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Filter performance with non-uniformly distributed concentration of dust-evidence from experiments and models

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ABSTRACT

Cleanable fabric filters such as bag filters are widely used in industrial processes to remove large quantities of solid particles from gas streams. Intrinsically, such a filtration process is as non-uniform as it is semi-continuous; that is, filter cake build-up processes are successively followed by a short-duration cleaning step. Moreover, heterogeneous flow conditions and, thus, concentrations of particles entering the filter housing and flowing toward the filter contribute to rather non-uniform filter conditions. Since cleaning is not necessarily performed in a homogeneous manner, and patches of cake might remain on the filter fabric, the subsequent filtration is also non-uniform. Finally, the filter medium itself is largely heterogeneous certainly on micro-, but often also on a macro-scale.

The influence of a heterogeneous dust concentration as a common filter non-uniformity is investigated on filter performance, i.e., pressure drop increase as a measure for filter cycle cleaning frequency being a precursor for filter life-time, dust emissions and operating costs.

Laboratory tests were performed whereby the pressure increase curves are recorded at basically constant gas flow. As a baseline the entire filter area was exposed to a homogeneous dust concentration. Comparatively the filtration area was split into two zones where cake formation occurred under a high and a low particle concentration mimicking a distinctive heterogeneous dust concentration situation. The transient pressure increase profiles of both, the homogeneous and heterogeneous cake formation situation, were compared with each other.

The apparent filter cake resistance was slightly higher under homogeneous dust concentration conditions, i.e., the pressure drop increased faster compared with the situation of a heterogeneous dust concentration. These results suggest that, in practical terms, a filter exposed to non-uniform dust concentrations exhibits a better overall performance. Consequently aiming for a most uniform dust concentration is to no avail, though often intended in industrial operation.

1. Introduction

The removal of fine particles from large gas streams is often accomplished using bag or envelope filters [1]. The particle laden gas stream enters the filter medium, and particles are retained on the surface of the filter medium, effectively resulting in the accumulation of layers of particles (i.e., filter cake). Both the filter medium and filter cake are highly efficient particle removal tools, which result in an almost entirely particle-free gas stream. Large process installations are preferentially operated under conditions of continuous gas flow. In order to maintain continuous process operations, a gradual increase in pressure as measured across the filter as a consequence of filter cake build-up is permitted. Periodically, the filter is cleaned – often by applying short-term, high-pressure pulses of air in the reverse direction or mechanical shaking – removing the filter cake and restoring a lower pressure level, which leads to semi-continuous process operation conditions.

The number most relevant to filter design is the so-called air to cloth ratio, which relates the gas volume flow to the available filtration surface area. These numbers have been derived for a certain combination of dust, gas and filter medium properties mostly on the basis of experience or the results of laboratory tests. Löffler et al. [1] and Gabites et al. [2] give an overview of the filter design guidelines available. Requests for maintenance, cake cleaning and removal, as well as improvements in overall filter unit size have led to the development of either cassette- or bag-type filters with the minimum of spacing between the bags/cassettes, which prevents the immediate re-deposition of the cake on adjacent filter elements after cleaning [3,4]. Single filter units have been increasing in size in terms of the number of their filter elements and element size (i.e., bag length) [5]. Filter unit design has been, therefore, confronted with a challenge to provide for the uniform distribution of gas and particles, respectively, throughout the filter.

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In general, the filter medium and the steadily growing filter cake are the dominant contributors to flow resistance and lead to a relatively homogeneous gas distribution in the filter housing [2]. A direct flow impact on the filter elements located in the immediate proximity of the gas entrance is only prevented by redirecting the flow through guiding plates [6]. However, particles do not strictly follow the gas flow [9], and, as the filter size and residence times increase, particle settling occurs. This especially occurs when particle aggregates are present, which aids overall particle removal. Moreover, particle segregation can also be an issue that leads not only to lower particle concentrations, but possibly to different particle bulk properties [7]. Since the larger particles preferentially settle, the smaller particles remain and tend to form more challenging filter cakes [8] (i.e., cakes with higher specific flow resistances and that are more difficult to clean). The occurrence of such a situation is difficult to predict and account for when designing filters. For these reasons and because the entire filter experiences homogeneous wear and tear, filter units have been designed to ensure a homogeneous situation by, for example, compartmentalizing the filter and ensuring constant gas velocities irrespective of the location of the compartment by altering the cross sectional area of the gas distribution channels [6].

In general, experimental tests aim for homogeneous conditions particularly when using standardized test stands such as [18]. The influence of different filter media, test dusts or operating conditions on the filter performance (e.g. in terms of rate of pressure increase or dust collection efficiency) is determined by a comparison of respective test results (see e.g. [10]). Of course, filter media are often quite inhomogeneous locally in terms of their permeability due to their set-up and how they are produced [11,22]. On the other hand, pilot scale tests are intrinsically heterogeneous in nature since they resemble the large scale situation more closely [12]. But the heterogeneity is difficult to quantify and thus the obtained test results are valuable for scale-up but difficult to interpret in terms of governing mechanisms and particularly compensating effects that are problematic to extract from overall performance data such as a transient pressure drop rise or volume flow decrease. Theoretical methods [13] as well as in-situ measurement techniques as described by [14,15] help to quantify non-uniformities and their transient development. In this study ([14]) a used filter fabric sample was exposed to a test dust and it was observed that cracks are filled of an existing filter cake with dust more readily during a filtration cycle indicating that ultimately the overall filter performance tends to become more homogeneous. The influence of the gas flow uniformity on the filter performance was investigated by [16] and they found that a more homogeneous flow results in a more even particle deposition and thus a better overall filter performance in terms of particle collection efficiency as well as a longer duration of the filtration cycle. However, a transient compensating effect was not allowed for. While an attempt to homogenize the situation in a filter would intuitively seem to be logical, it is questionable whether the strong self-equilibrating capacity of the filter renders any geometrical aspects or design measures moot, at least in terms of the most dominant and immediate filter performance responses, with respect to the transient pressure drop that occurs across the filter [17].

In this research, an experimental and numerical study of the influence of uneven concentrations of dust on cake filtration has been carried out. The chosen setup was derived from a standard gas filter test stand, which was modified to mirror filtration with a distributed concentration of sample dust on the raw gas side. The filtration in the setup was simulated using a filter model specifically adapted from those described in the literature.

2. Experimental

The experimental setup consisted of a rotating brush feeder (PALAS RBG-2000) which was used to disperse standard sample dust. The filtration took place in a modified VDI/ISO 3926 Type 2 filtration test stand [18]. The filter medium sample used was a Gore membrane filter bag sample with a 150 mm diameter effective filtration area. The gas (air) was sucked through the setup by an induced draught compressor, and the volume flow was adjusted by a restrictor valve attached to a suction line that led to the compressor. A schematic flow sheet of the test stand is shown in Fig. 1.

Instrumentation used was a capacitive differential pressure transducer (Keller PD-41) that was used to measure the pressure drop across the filter medium in the range of $\Delta p = 0$–5000 Pa, and which was installed according to the VDI/ISO 3924 standard. In addition, the absolute (under) pressure on the raw gas side was recorded (Keller PAA-23S). The volume flow was measured beyond the restrictor valve on the filtered gas side by means of a critical nozzle. The vacuum downstream from the nozzle was typically held at less than 0.2 bar absolute pressure. The restrictor and nozzle valve together were responsible for about 90% of this under pressure. Thus, the volume flow was independent of the pressure drop caused by the filtration rig. The test rig and measurement equipment were designed for experiments up to a pressure drop of 5000 Pa maximum though most tests were performed in the range up to 1500 Pa which is a typical range in practise.

In order to be able to adjust the profile of the dust concentration (in a stepwise manner) in the raw gas that reached the filter medium, the VDI/ISO 3926 rig was modified on the raw gas side. Unlike the original design, which allowed for the ambient air to be sucked in an uncontrolled way together with the air containing the dust dispersion, the 400 mm long cylindrical raw gas channel was closed off with a cone identical to that on the clean gas side. The dust feeder was connected axially to this cone. Since the total gas volume flow being sucked through the rig was typically higher than the dispersion air flow, an opening for ambient air was provided, offset by 90° radial to the pressure measurement nozzle (i.e., 200 mm before the filter medium). A rotameter with another restrictor valve was connected to this opening. The rotameter was used to measure the volume flow into the raw gas channel and control it with its restrictor valve. The setup basically resembled the standard rig, which can be used to measure the additional ambient air volume flow (although that was, of course, not necessary, since the total volume flow through the filter was measured anyway).

The standardized test rig was further modified so that additional experiments with different dust concentrations could be carried out: a separation wall that extended to the surface of the filter medium was inserted vertically in the cylindrical part of the raw gas channel, thereby dividing the raw gas channel into two sections. The edge of this separation wall, which faced the filter medium, was adapted to fit the form of the filter medium (i.e., concave due to the differential pressure applied). The inlet that provided additional ambient air was attached to only one of the channel sections, and thereby only diluted the dust-laden gas in this section. On this side, which is the right side of the raw gas channel illustrated in Fig. 1, a lower dust concentration than on the other side was created by dilution. Experiments were carried out with and without this separation wall installed.

An experimental run was conducted by disconnecting the dust feed from the raw gas channel inlet. The gas flow was then turned on and adjusted to the desired value. Nearly the entire volume flow was sucked into the raw gas channel though the hose that led to the dust feeder, since the flow resistance in that 1/4" hose was much lower than that in the rotameter or the tube connected to provide additional ambient air. The rotary dust feeder was turned on, but remained disconnected. A pressure regulator was used to adjust the dispersion air pressure of the feeder. It was possible to make slight adjustments to the dispersion air volume flow by altering the dispersion air pre-pressure. The dust feeder manual included a quantified relation between the pre-pressure and volume flow, which, however, was not accurate enough for the current experiments. After operating the dust feeder for about one minute, the hose was connected between the feeder and the raw gas channel. The dust laden gas entered the channel and a slight under-pressure built up. As a consequence, the ambient air that was