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Influence of regeneration variables during backwashing treatment into gas-phase after liquid filtration

Patrick Morsch[a,*], Pascal Ginisty[b], Harald Anlauf[a], Hermann Nirschl[a]

[a] *Institute for Mechanical Process Engineering and Mechanics (MVM), Process Machines (VM), Karlsruhe Institute of Technology (KIT), Germany*
[b] *Institut de la Filtration et Techniques de Séparatives (IFTS), France*

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ABSTRACT

In industrial solid/liquid separation, the removal of fine particles occurs in a wide array of industrial production applications and can be found in nearly every process plant. Especially the cake filtration is emphasized as advantageous principle for separation of suspension with a low solids content (0.01–1 v/v %). To maintain the separation performance, it is required to replace or regenerate the used filter cloth. The latter one can occur through backwashing treatment into liquid or gas phase whereby the gas discharge required an upstream drying process. The main task of that regeneration procedure is a most complete filter cake discharge to reduce the flow resistance of the filter for the subsequent filtration step. Recommendations for advantaged process variables doesn't exist and should be evaluate during this investigation. Investigations regarding to the regeneration procedure has shown, that the cake discharge into gas phase has significant differences to the discharge into liquid phase. Whereas the discharge into gas phase is created through an impulse, the liquid discharge can be interpreted as a slide on the filter cloth surface. Moreover, the backwashing variables are highly different (influence of backwashing pressure, filter cake thickness) between the different backwashing environments as a result of the characteristic surface forces. In this work, main attention is given to the particle system (particle size and filter cake thickness), the different weave types, assembly of the filter cloth and, of course, the backwashing pressure. The difference between a discharge in gas phase and liquid phase is described and its effect on the quality of the regeneration.

1. Introduction

Separation and recovery/recycling of particles separated from liquid streams are commonly used techniques to reduce waste streams, save operating material, and increase the economic efficiency of the process. They are applied for the removal of impurities from salt water streams for electrochemical processes, recovery of catalytic particles in pharmaceutical processes, removal of activated carbon in corrosive solutions, and cleaning of process streams in the natural gas and petrochemicals industries. Separation is particularly profitable in case of low concentrated suspensions. Depending on the valuable product to be separated, two types of filtration processes are distinguished.

In case of clarification filtration, the valuable product is the liquid phase and any particles contained must be removed, as they contaminate the liquid. Here, regeneration starts directly with the subsequent filtration step. The detached filter cake deposits on the bottom of the filter vessel and get removed. Secondly, separation filtration may be aimed at removing the particles as the valuable product. In this case, subsequent process steps, such as washing out of liquids and drying, are needed. It may be necessary to dry the built-up filter cake mechanically before discharge in the gas phase.

In both cases the periodic discharge of the filter cake and particle cluster from the surface is required. The latter is already part of research projects [1,2], whereas the cake discharge into the gas phase is only known from the previous filtration in gas phase [3]. The cake discharge in gas phase from previous liquid filtration is only known from vacuum filtration with continuous filters and is therefore the content of this paper for discontinuous filters. Regeneration occur with an reverse gas impulse from inside the filter cloth to detache and remove the built-up filter cake. This option is mainly used in discontinuous filters, such as candle and leaf filter systems and thus covers a widespread regeneration process.

2. Theory

Such filtration processes with implemented regeneration are

* Corresponding author.
E-mail address: patrick.morsch@kit.edu (P. Morsch).

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Nomenclature

$\Delta p_{Backwash}$	Backwashing pressure, bar
F_{Detach}	Detachment force, N
F_A	Adhesion force, N
F_C	Cohesion force, N
H_{FC}	Filter cake thickness, m
m_{remain}	Mass fraction remaining on filter surface, g
$m_{remain,\ dry}$	Mass fraction remaining on filter surface after drying, g
$m_{remain,\ wet}$	Mass fraction remaining on filter surface with liquid, g
$m_{removed}$	Discharged mass fraction, g
$m_{removed,\ dry}$	Discharged mass fraction after drying, g
$m_{removed,\ wet}$	Discharged mass fraction with liquid, g
p_E	Dehumidification pressure, bar
S	Saturation, -
s	Acceleration distance, m
S_∞	Limit saturation, -
t	time, s
t_E	Dehumidification time, s
v_{max}	Maximum velocity of the filter cloth, m/s
W	Surface weight, g/m^2
$x_{i,\ 3}$	Descriptive Mass/volume-related modal value of particle distribution (i = 10, 50, 90%), m
α_H	Specific flow resistance, 1/m^2
η	Dynamic viscosity, Pa s
ρ_{Liquid}	Density of the liquid phase, kg/m^3

performed with different types of equipment and can be divided into continuous and discontinuous filters. Examples of continuous filters are drum, disk, and belt filters. Their differences result from time-related and locally resolved stationary filtration conditions. The filtrate flow is constant, because the filter cake is built up, dried, and discharged at different locations. Each of this location is stationary and allows for a continuous filtration flow. Contrary to continuous filters, discontinuous filters are highly transient. This is shown by the fact that the filtrate flow decreases with time as a result of the building up of filter cake. Higher filter cakes with a constant filtrate pressure result in a decrease of the filtrate flow and require periodical removal by discharge. Given the fact that these subsequent process steps (drying, discharging) cannot take place in parallel, the process sequence is split into the three parts of filtration, drying, and discharging. Each part is transient in time and takes place at the same local position. For this reason, good discharge is required to increase the time difference between filtration and regeneration for a good process performance. Examples of such commonly used discontinuous filters are candle filters, which are the focus of this work.

The dominating adhesive forces are defined between the first particle layer and the filter cloth (adhesion) and inside the filter cake proper (cohesion) [4–6]. Adhesion and cohesion may differ considerably depending on the surrounding environment. In case of a liquid phase, the dominating forces are the Van der Waals (VdW) forces. In contrast to the liquid phase, the dominating force in gas phase is the liquid bridge force. These forces may be higher than the effective VdW forces [7]. For this reason, the effective force between filter cake and filter cloth must be reduced by desaturation of the filter cake. Experiments with other filter elements (chamber filters) revealed that cake moisture should have a maximum level of 25% for a good regeneration [8].

With reference to previous investigations, main attention is given to dry discharge after gas filtration [3,8,9]. It is found that the intensity of discharge (backwashing pressure), filter cake thickness, and geometry of the particles (size and shape) have a strong effect on the discharge behavior. In case of a stable filter cloth, the amount of discharged mass increases with increasing cohesive particles (higher filter cake thickness and smaller particle shape) and higher backwashing pressure in case of backwashing into the gas phase after gas filtration [3]. This increase is much more pronounced in case of an unstable, movable filter cloth and can be formulated mathematically by a normal force balance as derived in Eq. (3) in the chapter 5 [9].

Investigations, based on gas discharge after gas filtration, differs considerably from the discharge behavior in the gas phase after liquid filtration. The filter cake is subjected to a high liquid load, called saturation, whereas gas filtration is affected by air humidity which is infinitely smaller. The latter is associated with a much smaller liquid bridge forces and the saturation level is assumed to decrease the surface load in weight per filter area compared to the former filtration method. To sum up, comparing between these discharge processes is quite difficult, because the boundary conditions of gas and liquid filtration are different.

Investigations of liquid filtration with subsequent drying and discharge are reported for disk filters [3]. This publication also includes a theoretical approach to determining the influence of filter cloth movement based on the discharged mass fraction. These can be used to compare the following results and discuss them for different shapes of the filter element. The effective force in case of discharge (liquid and dry) largely depends on the filter cloth in terms of contact surface (weave type and thread thickness) and less on the material [5,10,11].

For complete discharge, the removal force applied must be larger than the adhesive forces. This universally valid statement was already published by [12] and is independent of the specific adhesive force in the enclosed continuous phase. The effect is summarized by the

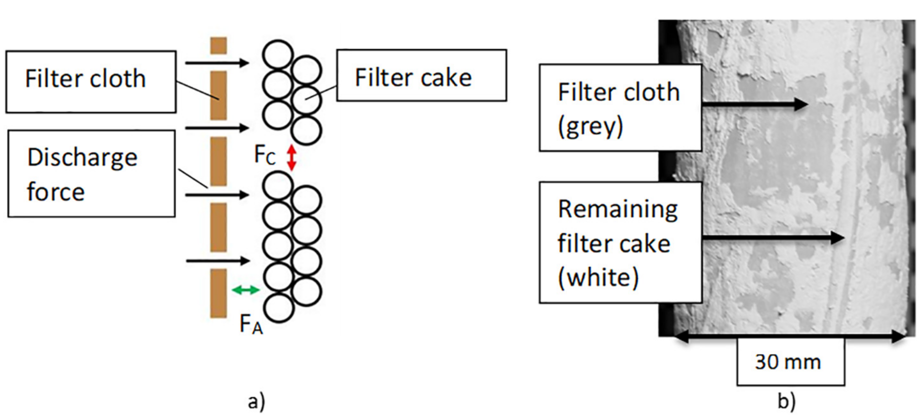


Fig. 1. Force condition inside a filter cake during the backwash procedure (a). Adhesion (F_A) has to be smaller than the discharge force. If these conditions are not fulfilled, particles remain on the filter surface (b).

inequation "Detachment force F_{Detach} > Adhesion on filter cloth F_A". The detachment force is provided by a pressurized air pulse. This process is supported by the acceleration of the filter cloth with a sudden stop by the mechanical inertia force. Generally, it can be assumed that a more stable filter cloth needs a higher backwashing pressure/backwashing impulse [3]. The same can be expected for filter cloths with a larger contact surface and/or smaller particles [12]. Both values increase the adhesion force.

Apart from adhesion, cohesion is also important with regard to the size of the discharged fragments. For this, cohesion must be much higher than adhesion and discharge is to occur in bigger fragments [3]. And cohesion also affected by the drying procedure. In case of a high desaturation velocity, the saturation gradient is very high between the upper and lower level of the filter cake. This may lead to some cracks inside the filter cake with a lower flow resistance than the remaining cake [13,14]. Hence, the air stream preferably flows through these cracks and results in poor drying. The effects can already be noticed during subsequent discharge, because discharge will not take place at all or be poor, because cracks also reduce the discharged fragments and allow smaller pieces to remain on the filter surface. Bigger fragments are desired, because they are able to carry away more filter cake fragments from the filter surface. The desired force condition for cohesion is reflected by the inequation "Detachment force F_{Detach} < Cohesion inside the filter cake F_C".

The effective forces are shown schematically in Fig. 1a. The particles remaining on filter cloth surfaces after discharge in the dry phase are shown in Fig. 2b.

3. Method

Within the scope of the investigation, the backwashing properties of various fabrics and particle systems are assessed using a laboratory cartridge filter. The backwashing treatment is evaluated using the experimental setup shown in Fig. 2, which is reduced to the essential area. The test procedure can be split into three main phases in case of dry discharge. Phase 1 covers the filtration process shown in Fig. 2a. During this step, the filter cake is built up until a defined thickness is reached. In this case, suspension flow enters the process chamber at the bottom and leaves at the top. The filtration pressure can be adjusted. The filtrate flows from inside of the laboratory-scaled candle filter through the filtrate pipe and leaves the vessel at the top. After cake buildup, the second phase starts when the suspension is replaced by air pressure in the vessel (Fig. 2b). As a result of the steady air pressure, the filter cake always is subjected to a pressure. When the suspension is replaced by air, the bottom pipe closes and the filter cake is dried mechanically with the help of the filtrate pipe. The drying pressure p_E and drying time t_E can be varied. After drying the filter cake, discharge starts immediately (Fig. 2c). For this purpose, an air pressure flowing opposite to the filtrate is used. The air pressure acts on the filter cake and filter cloth and a sudden stop with the resulting moment of inertia detaches the cake. In order to release the pressure in the process chamber, the valves open at the bottom of the vessel. The detached filter cake falls onto a metal grid and can be removed. The weight of the filter cake and its saturation can be determined with gravimetric methods after discharge ($m_{removed,\ wet}$) and subsequent drying at 100 °C ($m_{removed,\ dry}$). This procedure can also be applied to the filter cake remaining on the filter candle ($m_{remain,\ wet}$ and $m_{remain,\ dry}$). For this, it is necessary to remove the filter cake mechanically. Apart from the saturation of the filter cake (Eq. (1)), the mass fraction of the discharged filter cake (Eq. (2)) can be determined. The interpretation given below will be based on these values.

$$\text{Saturation}\quad S = (m_{removed,wet} - m_{removed,dry})/(\rho_{Liquid}\cdot V_{Filtercake}\cdot \varepsilon_{Filtercake}) \tag{1}$$

$$\text{Discharged mass fraction} = m_{removed}/(m_{removed} + m_{remain}) \tag{2}$$

To obtain reproducible test conditions in terms of filter cake thickness, the filtrate volume is kept constant by varying the concentration of the suspension in defined steps. The used particle systems and filter cloths are documented in the following chapter 4.

4. Material

The investigations are carried out using a lab-scale filter element. This laboratory candle filter has a diameter of ~30 mm and the length of the filtration area is 110 mm (total length without thread: 140 mm). The structure of the lab-scale candle filter is shown in Fig. 3a. The filter cloth can be fastened on the supporting tissue with mounting rings. For sample preparation, accurate sealing with a rubber underlay in the mounting area is required. After assembly of the filter cloth, the filter candle can be installed in the test station and is ready for the experiments. For dry discharge, two different filter cloths are studied:

- Plain-Reverse Dutch weave (PRD; Filter cloth #1)
- Satin weave (STN; Filter cloth #2)

In case of PRD, the mesh size determined by a bubble point test is 12 µm. The material is polyethylene terephtalate (PET) and the weave is very filigree/unstable. In contrast to this filter cloth, the satin weave is very stable and has a mesh size of 18 µm. The material is polypropylene (PP). In case of discharges in the liquid phase, the stability and diameter of the filter cloth have a direct effect on the backwashing volume. In case of dry discharge, this behavior can be expected when looking at the test reported in [5,6,15]. For this purpose, however, it is necessary to select a fabric diameter larger than the diameter of the candle filter for accelerating the filter cake. For both materials, two

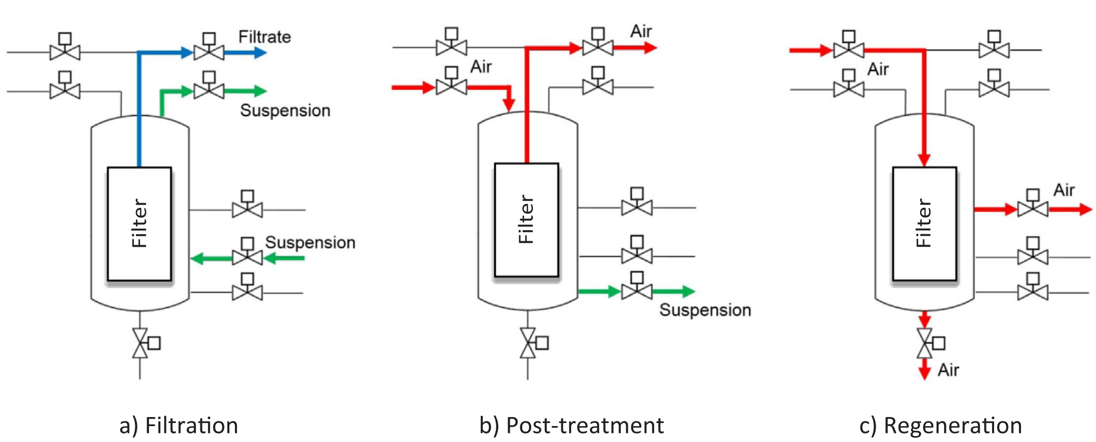


Fig. 2. Schematic flowchart of the experimental facility during filtration (a), replacement of the suspension and drying (b), and discharging into the gas phase (c).

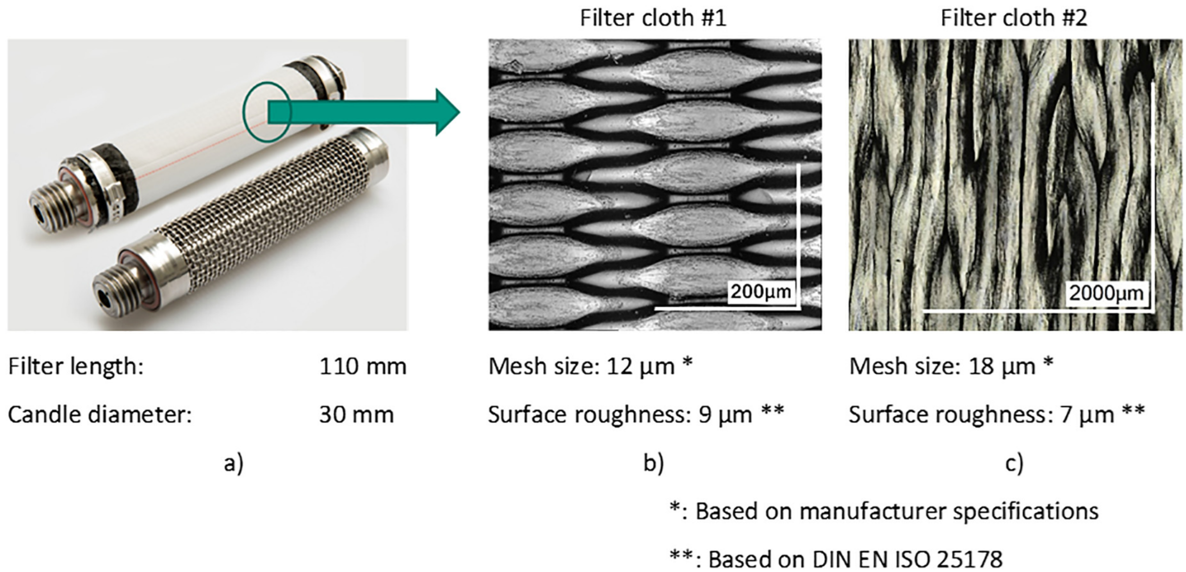


Fig. 3. Illustration of the lab-scale candle filter with and without filter cloth (a) and enlarged images of the used filter cloths of 12 μm plain reverse Dutch weave (PRD) (b) and 18 μm satin weave (STN) (c).

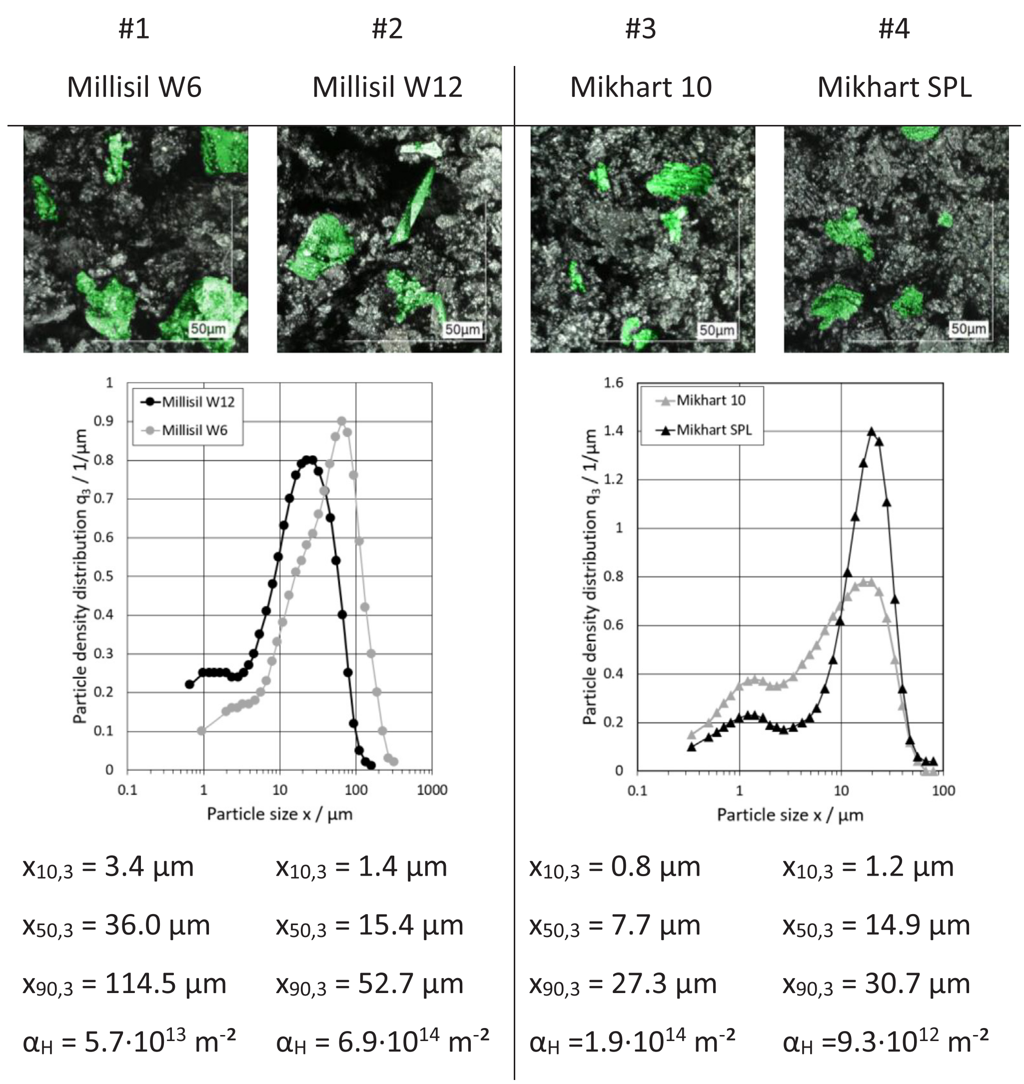


Fig. 4. Particle systems Investigated for cake discharge in the gas phase. The shape of the particles is orthorhombic. The particle sizes results in high specific flow resistances α_H (VDI 2762-2).

different filter cloths (inflexible/flexible) and 3 different filter cloth diameters (30, 35, 40 mm) with a potential motion range of 0, 2.5, and 5 mm are studied. The investigated filter cloths are summarised in Fig. 3 b and 3c. In addition to the mesh size as the manufacturer's specification, the surface roughness according to DIN EN ISO 25178 is also listed. This is approximately similar for both fabrics with 9 µm (Filter cloth #1) and 7 µm (Filter cloth #2).

The investigated particle systems for backwashing filtration mainly differ in particle size, as is shown in Fig. 4. First, attention should be given to the porosity and the resulting capillary pressure for drying. In case of a very high capillary pressure, a high drying pressure is required for lower saturation levels. As already known, the saturation has to decrease before discharge, because a high saturation leads to high cohesive and adhesive forces and results in a poor or more complicated regeneration due to inhomogeneous force distribution [15].

Four particle systems are used, of which two each have the same mineralogical composition but different mass-based median values $x_{50,3}$. This results in different contact points between the first particle layer and the filter cloth (adhesion), and different particle-particle interactions and associated cohesions. The different mineralogical composition of the two particle systems also makes it possible to transfer the results to another particle system [4].

5. Interpretation

Investigations covered the process of filtration with the formation of defined filter cakes, drying by air pressure, and regeneration of the filter by discharge into gas phase. Research revealed two possibilities of cake discharge [19]:

- Complete discharge and
- Incomplete cake discharge

For complete discharge, also called patchy cleaning, the adhesion force over the whole filter is overcome and the whole filter cake is detached and discharged. Of course, cohesion has to be high enough to prevent breakthrough of the air flow [3]. This kind of discharge obviously is preferred, especially when considering subsequent unit operation. After discharge, the aggregate material at the bottom of the vessel is removed and some further process steps may follow. In case of filter cake fragments remaining on the filter cloth, the retention of the valuable product (the particles) increases and the performance of the subsequent filtration process decreases as a result of the decreased filter area. In Fig. 5, the complete discharge is exemplarily shown. Compared to discharge in the liquid phase, the backwashing time for dry discharge is much shorter [16,19].

When considering the higher adhesive forces in gas phase compared to liquid phase [7], the mechanisms of dry and liquid discharge are supposed to be different. It can be expected that the discharge force has to be higher for a good discharge. The main question is which process variable leads to an increased detachment in dry discharge. To answer this question, four process variables are analyzed:

I. Backwashing pressure: an increase in this variable increases the stress on the filter cake. According to [3], discharge in gas phase after gas filtration are improved and this can also be expected after liquid filtration.
II. Filter cloth diameter: An increase in the filter cloth diameter relative to the filter element (e.g. candle filter) increases the acceleration distance and the detachment force [9].
III. Filter cake thickness: in case of filter presses, heavier filter cakes can be discharged more easily [6]. This behavior can also be expected for candle filters, because the force of inertia increases with the filter cake thickness.
IV. Filter cloth type: rougher and less elastic fabrics are expected to result in a reduced discharge of filter cake fragments.

5.1. Backwashing pressure (I) and filter cloth diameter (II)

The basic conditions of the experiments were that with filter cloth 1 and different diameters of the filter cloth (30, 35, 40 mm), a cake of H_{FC} = 1.5 mm was built up, dried and discharged at air pressures of 1–1.5, 2–2.5 and 3–3.5 bar. The discharged filter cake was collected and described gravimetrically. The filter cake remaining on the filter cloth was subjected to the same process after mechanical removal from the surface of the filter cloth. With the measured masses and Eqs. (1) and (2), a discharged mass fraction – backwashing pressure plot is obtained, see Fig. 5a.

When using a 30 mm filter cloth on a 30 mm filter candle, only ~20% of the filter cake of W6 will be discharged. The amount discharged remains constant from 1 to 3 bar backwashing pressure. This observation leads to the conclusion that the backwashing pressure has no impact on the amount of discharged filter cake like discharging in liquid phase [19]. This result does not agree with the high impact of backwashing pressure observed in [3] for gas filtration/regeneration. Further studies for disk filters in case of liquid filtration and gas discharge revealed that the filter cake may be rewet from the bottom of the candle. This effect leads to a disturbed distribution of adhesion force. As

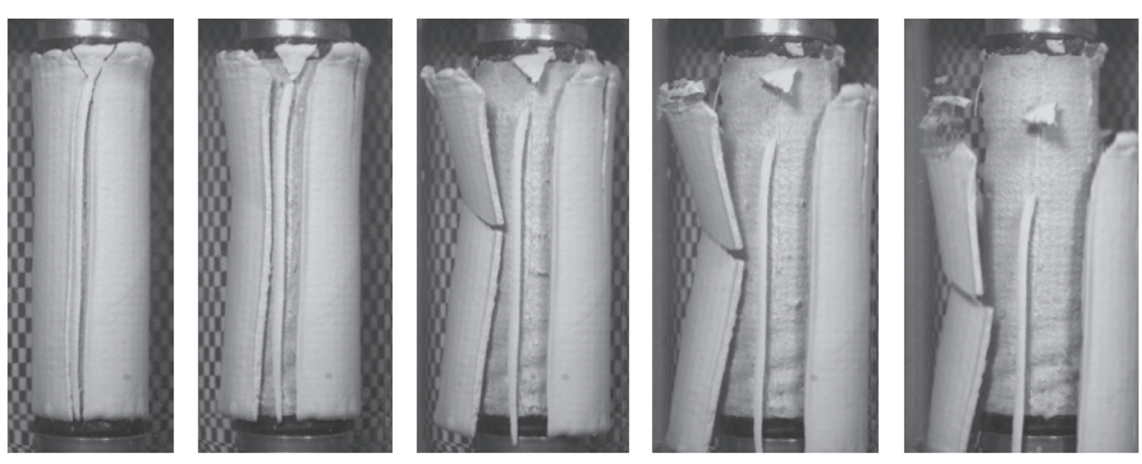


Fig. 5. Regeneration of the lab-scale candle filter (Millisil W6; H_{FC} = 1.5 mm; $\Delta p_{Backwash}$ = 1 bar). Discharge in the liquid phase under the same conditions takes six times longer.

obvious from Fig. 7a, this also happens in case of a dry discharge of a 30 mm filter cake. The lower part of the candle locally experiences a saturation = 1 and adhesion decreases. Then, the same amount of filter cake is detached from the rest, which may be interpreted wrongly as a constant mass discharged at increased pressure. Hence, discharge is not a result of an impulse, but a normal fall by gravity.

The impact of the backwashing pressure is reflected by the discharge for a 35 mm filter cloth and particle system W6. With an acceleration of 2.5 mm, ~28% of the filter cake are discharged at 1–1.5 bar. The discharged fragments come from the whole candle area and not only from the lower part (see Fig. 7b). Moreover, the discharged mass fraction increases with the backwashing pressure to ~37% at 2–2.5 bar to ~55% at 3–3.5 bar (11.2 w%/bar). When the filter cloth diameter is increased to Ø 40 mm (5 mm acceleration; 18 w%/bar), the same mass is discharged at 1–1.5 bar like with Ø 35 mm filter cloth and 3–3.5 bar.

When the acceleration distance s is doubled, pressure can be reduced by factor of 3. Analogous results are found in [9] for gas filtration and gas discharge (Eq. (3)).

$$v_{max} = (9 \cdot s^2 \cdot 0.5 \cdot W^{-1})^{1/3} \cdot (d(\Delta p)/dt)^{1/3} \quad 3)$$

According to [9] the maximum speed v_{max} of the filter cloth depends on the acceleration distance s, surface weight W, and the increasing differential pressure versus time $d(\Delta p)/dt$. Based on the proportionality $v_{max} \propto s^{2/3} \cdot (d(\Delta p)/dt)^{1/3}$, the impact of s exceeds that of the pressure rising ($d(\Delta p)/dt$). In this context, it means that the same amount of discharged mass fraction can be reached at a much smaller backwashing pressure by increasing the acceleration distance s.

When the backwashing pressure is further increased to 2–2.5 bar, the discharged mass fraction amounts to ~72% and a complete discharge is reached at 3–3.5 bar (shown in Fig. 7c). Using this combination of particle system and filter cloth, adhesion can only be overcome by an acceleration distance of 5 mm and a pressure of 3–3.5 bar. Under this condition, the detachment force is higher than adhesion over the whole filter cloth.

In Fig. 6 b, the influence of the filter cloth diameter is obvious for the W6 particle system. This corresponds to an overall increase of discharged mass fraction/ (bar backwashing pressure · filter cloth diameter) by 1.8% and reveals the high impact of the effective acceleration of the filter cloth (1–1.5 bar: 3.7%/mm; 2–2.5 bar: 5.3%/mm; 3–3.5 bar: 8%/mm).

Apart from the particle system W6 with a $x_{50,3}$-value of 36 µm, investigation also covers W12, with a $x_{50,3}$-value of 15.4 µm (see Fig. 4). Finer particles can be expected to have a higher adhesion to the filter cloth due to the increased number of contact points [17,18]. When looking at W12 (1–1.5 bar; 35 mm), it can be noted that the backwashing efficiency is below the efficiency for W6 at same conditions. With an increase of the backwashing pressure, the discharged mass fraction for W12 is higher.

The increase in the mass fraction discharged at a higher backwashing pressure, however, cannot be explained by the effective adhesive forces. According to Eq. (3), the momentum on the filter cake decreases and results in the discharged mass fraction being smaller at smaller v_{max}. This can be implemented by a decrease of the surface area W and it is the reason for the increase of the discharged mass fraction of W12. A decreasing particle size results in a decrease of the bulk density and, hence, in a smaller number of particles for the same filter cake thickness. This goes hand-in-hand with a smaller surface weight (~3.8 kg/m^2 for W6 and 2.1 g/m^2 for W12) and results in a higher v_{max} and a higher momentum by discharge. To sum up, adhesion is expected to be higher for W12, as is the force for discharging these particles. The same observation can be made for W12 with the filter cloth 1 and a diameter of 40 mm (0.25 bar: 38%; 0.5 bar: 63%; 1.0 bar: 93%). When using W12, a discharged mass fraction of ~63% can be reached when the filter cloth is 40 mm in diameter and 0.5 bar (35 mm requires 3–3.5 bar).

In conclusion, it should be noted that by choosing an adequate acceleration distance s and a high velocity of the filter cloth/cake, the discharged mass fraction can be increased.

5.2. Filter cake thickness (III)

Based on the finding that the initial force must be high enough for a complete discharge, it can be assumed that a good discharge can also be reached by a variation of filter cake thickness. To study the impact of filter cake thickness in case of dry discharge, defined filter cake thicknesses of 0.5, 1.5, and 2.5 mm are chosen, dried and discharged. The plot of the discharged mass fraction versus filter cake thickness is shown in Fig. 8.

It is evident that an increase of the filter cake thickness results in an increase of the discharged mass fraction. While only a few fragments are detached at a thickness of 0.5 mm, the weight fraction discharged

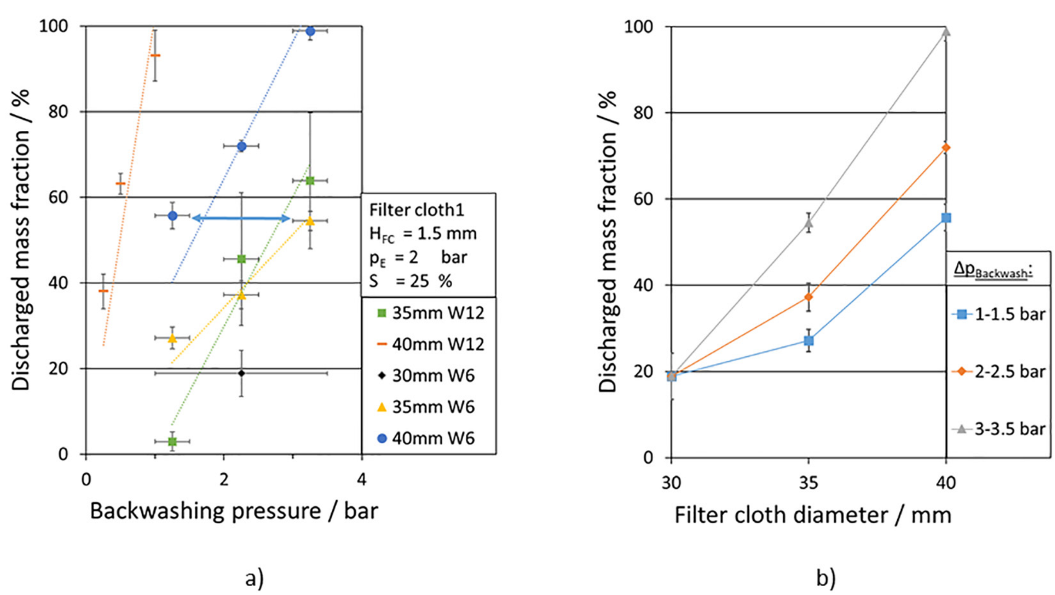
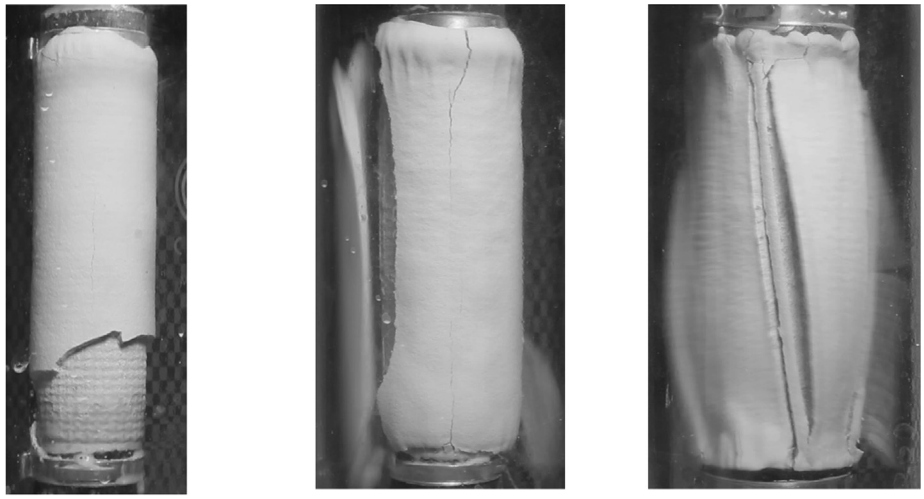


Fig. 6. Discharged mass fraction of the lab-scale candle filter as a function of the backwashing pressure (a) and the diameter of the filter cloth 1 (b) at a constant filter cake thickness H_{FC} = 1.5 mm.



a) b) c)

Fig. 7. Filter cake remaining when removing a cake of 1.5 mm thickness by backwashing with air. The filter cloth diameter for a discharge at 30 mm (a), 35 mm (b) and 40 mm (c).

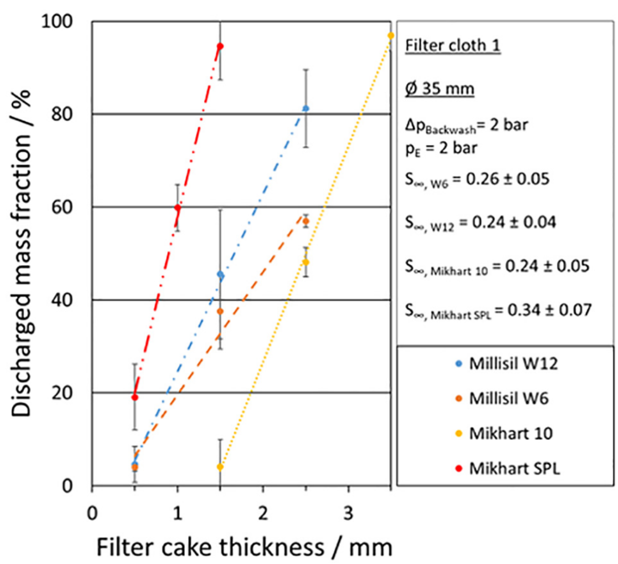


Fig. 8. Discharged mass fraction for the lab-scale candle filter as a function of the filter cake thickness.

increases rapidly with increasing thickness. It is remarkable that a linear behaviour can be observed for all 4 particle systems.

A look to Fig. 8 rises the question, why the mass fractions discharged are higher for smaller particle systems. It is well known that smaller particle systems have a higher number of contact points and therefore adhesion between the surface and filter cloth. But a worse regeneration cannot be observed. An assessment is also made here on the basis of the specific mass on the surface.

At a filter cake thickness of 1.5 mm, W12 has a surface weight of 2.35 kg/m^2, whereas that of W6 is ~3.05 kg/m^2. As in case of the variation of the filter cloth diameter, this results in a lower v_{max} and, hence, in a smaller momentum for discharging the built-up filter cake. The result is a higher force of inertia and an increased inertia of the discharged cake. With regard to the Mikhart particle systems, this behaviour is exactly opposite. Here, the coarser Mikhart SPL with a basis weight of 2.40 kg/m^2 is, as expected, thrown off much better than Mikhart 10 with 1.57 kg/m^2. With regard to the cake resistance ($\alpha_H = 9.3 \cdot 10^{12}\,m^{-2}$), a more porous structure can be assumed for this particle system with the resulting very good release. The discharge process is therefore a process in which, on the one hand, the greater adhesion of finer particles to the lower inertia can be counteracted by the smaller surface loading. The liquid load inside the filter cake can increse the liquid bridge forces (adhesion; $\propto x$) and also the basis weight of the filter cake ($\propto x^3$). Therefore, it is not possible to make a general statement on the extent of the adhesive forces, including saturation, and the interaction of the fabric (meshes) with the particle size distribution.

When looking at Eq. (3), proportionality of v_{max} to the surface weight W is given $_{by}$ $v_{max} \propto W^{-1/3}$ and this results in a reduction of v_{max} at higher surface weight W. It must be assumed that the discharge behavior is no mono-variable interaction and depends on more variables than just specific weight. According to the original force condition, the detachment force F_{Detach} counteracts the force of inertia (mass m multiplied by the acceleration $a = dv/dt$) and adhesion force F_A. This force condition $F_{Detach} - F_A = m{\cdot}a$ clearly shows that detachment is not only influenced by the speed of discharge, but also by the mass.

With a look to the proportionalities, the presumption is that the increase in weight is more important the the increase on adhesive forces. The accuracy of this derivation can be verified by observing the limit values of chamber filters. In case of these filters used in e.g. beer filtration, the filter cake is detached only as a result of the gravity force and v_{max} is zero.

5.3. Filter cloth type (IV)

In addition to the previously investigated parameters, the filter cloth itself is varied as well. Here, special attention is paid to the stiffness of the tissue. In contrast to the filigree filter cloth 1 (Thickness: 80 µm), filter cloth 2 is of higher strength (Thickness: 714 µm). The two fabrics are shown in Fig. 3. It can therefore be assumed that, as a result of the higher thickness and, hence, lower flexibility, acceleration of filter cloth 2 is smaller than that of filter cloth 1. This is supposed to result in a smaller filter cake discharge. Deviations from this behavior may be caused by different adhesive forces and stiffnesses of the filter cloth exclusively.

For the first validation of the hypothesis "stiffer tissue leads to reduced filter cake discharge," regenerations are carried out with variable filter cake thicknesses H_{FC} and backwashing pressures $\Delta p_{Backwash}$ using a tissue diameter of 35 and 40 mm, and the particle system W6. The results can be compared with the values obtained for the 12 µm tissue in Fig. 6. In addition, adhesion measurements are carried out according to [17–19].

A look at the discharge rate in Fig. 9 suggests that a discharge for 35 mm isn‘t possible (H_{FC}: 6 mm and $\Delta p_{Backwash}$: 4 bar: < 5%).

When the tissue diameter is increased from 35 to 40 mm, the first fragments are loosened at cake heights of 1.5 mm and a backwashing pressure of 2 bar. With increasing cake thickness to 2.5 mm, the quantity of filter cake thrown off increases to 50%. Compared to filter cloth 1, the particle layer remaining on the fabric is much thicker. With a further increase of the cake height to 3.5 mm, a large part of the filter cake is discharged (~69%). Remaining fragments can be found mainly in low-movement zones, such as the upper and lower sides of the filter fabric. In addition, the particle layer remaining on the filter fabric should not be neglected. When the backwashing pressure is increased from 2 to 4 bar, no significant increase in the discharge rate can be observed. While the discharge rate is nearly zero at a cake thickness of 1.5 mm, it amounts to 40% only at 2.5 mm, and to 79% at 3.5 mm. Considering the standard deviation, no significant differences between 2 and 4 bar backwashing pressure must be assumed. The small pressure dependence can be explained by the rigidity of filter cloth 2. Large increases in force cause small changes of elongation only. Hence, higher pressures do not have the desired effect of increased cake discharge. Direct comparison with filter cloth 1 shows that the more elastic and less rough fabric results in discharge rates of ~38% even at a filter cloth diameter of 35 mm and a cake thickness of 1.5 mm.

To study particle masses remaining on the surfaces of different tissues, adhesion measurements were carried out according to [17,18]. For this purpose, a filter cake was built up on a filter fabric with the help of a pressure filter cell and the fabric was then pulled off the surface. The effective force was evaluated using Eqs. (4) and (5).

$$\text{Break-up stress } (\mathrm{N \cdot m^{-2}}) = (\text{Maximum force}) \cdot (\text{Area of contact with filter cloth})^{-1} \tag{4}$$

$$\text{Break-up energy } (\mathrm{J \cdot m^{-2}}) = (\Sigma \text{Force} \cdot \Delta x) \cdot (\text{Area of filter cloth})^{-1} \tag{5}$$

from $x = 0$ to $x = x$ Detachment

The break-up stress consists of the maximum force measured in a test relative to the filter area. In addition, a break-up energy is defined taking into account the force as a function of the tensile length. Thus, the different stages of force measurement (static friction, idling and sliding friction according to [18]) are considered according to their proportions. Measurements were made using both filter fabrics shown in Fig. 3 and are summarized in Table 1.

It was found that the break-up stresses in $\mathrm{N \cdot m^{-2}}$ of filter cloths 1 and 2 differ with respect to the mean value. However, no significant difference can be assumed. This can be explained by the surfaces of the tissues and the acting shear planes in the experiments. Due to the periodic surface of the filter fabric and the shear plane, the first particle layer is not completely moved over the fabric but also over the particle layer. The measured adhesion thus refers to a mixture of particle and filter area. Since the particle–particle interaction is much more pronounced, any differences between the tissues are levelled out. This is clearly shown by the high standard deviation of ~ 30% for both fabrics. Taking the break-up energy in $\mathrm{J \cdot m^{-2}}$ into account, no difference in position between the two filter cloths used can be detected. Both measured values are in the same range.

Conclusions drawn from these measurements with respect to the discharge rates of the fabrics suggest that discharge is affected only slightly by the adhesion of the fabric types but influenced largely by the stiffness that determines resistance to the discharge impulse and the movement of the fabric (momentum).

6. Conclusion

The experiments shows that the filter cloth diameter, backwashing pressure, weave type, and filter cake thickness have a big influence on the discharged mass fraction. It is highly recommended to use a filter cloth with a diameter enabling proper motion. Only with such acceleration can a discharge be accomplished successfully. In particular, flexible fabrics are suited for a good regeneration. In addition, larger fabric diameters relative to the candle diameter are to be preferred for cake discharge in the gas phase.

Apart from the movement of the filter cloth, backwashing pressure also has a high impact on the discharge process. Higher backwashing pressure leads to a higher impulse which produces a better discharge. Here a clear difference to regeneration in liquid phase can be observed [19]. The combination of the filter cloth diameter and backwashing pressure can lead to a good discharge.

Taking Eq. (3) into account, an increased mass load of the surface, possibly due to a higher cake thickness, will also result in an increase in the mass discharged. This hypothesis is confirmed by experiments with variable cake thicknesses. Thicker cakes tend to a more complete discharge. Variations in particle size also confirmed this observation. Against all expectations due to their higher adhesion, smaller particles were not found to lead to lower discharge rates, but only particles with a smaller specific area loading. Here the multi-variability of the regeneration process becomes clear.

Summarizing the experience gained from all experiments, it can be stated that the success of discharge is a question of momentum. A great momentum can be created by changing various variables. In the worst case, regeneration quality decreases during liquid discharge, gas discharge is only made possible in this way. In addition, in contrast to liquid discharge, a significant pressure influence can be detected.

CRediT authorship contribution statement

Patrick Morsch: Conceptualization, Methodology, Software, Formal analysis, Investigation, Validation, Resources, Writing - original draft, Project administration. **Pascal Ginisty:** Investigation, Writing - review & editing. **Harald Anlauf:** Supervision, Writing - review & editing, Funding acquisition. **Hermann Nirschl:** Supervision, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

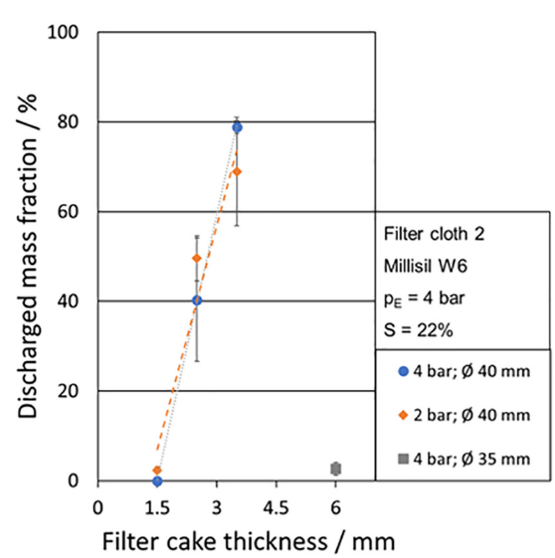


Fig. 9. Discharged mass fraction for the lab-scale candle filter as a function of the filter cake thickness H_{FC} for different diameters of the filter cloth 2 and backwashing pressure.

Table 1
Break-up stresses (Eq. (4)) and break-up energies (Eq. (5)) measured for filter cloth 1 and filter cloth 2.

Filter cloth number	Break-up stress [$N \cdot m^{-2}$]	Break-up energy [$J \cdot m^{-2}$]
1	323.33 ± 102.77	0.31 ± 0.11
2	408.47 ± 125.33	0.34 ± 0.07

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