

FILTRATION

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1. GENERAL

Filtration is the removal of solid particles from a fluid by passing the fluid through a filtering medium on which the solids are deposited.

Fluid flows through a filter medium by virtue of a pressure differential across the medium when solids are separated forming a filter cake. Filters are classified, therefore, into those that operate with a pressure above atmospheric on the upstream side of the filter medium and those that operate with atmospheric pressure on the upstream side and a vacuum on the downstream side. Pressures above atmospheric may be developed by the force of gravity acting on a column of liquid, by a pump or blower, or by centrifugal force. Filters are divided into three main groups: cake filters, clarifying filters and cross flow filters.

Filter used in this laboratory work is a typical overpressure filter. Its basic principle of operating is illustrated in Figure 1 (Ullmann's Encyclopedia of Industrial Chemistry, 1988). Overpressure in upstream side forces the fluid through filter cake and filter media to downstream side, which is in open air.

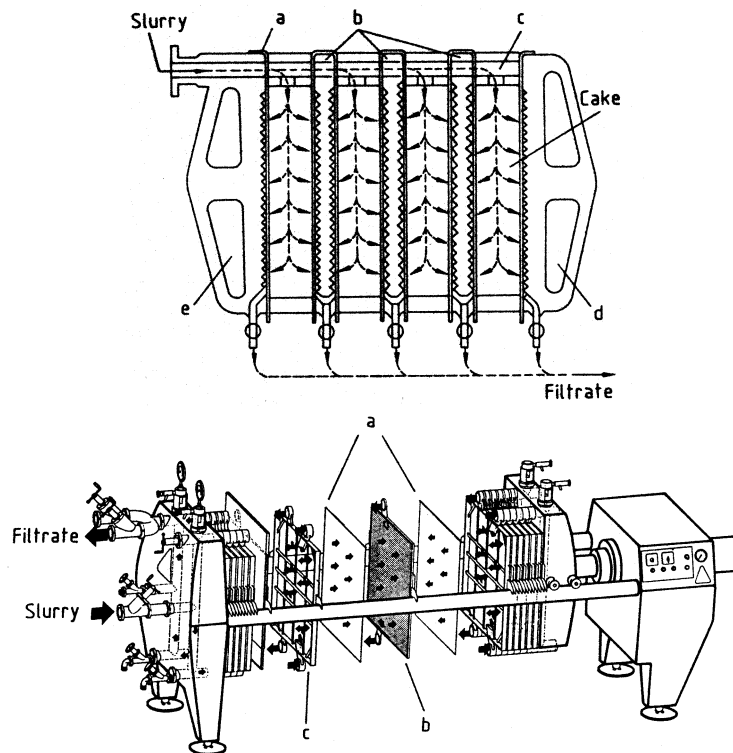


Figure 52. Sheet filter press (reproduced with permission of Schenk)
a) Filter sheets; b) Plate; c) Frame

Figure 1.

2. THEORY

In cake filtration the liquid passes through two resistances in series: that of the cake and that of the filter media, see figure 2.

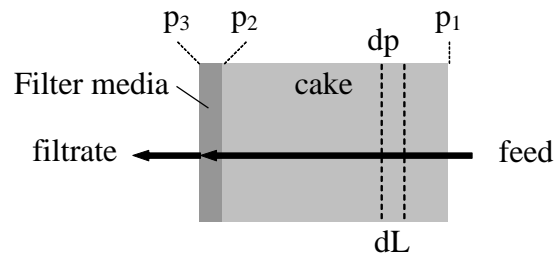


Figure 2.

The overall pressure drop (Δp) at any time is sum of pressure drops over medium (Δp_{sv}) and cake (Δp_K):

$$\Delta p = \Delta p_K + \Delta p_{sv} = (p_1 - p_2) + (p_2 - p_3) \quad (1)$$

2.1 CAKE FILTRATION

Filtration is a special example of flow through porous media. In filtration the flow resistances increase with time as the filter medium becomes clogged or a filter cake builds up. As time passes during filtration, either the flow rate diminishes or the pressure drop rises.

In cake filtration, the filter media resistance is normally important only during the early stages of cake filtration. The cake resistance is zero as the start and increases with time as filtration proceeds.

2.2 PRESSURE DROP THROUGH FILTER CAKE

In practice, fluid flow in the cake is always laminar, because of significant cake resistance. The pressure drop through the cake can be described with *Kozeny-Carman* equation (McCabe et al., 2001 p. 1005 and p. 159).

Kozeny-Carman equation to a differential part of the cake is following:

$$\frac{dp}{dL} = 150 \frac{\bar{u}_0 \eta}{\Phi^2 D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} \quad (2)$$

When total area of the cake is A , porosity of the cake is ε , and if ρ_p is the density of the particles, the mass dm of solid s in the layer is:

$$dm = \rho_p (1-\varepsilon) A dL \quad (3)$$

Elimination of dL gives:

$$\frac{dp \rho_p (1-\varepsilon) A}{dm} = 150 \frac{\bar{u}_0 \eta}{\Phi^2 D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} \quad (4)$$

Reorganizing:

$$dp = \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \frac{\bar{u}_0 \eta}{A} dm \quad (5)$$

Eq. (5) defines pressure drop in a thin layer of cake as function of thin bed of solids particles through which the filtrate is flowing.

Integration of Eq. (5) gives

$$\int_0^{\Delta p} dp = \int_0^{m_K} \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \frac{\bar{u}_0 \eta}{A} dm \quad (6)$$

If assumed that terms in the right side are constant, integration in certain time t gives:

$$\Delta p_K = \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \frac{\bar{u}_0 \eta}{A} m_K \quad (7)$$

Hence, pressure drop and total weight of the cake are time-dependent, is Eq. (7) valid only in certain time t :

$$\Delta p_K(t) = \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \frac{\bar{u}_0 \eta}{A} m_K(t) \quad (8)$$

2.3 FILTER CAKE RESISTANCE

Eq. (8) can be written following:

$$\Delta p_K(t) = \alpha \frac{\bar{u}_0 \eta}{A} m_K(t) \quad (9)$$

where term α is specific cake resistance (McCabe et al., 2001 p. 1006).

Specific cake resistance is according to Eq. (8) and (9):

$$\alpha = \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \quad (10)$$

Specific cake resistance depends on solids to be filtered and etc. pressure. Eq (9) can be used to calculate specific cake resistance:

$$\alpha = \frac{A}{\bar{u}_0 \eta} \frac{\Delta p(t)}{m_K(t)} \quad (11)$$

Hence, porosity of the cake ε , particle size D_p , particle shape factor Φ , and constant in Eq (10), are typically unknown, specific cake resistance is experimentally determined parameter, which is calculated from Eq. (9) or (11). If specific cake resistance is constant during experiment, Eq (11) can be written following:

$$\alpha = \frac{A}{\bar{u}_0 \eta} \frac{\Delta p}{m_K} \quad (12)$$

2.4 FILTER MEDIA RESISTANCE

Eq. (9) can be written following:

$$\dot{V}_0 = A\bar{u}_0 = \frac{\Delta p_K(t)}{\alpha \eta m_K(t)} \quad (13)$$

from which

$$\bar{u}_0 = \frac{\Delta p_K(t)}{\frac{\alpha \eta m_K(t)}{A}} = \frac{\Delta p_K(t)}{\frac{\alpha m_K(t)}{A} \eta} = \frac{\Delta p_K(t)}{R_K \eta} \quad (14)$$

where overall resistance is divided to cake resistance R_K and to viscosity of fluid. An analogical equation can be written to filter media:

$$\bar{u}_0 = \frac{\Delta p_{SV}(t)}{R_{SV} \eta} \quad (15)$$

from which

$$\Delta p_{SV}(t) = R_{SV} \bar{u}_0 \eta \quad (16)$$

where R_{SV} is filter media resistance.

2.5 TOTAL RESISTANCE

The total resistance can be defined by summarizing equations (9) and (17):

$$\Delta p(t) = \Delta p_K(t) + \Delta p_{SV}(t) = (R_K + R_{SV}) \bar{u}_0 \eta = \left(\frac{\alpha m_K(t)}{A} + R_{SV} \right) \bar{u}_0 \eta \quad (17)$$

2.6 CALCULATION

In practice, the total mass of solid in the cake m_K and the linear velocity \bar{u}_0 are replaced by function of the total volume of filtrate V collected to time t .

2.6.1 Flow rate

The linear velocity u is given by the equation:

$$\bar{u}_0(t) = \frac{\dot{V}(t)}{A} \quad (18)$$

where V is the total volume of filtrate collected from the start of the filtration to time t . Since filtrate must pass through the entire cake, V/A is the same for all layers and u is independent of L .

2.6.2 Mass of filter cake

It is assumed that all solid in feed will stay in the cake. This gives:

$$\frac{dm_K}{dt} = c\dot{V} \quad (19)$$

When the concentration of solids in feed is constant, integration between the limits (0,0) and (t, m_K) gives:

$$m_K(t) = \int_0^{m_K(t)} dm_K = \int_0^t c \dot{V} dt = c \int_0^t \dot{V} dt = cV(t) \quad (20)$$

thus total volume of filtrate is:

$$V(t) = \int_0^t \dot{V} dt \quad (21)$$

a.k.a.:

$$m_K(t) = cV(t) \quad (22)$$

2.6.3 Total resistance

The total resistance is already defined in Eq. (18):

$$\Delta p(t) = \left(\frac{\alpha m_K(t)}{A} + R_{sv} \right) \bar{u}_0 \eta \quad (235)$$

Substituting flow rate *u* and mass of solids *m_K* from Eq. (19) and (25) gives:

$$\Delta p(t) = \left(\frac{\alpha c V(t)}{A} + R_{sv} \right) \frac{\dot{V}(t)}{A} \eta \quad (24)$$

This is a basic equation for filtration, where assumptions are:

- constant concentration of solids in feed

2.6.4 Calculation in practice

The total volume flow of filtrate can be defined as time derivative of total volume of filtrate:

$$\frac{dV}{dt} = \dot{V} \quad (25)$$

From Eq. (26) and Eq. (27):

$$\Delta p = \left(\frac{\alpha c V}{A} + R_{sv} \right) \frac{dV/dt}{A} \eta \quad (26)$$

This is a basic equation for filtration in practice, where assumptions are:

- constant concentration of solids in feed
- constant density

2.7 CONSTANT-PRESSURE FILTRATION

If overall pressure drop is constant, Eq (28) can be integrated analytically. Eq (28) can be written:

$$\frac{dt}{dV} = \frac{\alpha c \eta}{\Delta p A^2} V + \frac{\eta R_{sv}}{\Delta p A} = KV + B \quad (29)$$

where new parameters are:

$$K = \frac{\alpha c \eta}{\Delta p A^2} \quad B = \frac{\eta R_{sv}}{\Delta p A} \quad (27)$$

Integration between the limits (0,0) and (t, V) gives:

$$\int_0^t dt = \int_0^V (KV + B)dV \quad (28)$$

Assume that parameters K and B are constant:

$$t = \frac{K}{2}V^2 + BV \quad (29)$$

from which

$$\frac{t}{V} = \frac{K}{2}V + B \quad (30)$$

This is a basic equation for constant-pressure filtration in practice, which assumptions are:

- constant concentration of solids in feed
- constant density
- K and B are constant

Thus a plot t/V versus V will be linear, with a slope equal to $K/2$ and an intercept of B . From such a plot and Eq. (30) and Eq. (33), the values of α and R_{sv} may be calculated..

2.8 PRESSURE EFFECT

Cake specific resistance is:

$$\alpha = \frac{150(1-\varepsilon)}{\Phi^2 D_p^2 \rho_p \varepsilon^3} \quad (31)$$

Hence cake porosity depends on pressure, can also specific resistance depend on pressure. The relation of cake specific resistance and pressure is following:

$$\alpha = \alpha_0 (\Delta p)^S \quad (325)$$

where parameter α_0 is constant specific cake resistance and S compressibility of cake. Eq. (35) can be written

$$\log(\alpha) = \log(\alpha_0) + S \log(\Delta p) \quad (33)$$

If constant specific cake resistance follows Eq. (35), a plot of Eq. (36) is linear from which specific cake resistance and compressibility of cake can be determined.

3. EQUIPMENT USED IN THE LABORATORY WORK

3.1 FILTRATION EQUIPMENT

Diagram of the laboratory equipment is shown in figure 3.

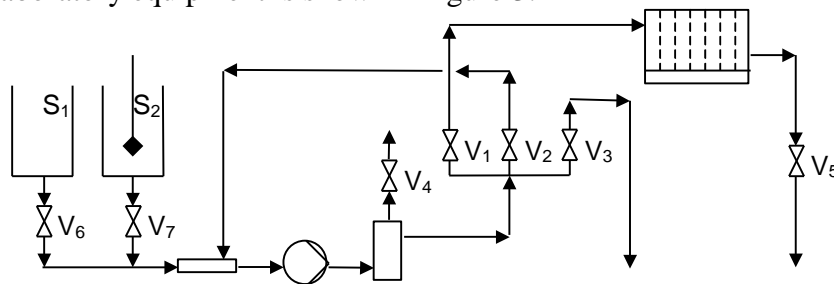


Figure 3.

What is needed:

- filter cloth
- perforator for filter cloth

3.2 USED FLUID

- Used suspension is mixture of water-calcium carbonate.
- Properties of used calcium carbonate (CaCO_3) are in appendix 1.
- Solid matter content is: CaCO_3 2 w-% a.k.a. 20 g/l.

3.3 MEASURING EQUIPMENT

Already installed to equipment:

- Pressure gauge

What is also needed:

- Thermometer
- Timer
- In short work 7 pieces evaporating dish
- In extensive work 11 pieces evaporating dish

4. OPERATING THE FILTRATION EQUIPMENT

4.1 GENERAL

In this work, constant-pressure filtration is studied. Compressibility, specific resistance and filter media resistance is calculated.

4.2 MEASUREMENTS

The laboratory equipment is used to measure filter media resistance and four constant-pressure filtration with different pressures. The fluid to be filtrated is limestone slurry. Measurements are done in a following way:

1. A feed tank S2 is filled with solution of calcium carbonate and water.
2. A water tank S1 is filled with water.
3. Install a filter cloth to the filter so that smooth surface is towards fixed end of the filter and the hole in the filter cloth is towards discharge outlet of the filter.
4. In the beginning, filter media resistance is measured with pure water. Check that open are
 - a suction line valve V6
 - a pressure line valve V1
 - a valve after filter V5
 - and closed are
 - a suction line valve V7
 - discharge valves V4 and V3
 - three-pass valve V2.
5. Start the pump. When pressure is desired, use valve V2 to control the pressure. Start the watch and begin to collect filtrate. Mark up every minute: time and volume of the filtrate. Collect filtrate five liters.
6. Stop the pump
7. Measure temperature of filtrate.
8. Install a new filter cloth to the filter.
9. Before starting filtration, make sure that open are:
 - a suction line valve V7
 - a pressure line valve V1
 - a valve after filter V5
10. and that closed are:
 - a suction line valve V6
 - discharge valves V4 and V3
 - three-pass valve V2.
11. Start the pump. When pressure is desired, use valve V2 to control the pressure. Start the watch and begin to collect filtrate. Mark up every minute: time and volume of the filtrate. Collect filtrate five liters.
12. Stop the pump.
13. Measure temperature of filtrate and take a 50 ml sample from filtrate to determine concentration of solids in feed.
14. Open filter and remove filter cloth and cake.
15. Measure area of filter a.k.a. a cross-section area of the cake.
16. Measure cake thickness (only extensive work).
17. Take sample of the cake (only extensive work).
18. Change a filter cloth.
19. Make corresponding measurements with next pressure value.

4.3 ANALYSIS

Analyze samples as following:

- Mass fraction of solids in feed is defined by weighting evaporating dish, evaporating dish + filtrate and in next day evaporating dish + evaporation residue. Three definitions are made from feed solution and one per each filtrate.
- In an extensive work, mass fraction of solids in cake is defined analogically.

4.4 FINISHING THE WORK

- Remove last cake and filter cloth from filter.
- Start the pump (filter should be open).
- Wait until feed is pure water.
- Stop the pump.
- Flush filter and sinks with water.
- Empty tanks and flush them with water.
- Next day take evaporating dishes away from oven and weight them.
- Wash evaporating dishes.

5. SPECIFICATION

Viscosity of filtrate can assumed same as water in same temperature.

5.1 SHORT WORK

- Fill the form.
- Appendices 1 and 2 can replace with print outs from Excel.
- Only qualitative incorrect estimate is needed.

5.2 EXTENSIVE WORK

- Calculate pressure drop through cake using *Kozeny-Carman* equation.
- Cake porosity ε can be determined, when concentration of solids in cake is known.
- Diameter of particles in cake can be estimated from Appendix 1.
- Assume that particles almost spherical when $\Phi = 0.8$.
- Compare result to measured values.
- Estimate results.

6. REFERENCES

McCabe, M.L. Smith, J.C. Harriot, P., Unit Operations of Chemical Engineering, 6th ed., McGraw-Hill, 2001.

Ullmann's Encyclopedia of Industrial Chemistry, Vol B2: Unit Operations I, 5th ed., VCH, 1988

7. APPENDICES

1. Properties of calcium carbonate (OMYACARB 10-GU)

8. NOMENCLATURE

α	specific cake resistance, m/kg
α_0	specific cake resistance, constant in Eq (36), m/kg
ρ	density of filtrate, kg/m ³
η	viscosity of filtrate, Pas
c	concentration of solids in suspension, kg(solid) / m ³ (fluid+solid)
Δp_K	pressure drop through cake, Pa
Δp_{SV}	pressure drop through filter media, Pa
Δp	overall pressure drop, Pa
A	total area of filter, m ²
R_K	cake resistance, 1/m
R_{SV}	filter medium resistance, 1/m
S	compressibility of cake, dimensionless
t	time, s
V	volume of filtrate, m ³
\dot{V}	volume flow of filtrate, m ³ /s

OMYACARB 10-GU

PRODUCTION PLANT: Gummern / Austria

SHORT DESCRIPTION OF THE PRODUCT: Fine, high purity, white marble powder.

CHEMICAL ANALYSIS OF THE RAW MATERIAL:	Carbonate content	≥ 98	%
	Fe ₂ O ₃	≤ 0.15	%
	HCl insoluble content	≤ 2	%

PHYSICAL PROPERTIES OF THE RAW MATERIAL:	Density (ISO 787/10)	2.7 g/cm ³
	Refractive index	1.59
	Hardness (Mohs)	3

OMYACARB 10-GU
Particle size distribution (Cilas 920)

