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Introduction and Overview

1.1 General Aspects of Solid–Liquid Separation in General and Cake Filtration in Detail

Cake filtration represents one of the several different mechanical methods to separate particles from liquids. Cake filtration offers, in comparison to other mechanical particle–liquid separation techniques, the advantageous possibility of direct solids posttreatment. This enables particle washing by cake permeation and the comparatively lowest mechanically achievable solid moisture contents. Particularly, if low residual moisture content of the solids is an important issue, cake filtration is the preferred technique. Unfortunately, not in every case, cake filtration can be realized from the technical and/or physical point of view. Figure 1.1 shows the principal steps of a cake filtration cycle.

After feeding the filter apparatus with slurry, a filter cake is formed under the influence of a pressure difference above and beneath the filter medium. If necessary, the cake can be washed in the next step to get rid of soluble substances in the liquid, which are still present in the wet cake. Finally, the filter cake is deliquored to displace further liquid from its porous structure. At the end of the process, the cake is discharged from the filter apparatus, and if necessary, the entire apparatus or the filter medium has to be cleaned.

The residual moisture content of the separated solids is considerably influencing the efficiency of a subsequent thermal drying and thus the energy consumption of the whole separation process. As a rule, the thermal methods are usually quite energy-intensive compared with the mechanical liquid separation. In the literature, guiding numbers of more than factor 100 can be found between the energy demands of mechanical and thermal deliquoring [1, 2]. In comparison to mechanical methods, thermal methods require not only heating of the wet system to the boiling point of the liquid but also a phase transition from the liquid to the gaseous aggregate state. The appropriate vaporization enthalpy must be raised. For this reason and also because of the often-undesirable load of temperature-sensitive products, it is in most cases advantageous to separate as much liquid as possible at low temperatures by mechanical means. For physical reasons, a final rest of liquid remains in any case after the mechanical liquid separation in the particle structure. However, this portion of liquid can only be removed from the solid material by thermal means. If a completely dry powder

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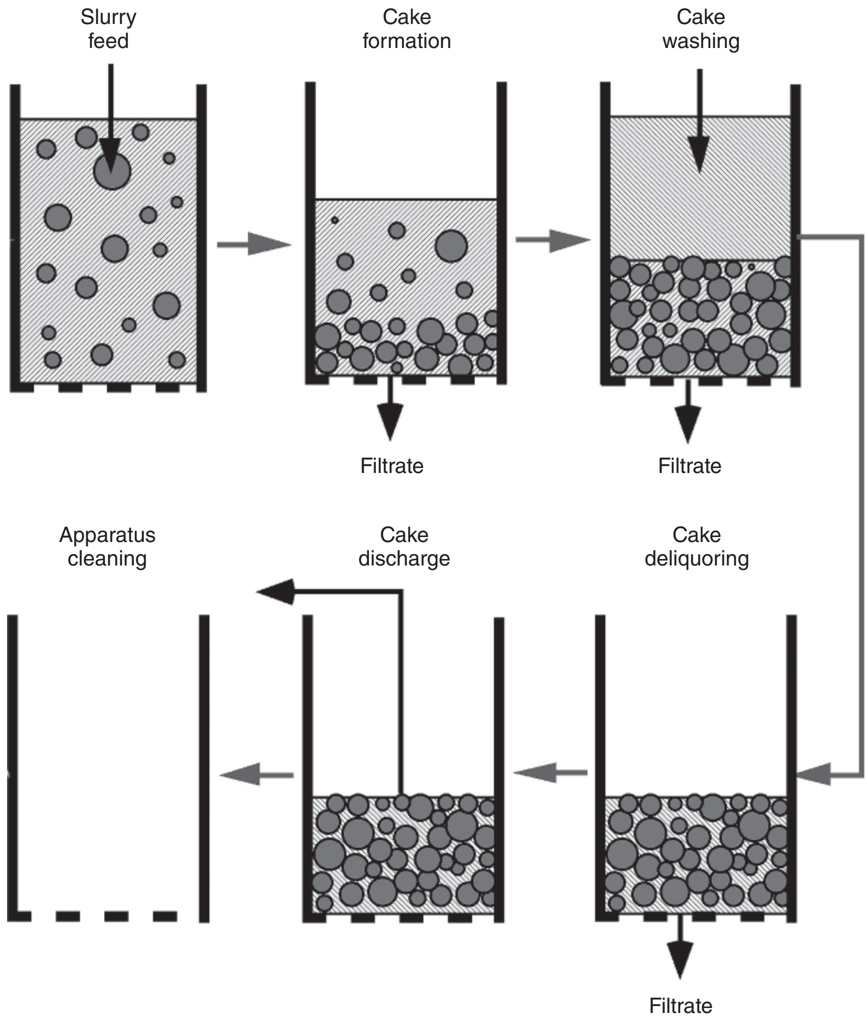

Figure 1.1 Process steps of a cake filtration.

is required as the final product, one of the tasks for the optimization of the whole separation process consists in determining the most favorable point of transfer from the mechanical to the thermal separation step. This interconnection point is very variable and defined by the requirements of the selected thermal drying process. For spray drying, a pumpable and sprayable slurry is still required, whereas the solids should be deliquored to the mechanical limit for a fluidized bed drying because the cake behaves brittle and powdery in that case. At the interface of these two basic processes for solid–liquid separation, combined mechanical–thermal processes have also been developed and established such as centrifuge dryers, nutsche dryers, and in recent times continuously operating steam pressure filters. The advantages of these systems consist in synergies, which result in energy conservation and compact and simplified process design.

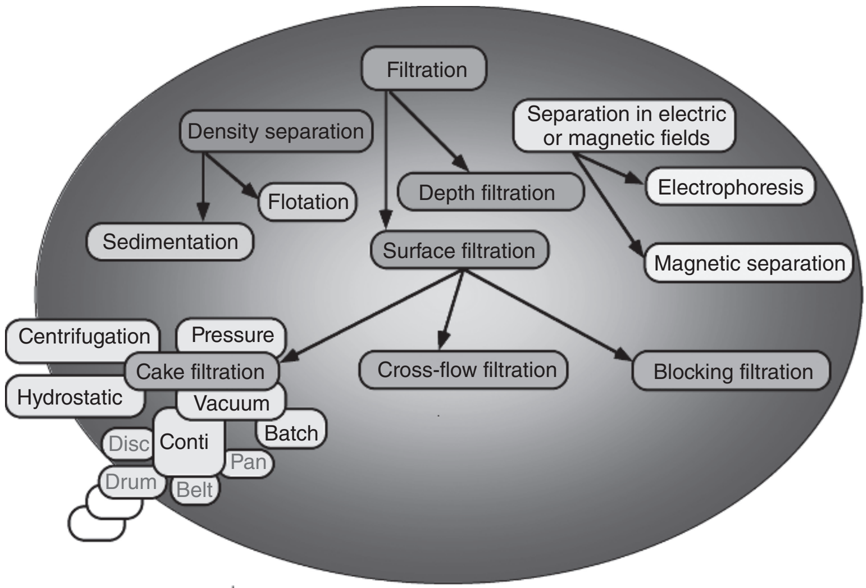

Figure 1.2 Physical principles of solid–liquid separation.

As mentioned before, the application of cake filtration is of course not possible in every case but limited by some boundary conditions. For example, in the case of submicron particles and very low solid concentration in the slurry, cake filtration makes no sense because of very high cake pressure loss of the cake and large quantities of liquid, which must penetrate such a tight cake structure. If the boundary conditions for cake filtration are not fulfilled, alternative separation techniques such as density separation, depth, cross-flow, or blocking filtration must be used. To enhance the filtration performance, electric or magnetic particle properties may be utilized additionally by the realization of an electric or magnetic field in the process room. In the literature, several comprehensive descriptions of more or less the entire technology are published [3–8]. Figure 1.2 gives an overview of the different available physical principles of mechanical particle–liquid separation.

Density separation is based on a difference of density between solid particles and liquid. If the solid density is greater, the particles are settling into the direction of gravity or a centrifugal field and are deposited at a solid wall as sediment, whereby the liquid is displaced to the opposite direction. Static continuously operating thickeners or clarifiers and many types of batch and continuous solid bowl centrifuges are based on this separation principle. If the particles have less density than liquid, they will float on the liquid surface. Also, particles of greater density than liquid float by froth flotation. For this purpose, gas bubbles are generated in the slurry, and if the particles are hydrophobic, they can adhere to the bubbles and float on the surface. This technique is often used to separate hydrophobic from hydrophilic particles of different materials in sorting processes of mineral beneficiation or waste paper recycling. If necessary, the flotation conditions regarding the wetting behavior of particles can be influenced by various surfactants. These are water-soluble molecules with polar (hydrophilic) and nonpolar (hydrophobic/lipophilic) parts. For example, the polar part of a surfactant adheres at the surface of a hydrophilic particle and thus the particle appears hydrophobic from outside. This process runs spontaneously because the systems decrease its free energy. If all particles are hydrophobic as in the case of organic matter, the complete solids can be floated and thus separated very effectively.

Filtration in contrast to density separation is based on the presence of a porous filter medium. Particles and liquid are moving under the influence of a gas pressure difference, a mechanical, hydraulic, hydrostatic, or centrifugal pressure toward the filter medium. The liquid penetrates the filter medium whereby the particles are retained inside the structure or on the surface of the filter medium.

In depth filtration processes highly diluted slurries of very small particles usually in the μm- or sub-μm range are separated. The particles are deposited inside of a three-dimensional network of pores. The pores of the filter medium must be much greater than the particles to be separated in order to minimize the flow resistance for the liquid and to allow the particles to enter the structure and to accumulate inside. The slurry concentration must be very low to prevent the filter from becoming spontaneously blocked by pore bridging at the filter media surface. The filter media can consist of a disperse particle layer from various types of materials such as sand, gravel, activated carbon, diatomaceous earth, and others or premanufactured filter elements made of fibrous materials such as cellulose, carbon, polymers, metal, and others.

Surface filtration can be subdivided principally into blocking, cross-flow, and cake filtration. Blocking or sieve filtration means that single and low concentrated particles are approaching the filter medium and plugging single pores. In the cases of sieve filtration, the pores of the filter medium must be smaller than all particles, which should be separated completely. Not in all cases, a total separation of particles is aimed, but only the retention of oversized particles to protect subsequent separation apparatuses such as hydrocyclones or disc stack separators. These apparatuses are discharging the separated solids highly concentrated through nozzles, which are in danger to become blocked by oversized particles. The particle spectrum, which can be handled by different types of blocking filters, is very broad from the cm to the μm range.

In cross-flow filters, a low concentrated slurry of small particles less than about 10 μm is pumped across a microporous membrane and is consecutively concentrated, whereas the filtrate (permeate) is discharged through the membrane. The formation of a highly impermeable particle layer (filter cake) is prevented as completely as possible by the cross-flow, which should wash away the deposited particles permanently. It depends on the force balance around a particle, whether it is sheared off or adheres at the membrane surface. The particle spectrum to be separated by cross-flow filters ranges from some μm down to small molecules such as Na^+ or Cl^- ions. As an example for reverse osmosis, "poreless" membranes are used to separate salt ions from seawater in order to produce drinking water. In such cases, not a convective liquid transport through real pores but a diffusive transport of water molecules through the molecular structure of the membrane takes place. If the cross-flow only by pumping the slurry across the membrane is not sufficient to limit the particle deposition dynamic cross-flow filters can be applied. Here, the shear forces between membrane and liquid are generated by a rotor/stator system (membrane/membrane or membrane/stirrer) or an oscillation of the membrane.

Last but not least, cake filtration is based on the formation of a relatively thick particle layer from a few millimeters to several decimeters on the surface of the filter medium. Normally, woven fabrics of different materials are used as filter media, but also needle felts, wedge wire screens, sintered materials, or sometimes microporous membranes are applied. The particle size and the slurry concentration must be great enough to enable the cake formation in a reasonable time. Otherwise, the process may be physically possible but will be not more economical or cannot be realized technically with the separation apparatus. All continuously operating apparatuses exhibit a limited residence time of the product in the process room. The particle size spectrum ranges usually from several hundred μm down to some few μm. The lower limit can be extended in many cases by particle agglomeration as one of the several slurry pretreatment techniques (cf. Chapter 5). To prevent pore blockage of the filter medium in most cases, relatively open fabrics are used (cf. Chapter 9). In contrast to the depth filtration, a sufficiently high slurry concentration must enable a more or less spontaneous pore bridging to seal the filter medium against particle penetration into the filtrate.

In Figure 1.2, the physical principles of solid–liquid separation processes are represented. As indicated before, there is hiding a great number of different processes and individual apparatuses behind the shown physical principles. This should be demonstrated exemplarily for the cake filtration principle. As can be seen in Figure 1.2, cake filtration can be carried out by using different driving forces, which are generated by centrifugation, vacuum behind the filter medium, gas overpressure above the slurry surface, and hydraulic or mechanical pressure. Each technique can be realized as a batch or continuously operating process. Continuous vacuum cake filters can be designed as drum, disc, belt, or pan filters, and each of these filters can be subdivided into several specialized modifications.

Figure 1.3 gives a rough overview of basic cake filter types, which are differing in the driving force, mode of operation, and design.

Comprehensive detailed descriptions of many apparatuses can be found in the literature [9].

From each of these filters, several special variants exist to adapt the basic design as optimal as possible to a specific separation problem. Taking the principle of a vacuum drum filter as an example, beside other modifications, different possibilities of cake discharge are possible as depicted in Figure 1.4.

Scraper discharge is well suited for well-desaturated brittle cakes, roller discharge for hard to filter slurries with thin and sticky cakes, leaving belt discharge and separate cloth washing zone for slurries, which extremely tend to clog the filter media, and last but not least precoat discharge to handle highly diluted slurries of very small particles. Here, in a first step, a precoat layer height of several cm and made of diatomaceous earth, cellulose, starch, or other materials is built up on the filter media. In a second step, the slurry to be separated is filtered and the

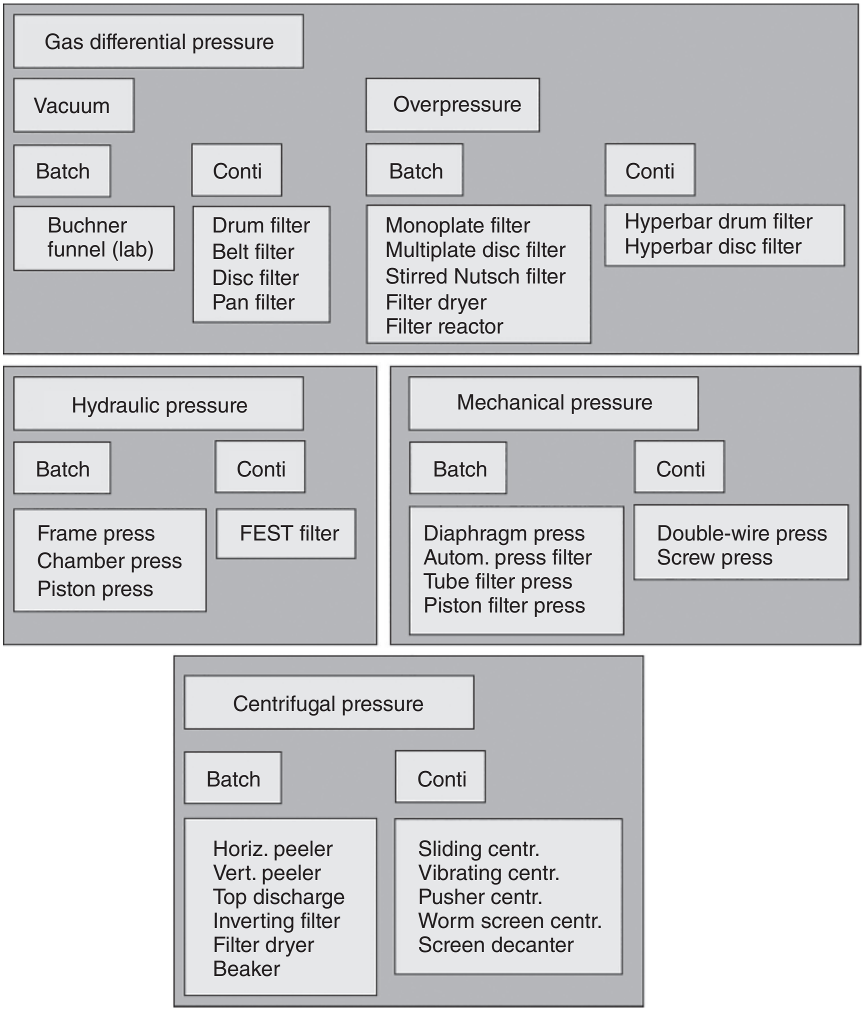

Figure 1.3 Overview of cake filter apparatuses.

precoat itself acts as a filter medium. During one cycle, the surface of the precoat becomes blocked and a very thin cake of often about 1 mm height or less is formed. A sharp knife cuts off this blocked precoat layer and again permeable precoat surface immerses into the slurry. The knife has to proceed permanently to renew the precoat surface until it is nearly consumed. Normally, the knife proceeds about 0.1 mm per revolution of the drum.

Figure 1.5 gives a rough overview of the whole range of cake filter applications and examples for apparatuses in correspondence to particle sizes and pressure differences.

The smaller the particles become, the greater the necessary forces are to separate them. The more difficult the filtration becomes, the longer the filtration periods are necessary, and the greater the pressure must be. These operation

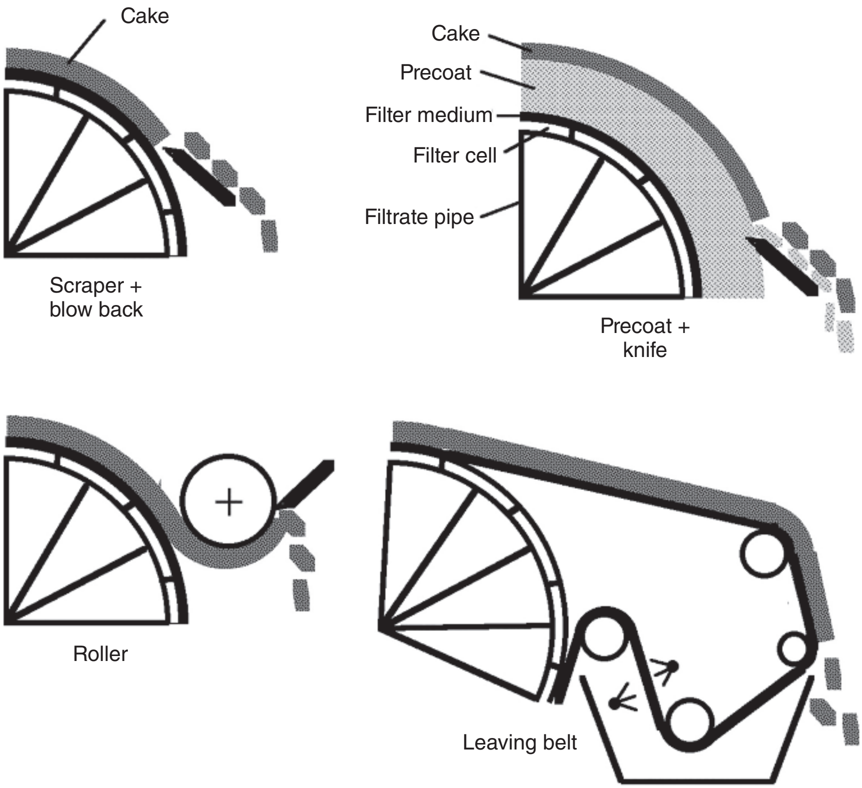

Figure 1.4 Variants of cake filter discharge from vacuum drum filters.

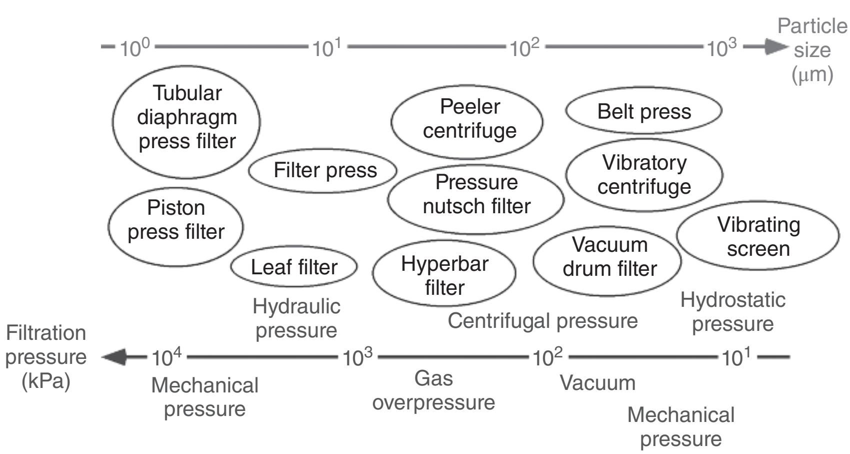

Figure 1.5 Cake filtration equipment depending on particle size and filtration pressure.

conditions are difficult to realize for continuously operating apparatuses, and thus, batchwise operating apparatuses are preferred here. Similar overviews of the ranges of apparatus application had been elaborated on the basis of empirical experience such as Gasper for filters in general [10], Trawinski for centrifuges [11], and Gösele for cake filters [12]. The boundaries of the ranges for apparatus application in such generalizing representations must not be seen as sharp and exact. The meaning is that within these ranges, often applications of the respective apparatuses can be found. The limits of application can be shifted remarkably, for example, by slurry pretreatment measures such as agglomeration.

Each physical principle in Figure 1.2 can be itemized in the described way to arrange all the different existing separation apparatuses in a systematic way. This large variety of physical separation principles and apparatuses is necessary to solve the extremely different problems of solid–liquid separation as cross-sectional technology. As can be seen in Figure 1.6, the separation of particles from liquids touches nearly every industrial process, our personal life, and the environment.

Solid–liquid separation can be focused on very different tasks such as thickening, purification, fractionation, sorting, extraction, or deliquoring. The separation has to be mastered for wide ranges of particle size and shape, specific solid and liquid weight, slurry concentration, chemical composition and rheology, flow rate, process and technical boundary conditions, and last but not least demands on the separation results. Because of the very complex boundary conditions of mechanical solid–liquid separation problems, the analysis of the specific separation problem is essential to find the best solution for getting a desired result [13]. However, in principle, there is nearly no particle–liquid system today, which cannot be separated anyhow. However, the final question is nearly in every case, how much does it cost. If the separation is not economical, the resulting product may not be saleable on the market. Thus, the challenge is to find an effective, economical, and sustainable solution. This is the motivation not only to look after the best suited state-of-the-art solution to get the desired separation result but to also search for the most cost-efficient separation processes. This is one driving force for permanent technical improvement of the equipment and most effective operating conditions. This evolutionary process of mutation and selection exhibits some similarities to biological processes. Driven by the need to improve a process, an ingenious (engineer!) idea leads to a technical mutation. If this mutation is more successful than its competitors, it will be implemented in the market. Otherwise, it will disappear again [14]. At present, more than 3000 particle separation apparatuses are on the market and consistently new developments can be recognized [15].

In most cases, not one single separation apparatus represents the optimal solution to find the best solution for a special separation task but an appropriate combination of apparatuses often in combination with slurry pretreatment. One example may be the combination of a static thickener and a pusher centrifuge (cf. Section 5.2). Although the pusher centrifuge may represent for a special case the best-suited apparatus to get lowest cake moisture, the centrifuge must be fed with adequately concentrated sludge to enable its function. If the slurry to be separated is too diluted, a prethickening is necessary. Otherwise, no complete cake

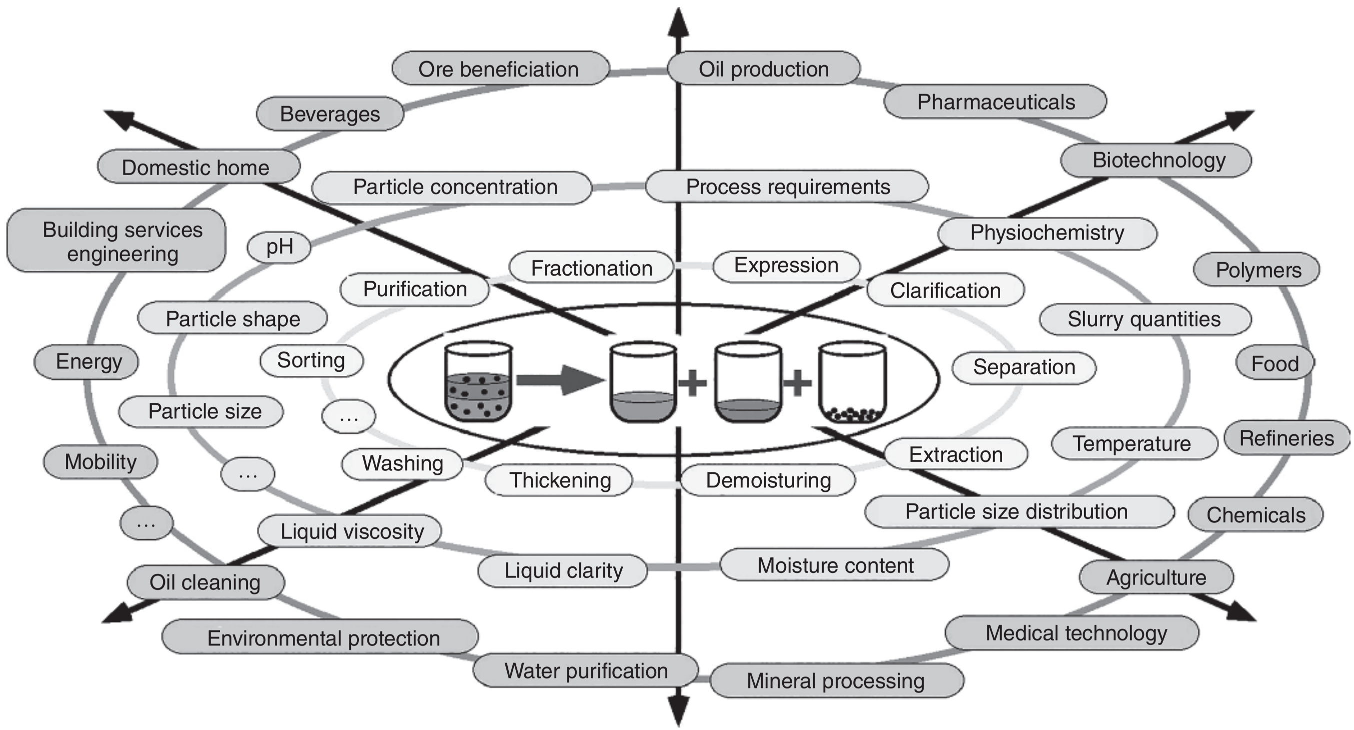

Figure 1.6 Tasks, conditions, and applications for solid–liquid separation processes.

is built in the short residence time of some seconds in the process room of the centrifuge and only sludge will be discharged.

The choice of a discontinuous or a continuous process can have great influence on the separation results. Discontinuous apparatuses enable to choose each process step independently from the other, but only during a part of the batch time cake is produced. This restricts the throughput. In continuous apparatuses, all process steps are linked together and the transport velocity and the geometrical length of the respective process zone are limiting the process time for each process step. On the other hand, cake is produced all the time and the throughput is remarkably higher than in the case of batchwise operating apparatuses.

Last but not least, other boundary conditions of the process can have an impact on the freedom to choose the apparatus, which seems from the view of pure physics to be best suited for solving a specific separation problem. If for an example a peeler centrifuge may be the best choice, in the case of a pharmaceutical application with very high demands on hygienic standards, a highly efficient siphon peeler centrifuge (cf. Section 6.5.2) cannot be applied because of cleaning problems and a conventional and less effective version must be used.

To find out the best suited solution for a separation problem in every case, the first step consists of the careful analysis of the entire process as well as the properties of the slurry to be separated (cf. Chapter 2) and the specification of the requirements regarding the separation results has to be formulated. This leads to first ideas for eventually well-suited processes. A cake filtration may be the result. The second step generally includes bench scale separation experiments to verify the principle feasibility of the hypothesis and to get the necessary database for scaling up considered types of apparatuses. On the basis of the laboratory results and already including economic and other superordinate aspects in most cases, a pilot scale test must be carried out. Now, specific apparatus parameters can be investigated, which cannot be captured by the simple bench scale test. From the successful realized pilot test, the final quantitative scale up to the size of the industrial equipment can be done. Special concepts for scaling up cake filtration processes under different boundary conditions will be given later on and can be found in the literature also for other solid–liquid separation processes [16]. The combination of model equations and filtration experiments guarantees realistic forecast data for the technical application, reduces experimental effort, and extends the inter- and extrapolation of the included parameters.

However, all these considerations about the optimal solution of solid–liquid separation problems are based on a fundamental knowledge of the physical phenomena and the key parameters, which are influencing the separation results. To characterize the whole cake filtration process, several experimental methods and model equations from different authors are available, which are all based on a similar physical fundament [17].

As mentioned before, the procedures and apparatuses for the mechanical solid–liquid separation in general and in particular for cake filtration are under permanent research and development in view of new challenges and requirements to the separation results. Actual results from the research are used permanently for the apparatus design. New materials and production engineering are used. Modern sensor and data transfer technology allows the remote monitoring of separation processes and a result-dependent control and regulation. One trend goes toward the "intelligent" machine, which reacts to changes of the feed conditions automatically.

Another trend toward numerical simulation tools will become in future a more and more powerful measure in these processes, although particle technology is always faced with distributed parameters, which makes things much more complicated than in the case of uniform phases. For example, the theoretical research to simulate the capillarity in porous particle systems has made notable progress and helps to understand the phenomena, but unfortunately cannot yet give quantitative data for the practical apparatus design until today [18]. Numerical simulation of cake filtration will not be discussed here in more detail. However, on the way to approach that target, a certain number of today's still unsolved questions of basic research in this field have to be answered. One of these questions is the quantitative correlation between separation results and real particle collective characteristics. Respecting the fact that each physically different particle size measurement method leads for nonspherical particles to different equivalent particle diameters, one has to answer the nontrivial question, which particle diameter is the relevant diameter for any further calculation with particle sizes (cf. Section 4.3). The solution of such kind of problems is not only of academic interest but relevant for the technical practice to make a safe forecast of the cake filtration results. If, for example, upstream in crystallization, milling, or fractionation process, the operation conditions are changing with the consequence of a change in the resulting particles size distribution or the particle shape, the filtration results are influenced seriously.

At the end, a digital twin of filtration apparatuses is desired not even as a three-dimensional design or training tool but also to study process conditions with different material parameters or critical conditions. This requires in general a simulation of the apparatus behavior not only for the stationary but also for the dynamic case. The main challenge for an extensive digitalization is the combination of the complex material behavior, which, as mentioned above, is very difficult to describe in a simulative environment, the complex geometries of the apparatuses, and combined with the complex process behavior. For the material behavior, characterization devices have to be developed, which help to implement the material properties directly into the simulation procedure. This is necessary because a direct numerical simulation on a microscale level, where each particle is approximated, is far too time-consuming. With multiscale simulations, it is necessary to derive shortcut models, which allow simulating the whole process within seconds or even faster. This allows simulating not just process parameters but also raw material or energy consumption relations. Those relations could be directly used to optimize the whole process according to inverse simulations.

References

1 Couturier, S., Valat, M., Vaxelaire, J., and Puiggali, J.R. (2007). Enhanced expression of filter cakes using a local thermal supply. *Separation and*

Purification Technology 57: 321–328. https://doi.org/10.1016/j.seppur.2007.04.020.
2 Reichmann, B. and Tomas, J. (2001). Expression behaviour of fine particle suspensions and the consolidated cake strength. *Powder Technology* 121: 182–189. https://doi.org/10.1016/S0032-5910(01)00336-9.
3 Anlauf, H. (2012). Mechanical solid-liquid separation – processes and techniques. In: *Modern Drying Technology*, vol. 4 (ed. E. Tsotsas and A.S. Mujumdar), 47–97. Weinheim: Wiley-VCH. ISBN: 978-3-527-31559-8.
4 Wakeman, R. and Tarleton, S. (2005). *Solid/Liquid Separation: Principles of Industrial Filtration*. Oxford: Elsevier.
5 Sutherland, K.S. (2005). *Solid/Liquid Separation Equipment*. Weinheim: Wiley-VCH. ISBN: 3-527-29600.
6 Svarovsky, L. (2000). *Solid–Liquid Separation*. Oxford: Butterworth Heinemann. ISBN: 0750645687.
7 Rushton, A.S., Ward, A.S., and Holdich, R.G. (1996). *Solid–Liquid Filtration and Separation Technology*. Weinheim: Wiley-VCH.
8 Luckert, K. (ed.) (2004). *Handbuch der mechanischen Fest-Flüssig-Trennung*. Essen: Vulkan. ISBN: 3-8027-2196-9.
9 Dickenson, T.C. (1997). *Filters and Filtration Handbook*. Oxford: Elsevier Advanced Technology. ISBN: 1-85617-322-4.
10 Gasper, H. (2000). Filterbauarten und ihre Einsatzbereiche – Übersicht. In: *Handbuch der industriellen Fest/Flüssig-Filtration*, 2e (ed. H. Gasper, D. Oechsle and E. Pongratz), 35–47. Weinheim: Wiley-VCH. ISBN: 3-527-29796-0.
11 Trawinski, H. (1983). Entwicklungstrends der Verfahren für mechanische Phasentrennung mit Zentrifugalkräften. *Chemie-Technik* 12 (6): 15–21.
12 Gösele, W., Leibnitz, R., Pongratz, E., and Tichy, J. (2004). Filterapparate – Physikalische Einflüsse auf den Filterwiderstand. In: *Handbuch der mechanischen Fest-Flüssig-Trennung* (ed. K. Luckert), 176–181. Essen: Vulkan. ISBN: 3-8027-2196-9.
13 Tarleton, S. and Wakeman, R. (2007). *Solid/Liquid Separation: Equipment Selection and Process Design*. Oxford: Butterworth–Heinemann. ISBN: 1-85617-421-2.
14 Anlauf, H. (2017). Towards mitigation of particle/liquid separation problems by evolutionary technological progress. *Journal of the Taiwan Institute of Chemical Engineers* 58 (2): https://doi.org/10.1016/j.jtice.2017.09.043.
15 Anlauf, H. (2006). Recent developments in research and machinery of solid–liquid separation processes. *Drying Technology* 24: 1235–1241. https://doi.org/10.1080/07373930600838066.
16 Wakeman, R. and Tarleton, S. (2005). *Solid/Liquid Separation: Scale-Up of Industrial Equipment*. Oxford: Elsevier Advanced Technology. ISBN: 1-85617-420-4.
17 Wakeman, R. and Tarleton, S. (2005). *Principles of Industrial Filtration*. Oxford: Elsevier Advanced Technology. ISBN: 1-85617-419-0.
18 Xu, J. and Louge, M.Y. (2015). Statistical mechanics of unsaturated porous media. *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics* 92, 062405 92 (6): 1–17. https://doi.org/10.1103/PhysRevE.92.062405.