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Cake filtration theory and practice[☆]

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1. Introduction

Cake filtration is basically a solid/liquid separation process and as such is part of solids processing technology that includes drying, communition, granulation, mixing, conveying and storage, and classification, as well as particle size measurement. Therefore, it is not easily described like other fluid transport unit operations such as heat transfer, mass transfer, fluid mixing, and fluid transport where properties are well defined and predictable. Solids can have widely different properties in addition to size distribution, and they depend on conditioning and processing. For example, particle size and shape can change with treatment, aging, flocculation, pH, and of course, pumping. In addition, they can segregate which also affects their properties. For these reasons, solids processing is a very difficult engineering discipline; and why I believe it is rarely studied in the USA. Cake filtration is no exception and is why Dr Frank M. Tiller stated so well early on that: “Experiment is a necessary part of any design procedure, and average filtration resistances are noticeably affected by slurry concentration, rate of change of applied stresses, and internal shear forces. Even under carefully controlled conditions, it is difficult to measure resistance within ±10%. Caution and judgment are essential to interpret and make use of filtration data correctly” [1,2].

A recent study by DuPont revealed that most project delays and cost overruns were caused by solids processing which resulted in plant stoppages. I have repeatedly had to correct the design engineers (typically employed by contract engineering firms) on how to properly handle solids since they are rarely trained in the field and simply apply typical fluid properties in their designs. As a consequence, their designs usually fail in the field. Specifically with respect to cake filtration one needs to worry about slurry transport upstream of the separation device as well as solids removal/transport downstream, as Dr Tiller has so often stated. In some cases, solids transport/accumulation within the device also needs to be considered. Some examples of these solids processing problems that I have encountered are:

- Outlet piping that plugged from a pusher centrifuge that prompted plant management to remove the centrifuge even though it was performing very well.
- A cartridge filter housing that plugged completed with upset solids and caused the cartridge springs to lift with the result that complete bypassing occurred.
- Replacement of a gentle pumping system with a perceived, more reliable, continuously operating, oversized centrifugal pump that caused a 50% reduction in filtration rate from a six-unit filter press system. As a result, the plan was forced to hire an outside dewatering contractor at a $600K annual cost penalty.
- Standard fluid piping that instantly plugged with clarifier underflow sludge such that transport to the filter was never achieved. Piping replacement cost was well over $250K.
- Overstuffed and improperly filled filter presses that caused many filter plates to break (replacement cost well over $100K).
- Improper slurry velocities which caused solids settling and segregation and eventual line pluggage in a filter aid system.
- Solids pluggage in a positive displacement pump loop which caused repeated rupture disc failure and process shutdown.
- Improper slurry agitation which caused solids segregation and an almost 2× reduction in filtration rate.
- Carefully controlled polymer flocculation that was irreversibly destroyed by a centrifugal pump which actually reduced filtration rate below that obtained without polymer flocculant addition.
- Improper solids cake dewatering which caused subsequent fires when discharged.
- Overflocced sludge which caused complete filter cloth binding.
- Arbitrary replacement of filter cloths with another vendor’s offering (so Purchasing could claim a cost savings) that resulted in absolutely little to no solids capture.

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- A change in operation that caused filter cake cracking and almost total loss of cake washing performance [3–5].
- Addition of a steam condensate stream to the filter feed tank that caused almost a 50% capacity reduction.
- Solids pump pluggage and rupture whenever the separation system was shutdown for any reason (cost in excess of $50M).
- Installation of solid/liquid separation (SLS) devices in many plants over the years without any data that has resulted in millions of dollars of losses.

As can be seen by these varied examples, solids processing including cake filtration must be considered in the overall filtration process. As Dr Tiller so eloquently stated: “Maintenance of an overall perspective is fundamental to solution in SLS problems. There are considerable differences in the SLS field as opposed to such conventional areas as distillation, heat transfer, and reactor design. It is not possible to find design data in the literature or handbooks. Whereas thermodynamic properties such as viscosity and specific heat are obtainable in precise form and friction factors or coefficients of heat transfer can be estimated, the essential SLS parameters of permeability (or filtration resistance) and porosity must presently by obtained anew for every material” [1,2] and is critical to SLS system success. I wholeheartedly agree and further add that total solids processing technology and education must be fostered in the US so that many of the pitfalls mentioned above can be avoided. Hopefully, this type of conference can foster this understanding at an industrial level in honor of Dr Tiller who has persistently advocated this for almost 40 years. I hope I can add to this legacy with this paper today as well as some of the general papers I have published over the years [6–9].

2. Cake filtration theory/practice

Solid/liquid separation (SLS) is a broad solids processing technology of which cake filtration is a part. Although cake filtration has been extensively studied for the past 60 years, it is only a fraction of the SLS technology field as attested by the voluminous volumes of AFSS proceedings as well as those by AlChE, AIME, INDA, TAPPI, NAMS, and others. Nevertheless, this paper will attempt to summarize cake filtration as a tribute to Dr Tiller’s extensive contributions to this field [1,2,10–22]. He truly can be considered the father of filtration theory and practice.

In my view, cake filtration predominates both in the usual separation devices such as nutsches, centrifuges, vacuum filters, belt presses, and filter presses, and also in automatic pressure filters [6,7], thickeners [2,20,22], candle filters [21,23–38], and filter aid filters, as well as in some instances cartridge filters [9,39]. As the late Harry Sandstedt reported [39], cake filtration can dominate in a variety of cartridge filter types.

Dr Tiller in his extensive contributions [1,2,10–23] extended the early work of D’arcy, Ruth [40,41] and Grace [42,43] into a practical and theoretical framework within which to design, scale-up, and implement cake filtration operations. I have personally used his work many times to design and troubleshoot cake filtration devices with much success. His lucid work can be relatively easily applied and understood. Professor W. Stahl and his students at Karlsruhe [3–5,44–46] and Shirato [47] extended this practical base in Europe and Japan, respectively.

Recent discussions [48–50] of the differences between Dr Tiller’s ‘ad-hoc’ and the ‘continuum’ theories propose that fluid-flow continuum theory is used to describe cake filtration. However, the continuum models require many parameters that are difficult to obtain and explicitly highlight that the interaction of solid particles with the filter medium governs the flux of filtrate and its rate of change for a specified liquid viscosity and pressure drop, i.e. the filter medium is no longer an isolated factor as in Dr Tiller’s ‘ad-hoc’ developments. However, I have found in over one thousand filtration tests that the medium resistance is generally negligible provided it is chosen to resist blinding, which is normally done in industrial applications for long medium life. For example, many suitable cloths can be chosen for filter presses (i.e. 33) [51]; and if selected properly, the filtrate flow curves are identical from cycle to cycle over many months of operation. Furthermore, I have conducted over 50 laboratory filtration tests with the same cloth and slurry to determine optimum conditioning and repeated control tests showed identical behavior of dominant cake and negligible medium resistance and similar t/v versus v plots, where t is time and v is filtrate volumes. Even the analysis in Ref. [49] ultimately results in the typical t/v versus v plot at constant pressure albeit it was forced through the origin. Although Collins’ case of a dilute fine impurity that caused medium blinding after prolonged recirculation to obtain filtrate clarity is interesting and well represented by the modified theory, a proper choice of medium would eliminate this impractical behavior. In addition, the final t/v versus v plot (Fig. 8 in Ref. [49]) is quite similar to the many plots I have developed using Dr Tiller’s method of plotting $p/\mu_{\rm av}$ versus $cv/2$, where p is applied pressure, μ is viscosity, $q_{\rm av}$ is average flow rate over entire cycle, c is mass of solids/unit volume of filtrate, and v is volume of filtrate/area. Thus, I feel that Dr Tiller’s ‘ad-hoc’ empirical theories are more suitable for industrial applications. I have also used Dr Tiller’s constant rate expressions quite successfully for highly flocculated slurries to unequivocally select the best polymer flocculant for dewatering. I have also used his extensive analysis of the capillary suction time (CST) [1] apparatus with great success. In addition, most industrial applications are rarely constant pressure or rate, which complicates the analysis. Only well controlled laboratory experiments at usually constant pressure can distinguish between pretreatments, media, solids concentration

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[1] CST is a measure of flocculation effectiveness: the lower the value the better the flocculation. In reality, it is directly related to the average specific cake resistance as Dr Tiller has shown [22].

effects, particle size distributions, etc. [52–55], but even then variations in solids, aging, mixing, and settling can cause significant variations greater then the ±10% that Dr Tiller states. Thus, I generally use a variable pressure/variable rate at the beginning of the filtration cycle to simulate a typical pump and then continue at constant pressure until cake formation occurs (or where the two adjoining cakes in a press come together). The middle portion of the filtration cycle is where cake resistance dominates and the typical t/v versus v plot applies and usually extrapolates through the origin.

The so called 'medium resistance' is rarely used but can be obtained from the curvature upwards at the origin of the p/μ_{av} versus $cv/2$ plot. A similar curvature can be seen in Figure 8 of Ref. [49] where t/v versus v was plotted for a cake filtration series from a tubular backpulse filter.

3. Summary

Dr Tiller's assertion that the essential SLS parameters of permeability (or filtration resistance) and porosity must be obtained anew for every material is as true today as when he proposed this. Furthermore, he has steadfastly stated over the years that cake filtration is just one part of SLS technology, and that the overall SLS process must be considered to avoid the many potential pitfalls. He has repeatedly fostered university and technical society education in the US as the means to educate the 'grass roots' plant engineer in at least the basics of filtration and SLS technology. I hope that his educational legacy will be realized as more and more students enter the SLS technology field.

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