Modeling the pressure drop behavior of cleanable dust filters during pressure-controlled operation

T. Laminger, M. Stecher, G. Mauschitz, and W. Höflinger

Vienna University of Technology, Institute of Chemical Engineering, Getreidemarkt, Vienna, Austria

ABSTRACT
Cleanable dust filter media are typically used in huge baghouse filter apparatuses. Thereby, the regeneration by back-pulsing from the clean gas side is done by either time-controlled or pressure-controlled operation, whereas the latter is more common. Hence, the need for a detailed knowledge of the clogging and filtration mechanisms during long time operation of a pressure-controlled filter aging arises.

A mathematical model describing the pressure drop evolution during time-controlled filter aging has been developed. The core of the developed model is the concept of dust masses that distribute themselves on a specific particle deposition area inside and on the surface of the filter medium. By altering this particle deposition area, various clogging mechanisms, occurring during an aging procedure, are covered by the model.

In this work, the model was adapted and coefficient parameters adjusted for pressure-controlled filter regeneration operation. A multitude of pressure-controlled test runs were performed in a specially designed filtration apparatus. From these tests, process-specific parameters were regressed and used to model the respective pressure drop curves. These model pressure drop curves show good accordance both quantitatively and qualitatively to experimental data and give a detail view on different clogging mechanisms.

Introduction
Because of their high fine dust filtration capacity, along with more stringent fine dust emission limits, cleanable dust filter media gain importance in the dedusting industry. The large number of influencing parameters (e.g., filter face velocity, raw gas concentration, and regeneration intensity) makes it difficult to predict the long-term clogging and pressure drop behavior of a certain filter medium.

There are various national standards specifying test procedures and lab-scale test rigs to get standardized results of filter media samples within hours and days (e.g., ISO 11057:2011,[1] ASTM D6830-2[2], JIS Z 8909-1,[3] GB/T 6719[4]). To get as close as possible to industrial filtration and cleaning behavior, the aging procedure of these standards has been adjusted within the past few years. Aging hereby is referred to the process in which a filter medium is exposed to a large number of filtration and regeneration cycles in a short period of time to simulate a long operation time. Intensive experimental studies on various filter test rigs have shown that a desired quasi-stationary residual pressure drop cannot be guaranteed. The clogging of a filter medium appears within a very broad time range and is strongly depended on operating parameters such as cycle time, filter face velocity, and valve opening time.[5–7]

As experimental filter tests are extensively time consuming, the prediction of the filtration and regeneration behavior of cleanable filter media can be done by simulation. The profound knowledge and integration of various filtration mechanisms such as depth filtration, surface filtration, and incomplete regeneration (e.g., patchy cleaning) have been successfully used to describe the development of pressure drop and filtration time for either a comparable low or high number of cycles.[8,9]

Duo et al.[10,11] modeled the patchy cleaning mechanism by probability theory, where the incomplete regeneration depends on the ratio of cleaned filter area to the entire filter area. This means that the dust cake is removed with a certain, predetermined probability, which also depends on how long (number of cycles) the dust adhering to patches is already on the filter medium. The incomplete regeneration causes an irregular dust distribution on the filter medium, thus

CONTACT T. Laminger thomas.laminger@tuwien.ac.at Vienna University of Technology, Institute of Chemical Engineering, Getreidemarkt 9/166, Vienna, 1060 Austria

Published with license by Taylor & Francis Group, LLC © 2017 T. Laminger, M. Stecher, G. Mauschitz, and W. Höflinger

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
influencing the flow conditions and flow resistances in the following filtration cycle and increasing the pressure loss thereof.

Stecher[12] picked up this approach for describing the pressure drop evolution during time-controlled filter aging. Experimental results using a modified VDI 3926 type 2 test rig[13] (“aging chamber”—details are given in chapter 3) with a broad variation of filter media, cleaning intensity, and test dusts showed good agreement with simulation results, and thereby, coefficient parameters could be extracted and used to study their influence on a certain filtration situation.

For industrial application, the pressure-controlled regeneration is much more interesting. Therefore, the aim of the present work is to adjust the existing mathematical model as well as the coefficient parameters that allow describing the pressure drop slope during pressure-controlled filter aging. Experimental data from filter tests using the “aging chamber” filter test rig are used to regress these coefficient parameters.

Model subject

Figure 1 shows a typical pressure drop slope during pressure-controlled aging in the aging chamber. From the initial pressure drop of the filter medium \(\Delta p_0\) (also Fig. 2), the pressure drop across the filter medium rises at the margin of the cake pressure drop \(\Delta p_K\) as dust is deposited in and on the filter medium. After a maximum pressure drop \(\Delta p_A\) has been reached, the filter medium is regenerated by jet-pulse-cleaning. Because of an insufficient filter regeneration, the residual pressure drop \(\Delta p_R\) increases, and the filtration cycle duration \(t_Z\) decreases with filtration cycle number \(N\).

When the curves of the pressure drop are analyzed in detail, the same filtration mechanism can be observed as found by time-controlled filter aging: from the initial depth filtration, on the patchy cleaning through to cake filtration.[14,15]

At pressure-controlled filter aging, the constant maximum pressure drop \(\Delta p_A\), according to Eq. (1), is the sum of the residual pressure drop \(\Delta p_R(N)\) and the pressure drop of the removed filter cake \(\Delta p_C(N)\) for each filtration cycle number \(N\) (see Fig. 2). Thereby, the pressure drop of the removed dust filter cake \(\Delta p_C(N)\) for filtration cycle number \(N\) equals the pressure drop of the build-up dust filter cake \(\Delta p_K(N+1)\) of the filtration cycle number \(N+1\).

\[
\Delta p_A = \Delta p_R(N) + \Delta p_C(N) = \Delta p_R(N) + \Delta p_K(N + 1) \quad (1)
\]

\[
\Delta p_R(N) = \Delta p_A - \Delta p_K(N + 1) \quad (2)
\]

The build-up dust filter cake of each filtration cycle \(\Delta p_K(N)\) is a function of the mass of filter cake, respectively, for a constant dust concentration of the filtration cycle duration \(t_Z(N)\). Therefore, to describe the whole pressure drop evolution of a pressure-controlled filter aging for a large number of filtration cycles, at least two models are needed: one equation model for the

![Figure 1. Pressure drop and filtration cycle duration as a function of the filtration cycle number for pressure controlled filter aging.](image-url)
filtration cycle duration and a second equation model to describe the evolution of the residual pressure drop.

Filtration cycle duration $t_2(N)$

The filtration cycle duration $t_2(N)$ is the time that is available for filtration in one filtration cycle $N$ until the predetermined maximum pressure drop $\Delta p_A$ is reached (Fig. 2). The filtration cycle duration is highly dependent on the operating parameters, in particular the filtration rate, the raw gas concentration, and the filter medium itself. Furthermore, the filtration cycle duration is steadily declining with each filtration cycle as the residual pressure drop $\Delta p_R(N)$ increases with each filtration cycle due to the insufficient filter medium regeneration (Fig. 1).

A mathematical approach of the filtration cycle duration $t_2(N)$ can be done by a power function:

$$t_2(N) = t_1 * (N)^{-j_1}$$  \hspace{1cm} (3)

where $t_2(N)$ filtration cycle duration of filtration cycle $N$ [s] $t_1$ filtration cycle duration of the first filtration cycle [s] $j_1$ time coefficient [-] $N$ filtration cycle number [-]

Residual pressure drop $\Delta p_R(N)$

To calculate the residual pressure drop $\Delta p_R(N)$ from Eq. (2), for the build-up dust filter cake $\Delta p_K(N+1)$, a well-known cake equation\(^\text{[16]}\) is used:

$$\Delta p_K(N) = \Delta p_A - \frac{\dot{V} \cdot \eta \cdot \alpha_K \cdot m_A(N + 1)}{A_K(N + 1)^2}$$  \hspace{1cm} (4)

where $\dot{V}$ air volume flow rate [m$^3$/s] $\eta$ air viscosity [Pa·s] $\alpha_K$ averaged specific filter cake resistance value [m/kg] $m_A(N+1)$ build-up dust mass of the filtration cycle N+1 [kg] $A_K(N + 1)$ averaged particle deposition area of the filtration cycle N+1 [m$^2$]

Dust mass $m_A(N)$

In Eq. (4), the build-up dust mass of the filtration cycle $m_A(N)$ is defined as the mass of dust separated at averaged particle deposition area $A_K(N)$. The total mass for each filtration cycle is thereby a function of the filtration cycle duration $t_2(N)$ (Eq. 3) and the constant parameters air volume flow $\dot{V}$ and dust concentration $c$ (assuming a 100 percent separation of the particulates from the raw gas):

$$m_A(N) = \dot{V} * c * t_2(N) = \dot{V} * c * t_1 * (N)^{-j_1}$$  \hspace{1cm} (5)

Averaged particle deposition area $A_K(N)$

The dust that becomes separated by the filter medium is responsible for the pressure drop increase with time. Thereby, different filtration mechanisms determine where the dust becomes collected.

Typically, depth filtration at the start of a filter aging test occurs.\(^\text{[14,15]}\) Thereby, the dust becomes separated within the high internal fiber surface of the filter medium, which has an averaged particle deposition area $A_K(N)$ larger than the filter face area $A_\phi$. The shape of the pressure drop within such a filtration cycle is convex. By an incomplete regeneration of the filter, the internal fiber surface of the filter media is permanently covered with dust and no longer available for dust to be deposited. Therefore, the averaged particle deposition area decreases with the filtration cycle number $N$.

With ongoing filter regeneration at a certain filtration cycle number $N_\phi$, the dominant filtration mechanism changes from depth filtration to patchy cleaning.\(^\text{[14,15]}\) Inhomogeneities of the filter medium and the clogging of certain flow channels through the filter medium can cause the formation of preferential flow channels through the filter medium. The constant air flow through the filter chooses the path through these flow channels due to the comparatively low flow resistance there. As a result, flow velocities increase locally with a corresponding strong increase in pressure drop. The dust particles are thus deposited on a comparatively smaller particle deposition
area. Regarding the filter medium as channel-like porous structure, preferred flow channels can be filled within a filtration cycle again by the deposited dust, whereby the flow resistance increases at these flow channels to a higher level, which corresponds to the surrounding denser fiber structure of the filter medium. Through this resistance balancing, the separated particles now spread over a larger particle deposition area again, and respectively the averaged particle deposition area $A_K(N)$ rises.

To cover the change from depth filtration to patchy cleaning, whereas on the one hand side the averaged particle deposition area firstly decreases and on the other hand side increases with the filtration cycle number $N$, a parabolic function can be formulated:

$$A_K(N) = A_0 \cdot [(N - N_x)^2 + j_2] \quad (6)$$

- $A_0$, filter face area [m²]
- $N_x$, filtration cycle number where the dominant filtration mechanism changes from depth filtration to patchy cleaning [-]
- $j_2$, filter area coefficient [-]

As can be seen in Eq. (6), the averaged particle deposition area passes a minimum at filtration cycle number $N_x$. Firstly, the averaged particle deposition area decreases until filtration cycle number $N_x$ is reached, and thereafter, the averaged particle deposition area becomes larger again.

Including Eqs. (5) and (6) to Eq. (4), a model equation for the residual pressure drop $\Delta p_R(N)$ as a function of the filtration cycle number $N$ follows:

$$\Delta p_R(N) = \Delta p_A - \frac{\bar{V} \cdot \eta \cdot \alpha_K \cdot \bar{V} \cdot c \cdot t_1 \cdot (N + 1)^{-j_1}}{A_0^2 \cdot [(N + 1 - N_x)^2 + j_2]^2} \quad (7)$$

All process-specific constant parameters $\eta$, $\alpha_K$, $c$, $t_1$, and $A_0$ can be summed up to one single constant value $j_0$ to give finally:

$$\Delta p_R(N) = \Delta p_A - j_0 \frac{\bar{V}^2 \cdot (N + 1)^{-j_1}}{[(N + 1 - N_x)^2 + j_2]^2} \quad (8)$$

- $j_0$, process-specific constant value [kg/m²]

With Eq. (8), the residual pressure drop can now be described for pressure-controlled filter aging. In the numerator of the right term, the declining dust cake mass per filtration cycle is essentially described. In the denominator, the average particle deposition area is given that passes through a minimum depending on the dominant filtration mechanism.

**Filter aging chamber for experimental filter tests**

To study experimentally the development of the filtration cycle time and residual pressure drop over filtration cycle number, the “aging chamber” (Palas®) was used. The schema of the apparatus is shown in Fig. 3.

The aging chamber bases on the VDI 3926 type 2 filter test rig with some modifications for long-time operation. The aging chamber is equipped with an identical control and measurement technique as the standard type 2 filter test rig by Palas. The regeneration of the dust loaded round filter sample (150 mm diameter) is done by compressed air (pulse-jet cleaning). The main modification consists in a vertical arrangement of the air channel with additional dust hopper. This dust hopper allows to achieve thousands of cleaning intervals without opening the raw gas air channel to remove the rising dust cake in front of the filter sample, which can occur in a horizontal air channel arrangement.

During pressure-controlled filter tests, the pressure drop over time was continuously measured until the filter sample was clogged completely (determined by a filtration cycle time of <3 seconds). From this data, the residual pressure drop and the filtration cycle time were derived for each filtration cycle number.

To fit the modeled equation and to regress the process constants, a set of data was used from filter tests using a calendared PI needle felt. A test series was performed whereas additionally the pressure of the pressure tank was changed (3, 4, 5, and 6 bar). Table 1 summarizes the further test parameters of the filter tests.

**Comparison of experimental and modeled data**

To demonstrate the usability of the model Eqs. (3) and (8), the data set of the experimental filter tests (see chapter 3) are used. Thereby, the pressure drop over time was continuously measured, and the residual pressure drop and the filtration cycle duration were determined.

Equation (8) was implemented in the software “Origin Pro” as a user-defined-function to regress the model equations coefficient (listed in Table 2) by non-linear curve fitting with chi-square minimization.

The obtained model curves are shown in Fig. 4 and compared to the experimental data. A good quantitative and qualitative agreement between both curves can be seen, which demonstrates that the model equation is suitable to calculate the pressure drop and the filtration cycle duration for pressure-controlled filter aging.

**Table 1**

| Process Constants | Data Range |
|-------------------|------------|
| $\eta$            | 0.01-0.05  |
| $\alpha_K$        | 0.1-0.3    |
| $c$               | 0.5-1.0    |
| $t_1$             | 0.1-0.5    |
| $A_0$             | 10-50      |

**Table 2**

| Model Equations Coefficient | Value |
|----------------------------|-------|
| $\alpha_K$                 | 0.25  |
| $c$                         | 0.75  |
| $t_1$                       | 0.35  |
| $A_0$                       | 15    |
A study of the regressed model equations coefficients (Table 2) allows a detailed view on how different filtration mechanisms depend on the variable test parameters tank pressure and valve opening time. For example, for the time coefficient \(j_1\) (see Eq. 3), a clear influence of the tank pressure can be seen. With a comparable low tank pressure, the filter gets clogged quicker, expressed by a high time coefficient \(j_1\).

A study of the total number of filtration cycles (Fig. 4), together with the coefficient value \(N_x\) (Table 2), allows to study how long the depth filtration mechanism or the patchy cleaning filtration mechanism is dominant. Table 2 shows that the coefficients \(N_x\) stay at low values (<50), whereas the total number of filtration cycles increases with higher tank pressure (Fig. 4). This indicates that patchy cleaning arises relatively more at higher tank pressure and dominates the long-term filter clogging mechanism at these filter tests.

The good agreement of experimental data and modeled functions showed that the model is capable of describing the different clogging mechanisms that occur during a pressure-controlled aging procedure in a laboratory test rig. Although the quantitative values of the process-specific constants cannot be easily compared to each other, they are useful for a detailed
study of the implemented filtration mechanism during long-time operation within a set of data found by parameter variation (e.g., valve-opening time, dust concentration, test dust variation, and tank pressure).

Summary
To predict the long-term filtration behavior of cleanable dust filter media, they are aged in laboratory filter test rigs such as the VDI 3926 type 2, although the aging procedure can also be done in an aging chamber (by Palas GmbH). A mathematical model describing the pressure drop evolution during time-controlled filter aging has been developed, and in this work, the existing model was adapted for pressure-controlled filter regeneration.

A fundamental concept of the model is the dust masses that distribute themselves on a specific particle deposition area inside or on the surface of the filter medium. By altering this particle deposition area, various clogging mechanisms, occurring during an aging procedure, are covered by the model. Thereby, depth filtration is mathematically traced back to a surface filtration mechanism. For describing the depth filtration, the averaged particle deposition area exceeds the filter face area. To include patchy cleaning mechanism, the averaged particle deposition may underrun the filter face area when the airflow is distributed comparatively unevenly across the filter medium due to the inhomogeneous filter medium itself or due to inhomogeneous dust depositions.

A multitude of pressure-controlled test runs were performed in a specially designed filter aging chamber. From these tests, process-specific coefficients were regressed and used to model the respective pressure drop curves. These model pressure drop curves show good accordance both quantitatively and qualitatively to experimental data and give a detailed view of different clogging mechanisms. From the analysis of the observed experimental data and regressed model’s constants, it was elaborated that a higher tank pressure shifts the long-time dominating filtration mechanism from depth filtration to patchy cleaning.

Funding
The authors acknowledge the TU Wien University Library for financial support through its Open Access Funding Program.

References
[1] ISO 11057. (2011) Air quality - Test method for filtration characterization of cleanable filter media.
[2] ASTM D6830-02. (2008) Standard test method for characterizing the pressure drop and filtration performance of cleanable filter media.
[3] IS Z 8909-1. (2005) Test method of filter media for dust collection — Part 1: Filter efficiency.
[4] GB/T 6719. (2009) Specifications for bag house.
[5] Höflinger, W.; Schuberth, J.; Mauschitz, G. (2009) Untersuchung des Alterungsvorgangs von abreinigbaren Staubbfiltermedien bei zeitgesteuerter Abreinigung. Gefahrstoffe Reinhaltung der Luft, 5: 180–188.

[6] Gäng, P. (1997) New approach to filter-testing and measuring of data for the design and operation of cleanable filters. Proceedings of the AFS Annual Conference, Minneapolis, MA, USA.

[7] Binnig, J.; Meyer, J.; Kasper, G. (2005) Influence of operating conditions and aging procedure on the emissions and operating performance of surface filters. Conference proceedings of FILTECH 2005, II: 131–138.

[8] Thomas, D.; Contal, P.; Penicot, P.; Leclere, D.; Vendel, J. (2001) Clogging of fibrous filters by solid aerosol particles Experimental and modelling study. Chemical Engineering Science, 56: 3539–3561.

[9] Mao, N.; Otani, Y.; Yao, Y.; Kanaoka C. (2006) Modeling the filtration process with a flat-type fabric filter. Advanced Powder Technology, 17: 237–256.

[10] Duo, W.; Kirkby, N.F.; Seville J.P.K.; Clift, R. (1997) Patchy cleaning of rigid gas filters – I. A probabilistic model. Chemical Engineering Science, 52: 141–151.

[11] Duo, W.; Seville, J.; Kirky, N.F.; Büchele, H.; Cheung C.K. (1997) Patchy cleaning of rigid gas filters – II. Experiments and model validation. Chemical Engineering Science, 52: 153–164.

[12] Stecher, M.; Mauschitz, G.; Höflinger W. (2012) Influence of test dusts on the aging behaviour of different cleanable dust filter media”, Proceedings of World Filtration Congress WFC11, G7.

[13] VDI-Guideline 3926 Part1. (2004) Testing of cleanable filter media: Standard test for the evaluation of cleanable filter.

[14] Stecher, M.; Mauschitz, G.; Höflinger, W. (2013) Modeling the pressure drop of cleanable dust filter media during aging in laboratory test rigs. Conference proceedings of FILTECH 2013, Nr. 074.

[15] Stecher, M. (2014) Analyse der künstlichen Filtermittelalterung bei der Abreinigungsfiltration und Modellierung der damit verbundenen Verstopfungsverläufe. PhD Thesis, Vienna University of Technology, Austria.

[16] Löffler, F.; Dietrich, H.; Flatt, W. (2000) Staubabscheidung mit Schlauchfilters und Taschenfiltern, 2nd Ed.; Springer: Karlsruhe, Germany.