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FILTRATION

(A LITERATURE SURVEY)

by

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ABSTRACT

Research up to the present on the theoretical aspects of filtration is reviewed. Major phases of work and respective schools of thought are summarized, and samples of the views of various workers are given. Outlines for future research are indicated, with special attention to the more neglected areas.

RÉSUMÉ

L'auteur présente une revue de la recherche qui s'est faite jusqu'à ce jour sur les aspects théoriques de la filtration. Il indique les phases importantes des travaux, résume les diverses écoles de pensée et donne des exemples. Il mentionne les domaines sur lesquels devront porter les recherches à l'avenir et s'arrête tout particulièrement aux aspects les plus négligés de la filtration.

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INTRODUCTION

Many well established industrial processes operate successfully without being completely understood theoretically. Crushing, grinding, flotation and filtration are good illustrations of this. For several decades, attempts have been made to clarify the scientific principles that actually underly these processes.

Flotation research uses highly developed techniques of surface chemistry. Comminution studies have produced a succession of "grinding laws" that are half empirical, half theoretical. For the time being, in most cases, there is a compromise between scientific principles and empirical observations. Theoretical research is strongly motivated by the fact that increased knowledge can widen the range of application for a process and, by allowing better control, result in overall improvements.

Theoretical progress made in filtration is also expected to aid practical applications. However, more often than not, theory and practice are not easily brought under one roof. This is due to the fact that some of the problems are too complex and it is almost impossible to arrive at a generally workable formula. Even when some theoretical relationship is finally available, it is usually so complex that it is of little or no use to the man working with the process. However, much effort has been displayed, in filtration, in trying to relate the numerous variables to some general form.

In this report, a summary of the research on filtration is given. It is quite impossible to include everything in great detail. Instead, general trends are indicated and the more outstanding problems highlighted. As a departure from typical summaries, in one section the quoted opinions of some of the workers are presented. It is hoped that from this summary, a better appreciation of the current problems of filtration will be obtained.

HISTORICAL DEVELOPMENT OF FILTRATION THEORY

From D'Arcy's Law to the Kozeny-Carman Equation

In 1856, D'Arcy formulated his law for flow in porous media, as follows:

$$u = K\frac{P}{L}, \qquad \text{.. (Eq. 1)}$$

where

u = the linear velocity of flow,
K = the D'Arcy coefficient,
P = pressure, and
L = thickness of filter cake.

The formula bears a definite resemblance to Poiseuille's Law, earlier conceived for flow in capillary tubes.

It soon became obvious that the flow also depended on the viscosity, η, of the liquid. This modified D'Arcy's law to:

$$u = K_1\frac{P}{\eta L}, \qquad \text{.. (Eq. 2)}$$

where K_1 now is called the permeability coefficient.

In Equation 2 the determination of K_1 presents difficulties. Originally an attempt was made to describe permeability in terms of equivalent capillary diameters, but this resulted in highly erratic results and cumbersome treatment of permeability calculations.

In 1927 Kozeny suggested that permeability could be expressed in terms of surface area per unit volume of pore space:

$$\frac{S}{E} = \frac{S_o\,(1-E)}{E}, \qquad \text{.. (Eq. 3)}$$

where

S = surface per unit volume of filter cake,
S_o = specific surface of particles, and
E = porosity = pore space per unit volume of a granular bed.

Kozeny's equation for flow in a porous medium is given as:

$$u = \frac{E^3}{k S^2} \quad \frac{Pg}{\eta L} \qquad \text{.. (Eq. 4)}$$

Substituting the value for S from Equation 3, Equation 4 takes the form of:

$$u = \frac{E^3}{k(1-E)^2 S_0^2} \quad \frac{Pg}{\eta L} \qquad \text{.. (Eq. 5)}$$

In Equations 4 and 5,

k = a dimensionless constant, that was determined by Carman to have a value of 5.0, and
g = the acceleration due to gravity.

From a comparison of Equations 2 and 5, the Kozeny-Carman equation is derived for the permeability of filter cakes:

$$K_1 = \frac{E^3}{5(1-E)^2 S_0^{\ 2}}, \qquad \text{.. (Eq. 6)}$$

where all terms are a previously identified. As will be shown later, this is still one of the central assumptions of filtration theory. The original Kozeny permeability coefficient was given as:

$$K_1 = \frac{CE^3}{S_0^2 . (1-E)^2}, \qquad \text{.. (Eq. 7)}$$

where C is a dimensionless number. Limits for C were given by Kozeny, from theoretical calculations, as 0.5 for circular channels and 0.66 for thin rectangular channels. Carman from extensive experimental work, found C to be 0.2.

Application of the Filtration Equations to Filter Cakes

The development of the first filtration equation warrants a detailed treatment. The flow in porous beds as given by Equation 2 may also be expressed as:

$$u = K_1 \frac{P}{L} = \frac{1}{A} \quad \frac{dV}{dt}, \qquad \text{.. (Eq. 8)}$$

where

V = volume of filtrate passed in t seconds, and
A = cross sectional area of filter.

The thickness of the filter cake is related to the filtrate volume by:

$$L = \frac{vV}{A},$$

where v = volume of cake deposited by 1 cm^3 of filtrate.

The fundamental differential equation is expressed as:

$$\frac{dV}{dt} = K_1 \frac{PA^2}{\eta vV}, \qquad \text{.. (Eq. 9)}$$

where K_1 is the Kozeny-Carman equation given previously by Equation 6.

In Equation 9 the permeability coefficient K_1 describes the filter cake and the other terms represent the slurry, or external conditions. The reciprocal of K_1 is called the specific filtration resistance, r. Considering actual cases of filtration, there is an additional resistance to the cake resistance, namely the so-called initial resistance, R. Theoretically this is the resistance of the filter cloth only, but in practice it must be considered after a few passes of slurry where the initial resistance R will be increased by a certain amount because of some blocking of the pores of the cloth.

Incorporating this initial resistance into the filter equation 9, we obtain:

$$\frac{dV}{dt} = \frac{PA^2}{\eta(rvV + RA)}. \qquad \text{.. (Eq. 10)}$$

Solving this equation for time:

$$t = \frac{\eta rv}{2PA^2} V^2 + \frac{\eta R}{PA} V. \qquad \text{.. (Eq. 11)}$$

For an easier practical application, Carman suggested plotting t/V versus V, which yields the equation of a straight line of the type:

$$y = mx + b.$$

From this plot, the slope can be measured and it represents the term:

$$\frac{\eta rV}{2PA^2}.$$

The only difficult parameter to measure is V, the volume of cake deposited by V volume of filtrate. Carman (1) suggests steps to overcome this difficulty. A filter cake can now be described in terms of its specific resistance.

Carman warns that the specific resistance measurements should not be taken from the very beginning of a test. The first layer forming on a cloth is very critical, and it should be deposited very gradually at low pressure to avoid excessive blinding of the cloth. If blinding occurs, the plugged cloth might represent the greatest part of the total resistance. Carman in his derivations assumed that the filter cake was incompressible and that the flow through the bed was directly proportional to the applied pressure; unfortunately, this seldom happens. Generally, filter cakes are compressible and there is no direct relationship between pressure and flow.

However, Carman argues that D'Arcy's law still holds, because if the pressure is maintained constant, the flow will still be indirectly proportional to the cake thickness. On the other hand, in such cases the specific resistance of the cake will not be constant but a function of P, the pressure. There are references given in paper (1) as to the tested validity of Equation 11.

Suggested relationships between the specific resistance r and P vary with individual workers and the type of materials being filtered. To illustrate, one equation advocated by Lewis et al.(1) is:

$$r = r'Ps,$$

where r' and s are constants, characteristic for each cake. A general relationship between P and r is not yet definitely established.

Initial resistance is very important in filtration. In theoretical work it is often assumed as another constant, but its origin and development seem to be more complex. Research into its nature is rather limited. Earlier investigators recorded their observations and some of the anomalies, but it remained a little known factor of filtration. Hatscheck in 1908 (1) and Gilse, Ginneken and Waterman in 1931 (1) presented their studies on initial resistance. Hermans and Bredee (1936) reported that when solutions or slurries are extremely dilute, no cake is formed at all and the solids are trapped by adhering to the walls of pores. Water purification by sand filters is based entirely on this principle.

After 1938 the major objective of filtration research was the so-called permeability-pressure relationship. The historical development of filtration is given an excellent treatment by Carman (1). This paper also gives a complete literature survey covering the period from 1856 to 1937, consisting of 179 listed references.

Filtration Research in North America

(a) Research in North America began with the recognition by Sperry, in 1916-17 (3, 4), that the initial resistance must not be omitted in theoretical calculations if any correlation between test data and theoretical results is to be expected.

b. A new era in research really started with Ruth (5) in the thirties. He began working on the factors affecting cloth resistance. Ruth was a strong advocate of applying theory to industrial filtration processes. He firmly believed that the existence of filtration research depended on its usefulness in describing and predicting filtration processes.

To study in more detail the dependence of cake porosity on applied pressure, Ruth and co-workers developed the compression permeability cell (5). In this cell, the cake was subjected to a mechanically applied stress while water passed through it at constant pressure. Timing the discharge for different stress loads, a permeability value could be calculated. Changes that occurred in the bed structure like volume decrease due to the stress were measured from changes in the position of the piston.

Ruth noted that beds, as a rule, were more permeable to air than to water. The magnitude of this difference in permeability suggested to him that, for liquids, a certain portion of the voids is not available for flow. This, he noted, was due to the "dead void volume".

Ruth suggested the following equation that includes a correction for the dead void volume (6):

$$\frac{dV}{dt} = \frac{(E-E_o)^2 \delta f^2 R_p^2}{K'''} \cdot \frac{A^2 Pg}{\eta W}, \qquad \text{.. (Eq. 12)}$$

where

E_o = dead void volume,
δ = density of granular solids,
f = shape factor,
R_p = average radius of particles,
η = viscosity,
A = area of filter,
P = pressure,
g = acceleration due to gravity, and
K''' = constant.

In this paper (6), Ruth gave detailed calculations for different filtration conditions and materials.

From the observation of the existence of "dead void volume", Ruth advanced the theory that it resulted from surface interactions between the solids and liquid. He believed that pores not available to fluid flow were created by resistances set up by the electrokinetic phenomena. Although Ruth's discussion on this topic is qualitative, there are ample results available to demonstrate that the resistance from surface interactions can be significant.

Other researchers, such as Grace (8), did not find any evidence of the dead void volume. Abramson (7) investigated the retarding effect of the electrokinetic phenomena on flow for capillaries used in viscosity measurements. The magnitude of retardation greatly depends on the size of the capillary. By similar reasoning, the multiplicity and the irregularities of capillary channels encountered in an actual filter cake can create sufficient resistance to halt the flow through certain paths.

c. Grace (8), with an improved version of the compression permeability cell, tested a wide range of materials. He found that for a number of materials the specific filtration resistance values agreed with results obtained from filtration test runs. However, Grace concluded that the Kozeny-Carman equation could only be used to correlate the results if a variable value were assumed for the specific surface term S_o. Grace's tests confirmed the effect of flocculation on cake porosity. With flocculation, porosity increased and resulted in an increased flow.

d. Under Professor Tiller, at the University of Houston, a graduate school of filtration research was established. The control problem was the porosity-pressure relationship. A number of papers were presented (9, 10, 11, 12, 13, 14) dealing with the subject in an analytical way. Tiller (10) gave equations for the porosity and local specific resistance as a power function of the solid pressure. He also proposed that the sum of the solid pressure and liquid pressure at any point is equal to the applied filtration pressure. In later papers (12, 13, 14), equations for flow through compressible media in which the discharge varies with cake thickness, and other equations for the average porosity of a cake as a function of applied pressure, are presented. These papers postulated the theory that the flow into a cake is not equal to the flow out of the cake. To quote: "Flow rate of filtrate into a cake is not equal to the flow rate out. Ignoring this fact may cause significant errors, especially when dealing with thick slurries." There may be other interpretations of this statement but the most obvious one is that this state can only exist if the liquid in question is compressible (2).

e. Porosity is accepted as the greatest single factor affecting flow through the filter cake. Alteration and modification of porosity in filtration by using flocculants is being thoroughly investigated by a research group under the leadership of Prof. V.K. LaMer at Columbia University. The emphasis in this work is on flocculation and flocculants, but their effect is assessed in terms of filtration rates, i.e. flow through porous media. From this work, a mechanism is suggested for the adsorption of the flocculants and the formation of flocs. Mixing and agitating the slurry and the high-polymer flocculant appear to be very critical in determining the final floc size. The major assumption in the LaMer group's work is that the flocs are essentially spherical and closely packed when formed; hence the other factors in the Kozeny-Carman equation, such as E the porosity, and L the thickness of the filter cake, will be constant (17).

According to the relationship found by LaMer et al., the curve of refiltration rate versus P_o, the initial polymer concentration, goes through a sharp maximum. LaMer gives the following equation for this:

$$Q - Q_o = \frac{k' P_o^{\,4}}{\left(\frac{1 + bkw}{b} + \frac{P_o}{1 + bkw}\right)^8}, \quad \text{.. (Eq. 13)}$$

where

Q = refiltration rate,
Q_o = refiltration rate without polymer,
k and k' = constants,
w = solid content, and
b = Langmuir adsorption constant.

This eighth-power relationship was tested and reported valid for phosphate slimes as well.

Further work regarding flocculation and filtration was carried out to investigate the variations of the optimum polymer concentration with varying amounts of solid content in the slurries, and a linear relationship was found. Methods for calculating some of the constants in Equation 13, and for calculating the fraction of the solid surface covered by the flocculants as a fraction of the added polymer concentration, are also outlined.

Other work by the LaMer-Group of researchers involves studies on the filtration of flocculated dispersions of both amorphous and crystalline silica (18, 19).

f. Some less theoretical work on filtration was carried out by a number of people, mostly to create some formulas that can be used with reasonable accuracy in practical filter applications. Here we find the first clearly defined interest in filtration as an important part of metallurgical processes.

Dahlstrom and Nelson (21) present an analysis method based on some theoretical considerations. They recommend the use of an approach factor that allows reasonably accurate results. The authors nevertheless give a very concise statement on what really ails filtration when they say: "The empirical methods are not reliable for untried applications, and the theoretical methods usually require prediction of filter cake variables which are difficult to determine."

A paper dealing with steam filtration research at the Eimco Corporation was published recently by Simons and Dahlstrom (34). The goal was the significant reduction of final moisture by applying steam to heat the filter cakes prior to dewatering. The success of the process is said to be based on the drastic reduction of the viscosity of water. An analysis of efficiency and economic feasibility is also given in this paper, with a good list of references regarding steam filtration.

g. There are also a number of papers offering various attempts at filtration theory. Sharbaugh (25) developed "practical filtration formulae" starting out with D'Arcy's equation. Another illustration of general approaches to filtration is a paper by Martin (26) who suggests that all filtration problems can be solved by analogy to heat transfer, on the basis that in both phenomena:

$$\text{Rate of transfer} = \frac{\text{Driving force}}{\text{Resistance}} .$$

Developing this further mathematically:

$$\frac{dV}{dt} = \frac{K(-\Delta P)A}{\eta L} , \qquad \text{.. (Eq. 14)}$$

where V is volume of filtrate.

When the above equation is compared with a material balance for filtration:

$$\frac{dV}{dt} = \frac{dL}{dt} A(1-E)\rho_s \left(\frac{1}{W}\right)\left(\frac{1}{\rho_L}\right) \qquad \text{.. (Eq. 15)}$$

and then integrated, it gives an expression for cake thickness as:

$$L = \sqrt{C_F \ (-\Delta P) \ t} \qquad \text{.. (Eq. 16)}$$

where the constant $C_F = \frac{2KW}{(1-E)\eta}$

and the symbols are:

$(1-E)$ = volume of solids per unit volume of cake,
ρ_s = density of solids,
ρ_L = density of liquids,
η = viscosity of liquid,
P = pressure,
K = permeability, and
W = solids concentration = $\frac{\text{Wt of solids}}{\text{Wt of filtrate}}$.

Unfortunately, this new approach to a solution does not eliminate the difficulty presented by the determination of C_F.

h. There are numerous periodical reviews of equipment development and lists of manufacturers in the literature. Some of them give a well organized list of references dealing with filtration (22, 23, 24).

i. Of the filtration research done abroad, Rietema's work on compressibility and incompressibility of cakes, in Holland, is interesting (27). German efforts were mostly summed up by Carman (1). It should be noted that in very recent work on filtration, German authors still persistently use Poisseuille's law for theoretical support of their points (28).

Attention should be drawn to two very interesting papers on the little known "filter effect" phenomenon (29, 30).

Russian literature on filtration to 1963 is summarized in a paper by Cooper (31). A more recent Russian paper hints that filtration rates could be improved by treating water magnetically (32). In general the Russians are mostly concerned with the theoretical developments of the sand-filter mechanism which is one of the basic water-purification processes (33).

WHERE DOES FILTRATION THEORY STAND?

In a summary of filtration research, the numerous exhibited efforts to apply scientific methods to this process inevitably bring out the question: "Where do we really stand now with filtration theory and practice ?".

The answer can be obtained from these various opinions, given below in chronological order, by people who were and are involved in this work:

Carman (1938) : "There are great difficulties involved in bridging the gap between theory and application in dealing with problems in filtration. It is seldom possible to produce a sludge with constant filtering properties and this has hindered the application of the results of laboratory experiments to the design of full scale plants". "...... the filtration constants themselves are so dependent upon conditions of filtration that it is too risky a procedure to rely on laboratory data".

Ruth (1946) : "In recent years the understanding of the basic mechanism of separation by filtration and sedimentation operations has been considerably advanced and unified". "The failure of filtration equations and theory to be more useful in industrial practice arises, not so much from inability to correlate resistances in various methods of testing more precisely, as from an inability of industry to control the properties that determine specific filtration resistance to a degree sufficient to make the application of mathematical analysis worth while. Without such control, the design and selection of filters are necessarily based largely upon rule-of-thumb estimates intended to provide for the least favourable conditions likely to be encountered".

Grace (1953) : "The single useful and proved tool for attacking a cake filtration problem is the filtration rate equation".

Tiller (1961) : "Several obstacles have impeded progress in the filtration and flow through porous media field. First, the complexity of even the most simple model discourages investigators from attempting solutions. Second, the nature of particles

and precipitates forming filter beds is such that reproducibility becomes a serious problem".
"Although empiricism still plays a preponderant part in formulation of useful analytical expressions, nevertheless, theoretical advances are beginning to make headway in elucidation of basic phenomena".
"Filtration aims at discovery of relations between: volume of throughput, overall pressure differential, rate of flow, average bed porosity, mass of solid deposited, and time".

Englesberg (1962) : "Theory, even though seldom used in actual design, is valuable for interpreting laboratory tests and finding optimum conditions".

Perry (1964) : "Filtration, although one of the most widely used techniques in industry, has received comparatively little attention from research workers. This may be because its apparent simplicity is soon dispelled on closer examination. For example, difficulties in the specification and control of the cases, so that unknown parameters may be introduced before a study of filtration process itself has even begun".
"The industrial user of filters and the designer are interested in the developments taking place in the research background to filtration, but as yet the work done has been insufficient to provide much to change the empirical and intuitive approach".

FURTHER RESEARCH POSSIBILITIES

1) Theoretical Research

Any successful theoretical work in filtration can only be expected from a coordinated group of surface chemists, physical chemists and mathematicians. Closer contact with the rapidly growing developments of aqueous interface research is imperative. The central problem that remains involves the porous filter cake, the resistances set up by it, mechanically or electrochemically, and its influence on flow. Equations such as the Kozeny-Carman still have to be more thoroughly evaluated, and testing methods for pressure-porosity relationships further developed or refined. Models should be developed in a systematic manner and gradually brought closer to actual, but well controlled, systems of filtration.

2) Equipment

Filtration equipment will continue to be designed on economic and operating fundamentals until theoretical problems can be solved with a high degree of certainty.

Filters used in the ore dressing field are vacuum filters of either the drum or the leaf type. Here the final product is more desirable with a low moisture content. In present practice the only mechanical control over moisture content is the reduction or increase of the filtration cycle. This is quite ineffective in terms of productivity and appreciable moisture reduction. When a filter operates in the dry cycle, it removes moisture mostly by replacing it with air and, for a negligibly short time, by evaporation. However, when a sufficient number of channels are opened to air passage the water removal lessens drastically in other voids in the cake. This can only suggest that combining vacuum with a period of compression in the dry cycle would be most advantageous.

3) Filter Cloths

Present knowledge of what happens to the filter cloth in the filtration process is limited to the facts that (a) it becomes almost impermeable with time and (b) it wears mechanically or chemically. Whichever occurs first will require the operator to replace the filter cloth.

Information is lacking on the blocking of pores and the rate of blocking. As yet, no standard test is available to forecast the behaviour of a cloth during a filtration process. Blinding influences the amount of solids removed by the filter. This amount is also influenced by the "filter effect", i.e. changes caused by the liquid-solid interactions or, more simply, ageing. Some systematic testing should be carried out for the evaluation of the behaviour of various types of filter cloths, particularly the progression of filter cloth blinding.

4) The Slurry

Slurry, being the source of filter cakes, should be added to the list of subjects to be considered theoretically. The nature and control of slurry characteristics are more strictly in the realm of surface chemistry. Flocculation and the forces involved in wetting and adhesion should be major topics of research, with a view to eventually facilitating control of these forces.

Control of slimes is perhaps the most involved problem of filtration. It is almost impossible to produce slurries with constant characteristics. Most of the problems of inconsistency in the filter cake itself are derived from the inconsistent nature of slurries.

SUMMARY

1. Continuation of both empirical and theoretical research in filtration is important, as well as coordination of work through discussions, publications and conferences.

2. Some entirely new techniques should also be tested. A combination of vacuum-pressure filtration could mean significant improvement in final moisture reduction.

3. A minimum effort was expended on the study of the filter medium itself. Research should be pursued to study the development, nature and measurement of resistance offered by the filter cloth. An independent scientific method of cloth evaluation for a filtration process would be highly desirable.

4. The so-called "filter effect" is a very intriguing phenomenon of filtration. The flow through a porous bed decreases with time even when pure liquids are used. Under some conditions sudden increases of flow are observed.

5. A more theoretical approach is called for in evaluating the effects of wetting and the forces of adhesion on minute particles. It is believed that an enormous amount of useful information is already available in some related fields.

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