filter surface. Additionally, the operation is simulated using a one-dimensional model and results are compared with experiments. The experimental results indicate that cake density and specific resistance increase with increasing velocity at constant dust concentration. The effect of dust concentration on filter cake density and specific resistance is small.

Keywords: Filtration velocity; Dust concentration; Bag filter operation; Cake formation; In situ thickness measurement

1. Introduction

Bag filters are used for the removal of fine solid particles from process gases [1]. Dust laden gas passes through the porous filter media forming a dust layer on the filter surface. The deposited dust, usually called as filter cake, is responsible for increasing pressure drop across the filter. The filter cake has to be removed either at the upper limit of pressure drop or at a pre-set filtration time to sustain a semi-continuous filter operation. Usually the process plants and hence the bag filters operate at steady gas flow. The gas flow is maintained by a downstream fan which provides the necessary head to overcome the increasing pressure drop across the filter. The dust cake is frequently removed by high pressure short duration reverse jet pulses. Intrinsically the filter operation is semi-continuous. Smooth operation of the filter is considered vital for the un-interrupted process operation. Thus, understanding the cake formation and cake properties is a subject of interest. Cake properties may depend on many factors like, for example, filtration velocity and dust concentration [1–3,5,8,9].

Mostly a one-dimensional flow and uniform distribution of cake area load (w), mass of filter cake per unit of filter surface area, is assumed for modeling filter pressure drop based on Darcy's law in the simplest approach [1]. Here the over all pressure drop is made up of two components; pressure drop across the conditioned filter (a filter that has been exposed to dust for some time), and pressure drop across the filter cake. The former is a function of filter permeability, filtration velocity, and fluid viscosity. The later depends on cake area load, dust concentration, filtration velocity, and a constant which accounts for cake properties, i.e. specific cake resistance. Up to now, the two parameters of the pressure drop equation have to be determined experimentally which are influenced by the operating conditions, dust and gas properties, and filter media [1].

Experiments with coal ash and char dust at high temperature with fabric filters made from ceramic fibers at dust concentration from 25,000 to 100,000 ppm (weight basis) and face velocity of 12–45 mm/s showed a linear increase in residual pressure drop with increasing velocity, and also an increase with increasing dust concentration [2]. Cake thickness was calculated using Carman–Kozney's equation because of no in situ measurements. Filter media was characterized in terms of permeability based on residual pressure drop. The filter cake formed at different filtration velocity may have different characteristics like porosity and specific resistance and, therefore, affects the cake formation

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Nomenclature

A	area (m^2)
c	dust concentration (g/m^3)
d	diameter (m)
l	length (m)
m	mass (kg)
N	number
Δp	pressure drop (Pa)
R	resistance (m^{-1})
t	filtration time (s)
u	filtration velocity (mm/s)
V	volume (m^3/s)
w	cake area load (kg/m^2)

Greek letters

μ	viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

c	cake
f	filter medium
max	maximum

and detachment. Effect of filtration velocity on cake compaction and cake resistance was studied by Ref. [3]. Cake resistance was found increasing with increasing filtration velocity. The cake thickness was measured using a laser displacement system. Cake porosity decreased and cake specific resistance increased with increasing velocity [4]. Increasing filtration velocity was reported to increase the mean particle size of the cake due to an altered segregation behavior of the incoming dust. Also the cake/fabric adhesion force was increased at the higher filtration velocity. Filtration velocity, in addition to pressure drop, also affected the cleaning performance of jet pulsed filters [5] in a study with fly ash and limestone dusts.

The effect of dust concentration and filtration velocity on filtration time, specific cake resistance and mean cake density is investigated in a pilot scale jet pulsed bag filter. An in situ optical system is used to measure cake thickness distributions on the filter surface. Additionally, the operation is simulated using one-dimensional model [8] and results are compared with experiments.

2. Experimental set-up

The experimental set-up (Fig. 1) consists of a dust feeder, dispersion unit, bag filter (three rows), a discharge fan, a jet pulse cleaning system, and measurement system for pressure drop and flow along with temperature and humidity. Data acquisition is continuous at 1s frequency. The filter cleaning starts at higher pressure drop and all bags are cleaned using one pulse per row of bags. The bag filter is designed to accommodate three rows of bags, two bags per row with total filtration area of 4 m^2. However, for the presented experiments one bag per row is employed with total filtration area of ~2 m^2 (πdlN). Where d is the diameter (0.12 m), l the length (1.8 m), and N is the number of bags (3). The filter houses a large glass window (448 mm × 1895 mm) on one side (Fig. 2). All bags are visible through the glass window. Thus, thickness measurements are possible from outside without disturbances to the cake. In front of the window is a stereo set-up (two complementary metal-oxide–semiconductor (CMOS) cameras and a light projector) mounted on a frame. The whole frame can be moved precisely vertically up and down for image acquisition. The robot motion is programmed and controlled from a computer interface. The set-up is presented elsewhere [6]. The optical thickness measurement technique is based on the principle of 'Stereo Vision'. Two images of the same object from different view are used to generate a 3D surface of cake. The clean bag surface is aligned after deformation to the bag behind the dust cake, which allows the relative height measurements. The reader is referred to Ref. [7] for details of the technique and its boundary conditions.

The filter is operated as normal. Before starting dust feed, the bags are jet pulsed, and images of the clean filter are acquired for reference. The dust feed is then started and filtration is performed. The pressure drop increases as the filtration continues.

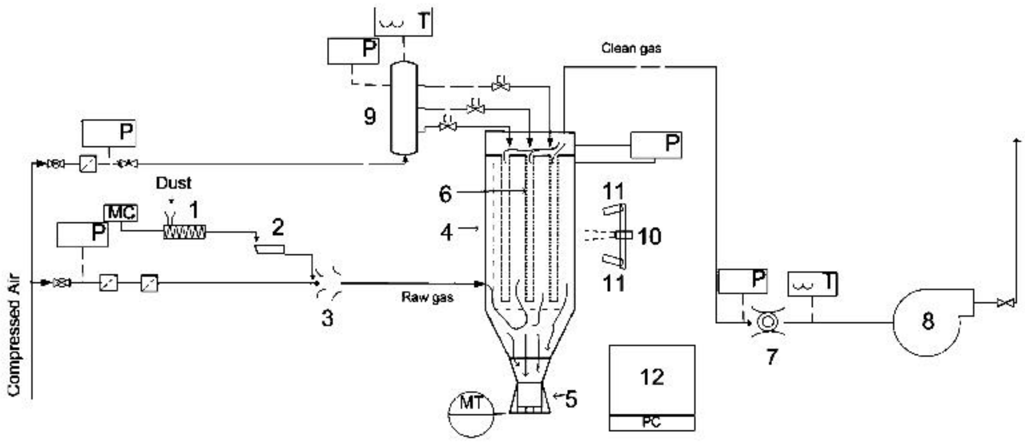

Fig. 1. Schematic of the filter test facility. (1) Dust feeder; (2) vibrator; (3) dispersion nozzle; (4) filter housing; (5) dust collector; (6) filter bags; (7) orifice plate; (8) centrifugal fan; (9) pulse air tank; (10) pattern projector; (11) CMOS camera; (12) data acquisition and storage.

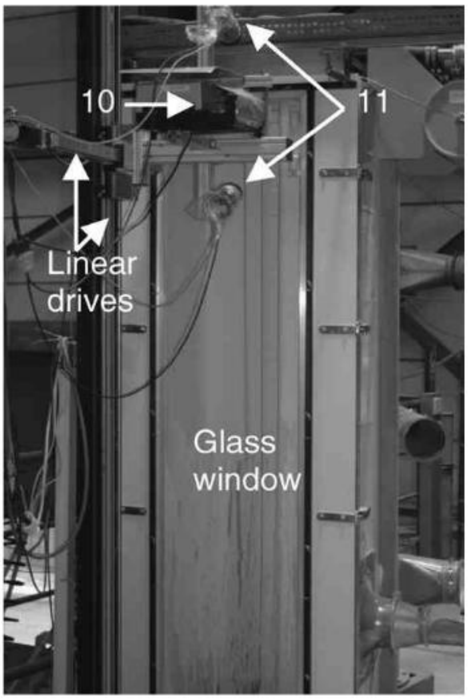

Fig. 2. A view of the optical measurement system (the stereo set-up).

The jet pulse cleaning is turned off. At the upper pressure drop limit (Δp_{max}) the dust feed is stopped while gas is flowing through the filter. When the gas is free of dust, the glass window is cleaned with double magnetic wipers from inside and outside. Then images of the filter surface are acquired. The jet pulse cleaning is turned on which removes the cake. All bags are cleaned with one pulse per each row one after the other. The gas is again allowed to become clean. The window is cleaned again and images are acquired. This allows the measurement of the residual dust distribution. Then dust feed is restored and filtration is continued. The procedure is repeated for different dust concentrations and filtration velocities. The images are processed and an arithmetic mean thickness is derived. The data of pressure drop, gas flow, dust feed and mass collected are manipulated to estimate the filtration time, specific cake resistance and cake density.

Limestone (OMYACARB 5 GU) with a weight mean diameter ($d_{50,3}$) of 5 μm, particle density of 2700 kg/m^3, and bulk density of 1200 kg/m^3 is used as dust. The filter bags are made of polyimide (PI) and polyphenylensulfide (PPS) needle felt. The felt has a specific weight of 624 g/m^3 and 73.5 l/dm^2 min permeability corresponding to 200 Pa pressure drop.

3. Filter model

The simulation is based on a model presented in [8]. The model assumes a number of areas based on classes of cake thickness at steady state filter operation. One equation based on D'Arcy's law for each area is used and the sum of individual flow streams equals total flow. The pressure drop is assumed to be uniform. The law of D'Arcy is defined as follows

$$\frac{dV}{dt} = \frac{A\,\Delta p}{\mu(R_c + R_f)} \tag{1}$$

where R_f represents the filter cloth resistance, which is assumed to be constant. R_c denotes the filter cake resistance, which is assumed to be proportional to the cake area load ($w = m/A$) on the filter surface:

$$R_c = \alpha_c \frac{m}{A} \tag{2}$$

4. Results and discussion

As expected, the slope of the transient pressure drop curve (Fig. 3) is higher at higher dust concentration and/or higher filtration velocity resulting in a decrease of filtration cycle time at the same upper pressure drop limit. Filtration cycle time decreases from 3388 to 3060 s at low dust concentration and from 2012 to 1560 s at higher dust concentration starting with thoroughly pulse cleaned bag filters provided the upper pressure drop limit remains the same (Fig. 4). Reduction of filtration time is due to some dust hold up on the bags after the previous filtration cycle. Moreover, also the upper pressure drop limit is slightly different (between 1233 and 1323 Pa) which also explains the changing filtration time. Of course, this reduction of the filtration time can also be attributed to an increasing specific cake resistance that was estimated assuming D'Arcy's law for a one-dimensional flow through the filter (Fig. 5). The filter cake resistance was obtained only from the linear section of the transient pressure difference profiles (see e.g. Fig. 3) leaving out the initial steep increase which is discussed in more detail by Ref. [9].

Under the premise of perfect filter cleaning and constant mean bag and actual cake resistance values (see Figs. 5 and 7, respectively), the filter operation is simulated. The simulated filtration cycle times are always higher than the experimentally observed ones but the trend is captured correctly (see Figs. 4 and 6). Starting from the clean bags the simulations predict pressure drop

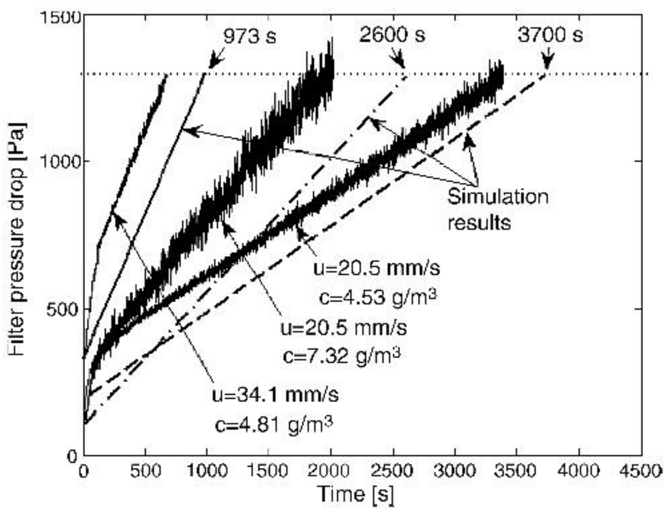

Fig. 3. Comparison of three transient pressure drop profiles at the beginning of the experiment, i.e. clean bags and simulated pressure drop curves taking filter medium and mean cake resistance as constant.

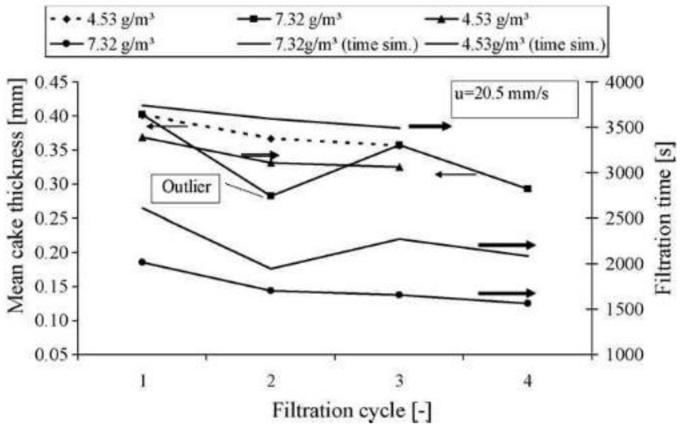

Fig. 4. Mean cake thickness and filtration cycle time for few consecutive filtration cycles at two dust concentrations ($c = 4.53$ and $7.32\ g/m^3$) and 20.5 mm/s filtration velocity (u).

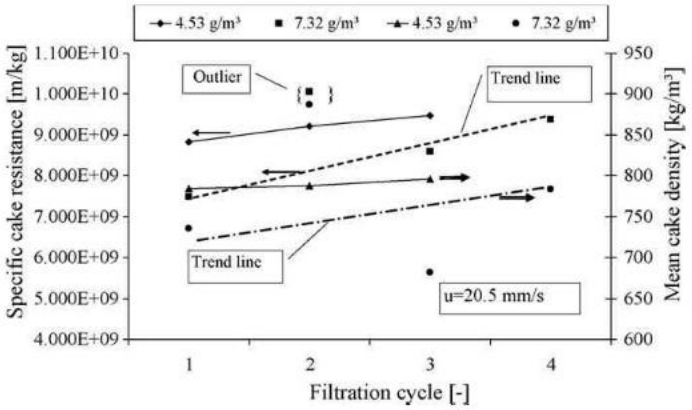

Fig. 5. Specific cake resistance and mean cake density for few consecutive filtration cycles at two dust concentrations and 20.5 mm/s filtration velocity.

using cake resistance parameter obtained from the linear part of the pressure drop curve. Therefore, between the same lower and upper pressure drop limits, the simulations predict a longer cycle than the experimentally observed (see Fig. 3 with simulation results). If the non-linear rise is considered, the mean cake

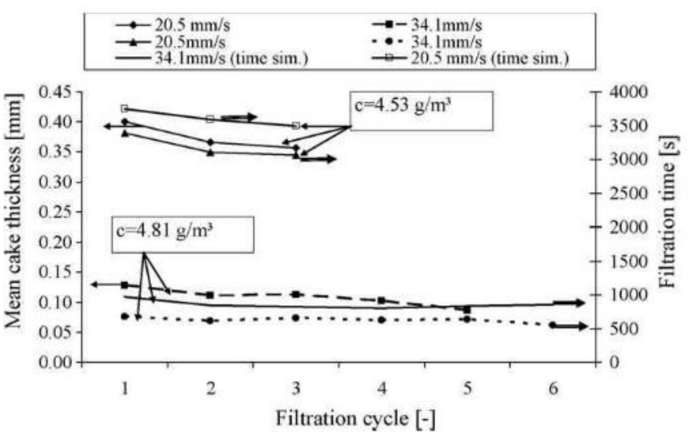

Fig. 6. Mean cake thickness and filtration cycle time for few consecutive filtration cycles at two filtration velocities ($u = 20.5$ and 34.1 mm/s) and dust concentration ($c = 4.53$ and $4.81\ g/m^3$). Filtration time from two simulations at corresponding filtration velocity and dust concentration is also presented.

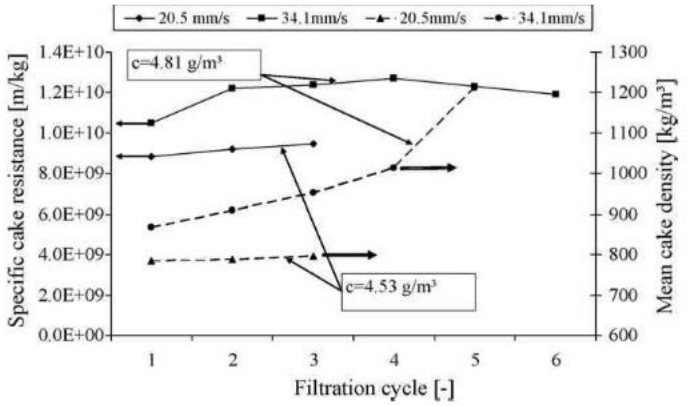

Fig. 7. Specific cake resistance and mean cake density for few consecutive filtration cycles at two filtration velocities ($u = 20.5$ and 34.1 mm/s) and dust concentrations ($c = 4.53$ and $4.81\ g/m^3$).

resistance parameter would be higher and a shorter filtration cycle would be predicted.

The in situ measured mean cake thickness is decreasing from first to the last filtration cycle at respective constant dust concentration. The mean cake density (Fig. 5) is calculated using corrected dust concentrations, gas volume flow, filtration cycle time, mean cake thickness, and filter area. The density is higher (785 compared to 735) at low dust concentration at the end of the first cycle. It increases from first to the last cycle in both cases. Data point 2 in data set corresponding to 20.5 mm/s and $7.32\ g/m^3$ is an outlier. The cake resistance is also higher at lower dust concentration and proportionately increases over cycles. At low dust concentration and constant filtration velocity, the filtration cycles are naturally longer. More compact cakes are formed which lead to higher cake density and cake resistance.

As expected a shortening of filtration time (Fig. 6) at higher filtration velocity at nearly the same dust concentration is found. The filtration time is again decreasing from the start of filtration to the end. At 20.5 mm/s the filtration time is 3387 s which reduces to 3060 at the end of third cycle at $4.53\ g/m^3$ dust concentration. At 34.1 mm/s filtration velocity, the filtration cycle time is only 674 s and decreases to 545 s in 6 cycles at $4.81\ g/m^3$ dust concentration. A small difference in dust concentrations (4.53 and 4.81) is due to different degree of dust settling in the filter.

The specific cake resistance and mean cake density (Fig. 7) are higher at higher filtration velocity. Fig. 8 shows the correlation between the average specific cake resistance and the filtration velocity where this trend is confirmed. Moreover, this graph also contains the results at different concentrations indicating that a higher dust concentration might have a reduction of the cake resistance as a consequence. However, this difference is not significant when looking at the error bars. Both, the specific cake resistance and the mean cake density, increase from start of filtration to the end again. At higher velocity, the increase in cake resistance seems to be leveled off after few cycles. However, the cake density is increasing. The reason may lie in the error in cake thickness measurement where the mean cake thickness is too low (<0.15 mm) at very low dust loads (<$200\ g/m^2$) and therefore percentage of error is higher.

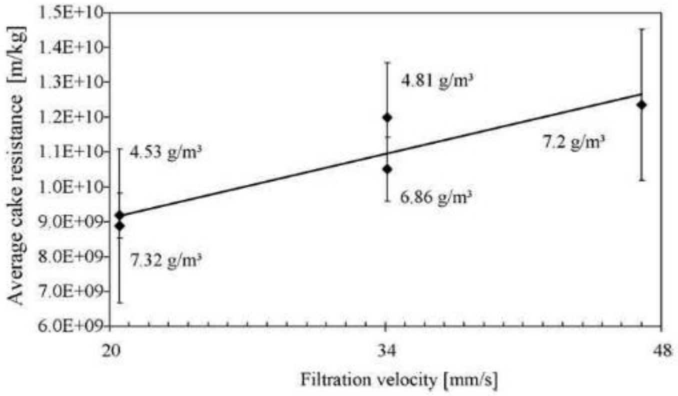

Fig. 8. Average cake resistance as a function of filtration velocity and dust concentration. Error bars are drawn at 95% confidence intervals.

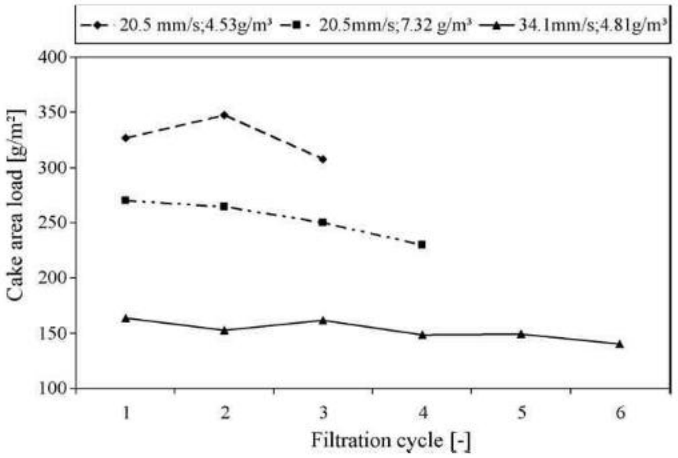

Fig. 9. Variation of cake area load at the end of filtration cycles for the three tests.

The cake area load (Fig. 9) at the end of filtration cycle varies with the dust concentration as well as filtration velocity due to shortened filtration cycles. Also in each case it is slightly decreasing over the cycles. Increasing cake resistance might be responsible for shortened filtration cycles which lead to reduced cake area load at constant dust concentration and gas flow conditions.

5. Conclusions and outlook

The experimental results indicate that the dust concentration has small influence on filtration operation at constant filtration velocity, and upper pressure drop level besides the obvious and proportional filtration time reduction with increasing dust concentration. The filtration velocity has a more pronounced effect as compared to dust concentration on pressure drop as well as cake properties, cake density and specific cake resistance. Specific resistance and density of filter cake are higher at higher filtration velocity at constant dust concentration. Cake density is also affected by dust concentration. A denser cake evolves at low dust concentration. Besides the obviously shorter filtration times at a higher filtration velocity but constant dust concentration, a more dense cake evolves and a higher cake resistance parameter is determined at higher gas velocities. However, the nature of this experimental evidence cannot be explained yet. Investigations with jet pulse pressure and cleaning mode will follow.

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